THE UNIVERSITY OF MICHIGAN

College of Engineering
Department of Civil Engineering

Technical Progress Report No. 2

RAIN SCAVENGING OF PARTICULATE MATTER FROM THE ATMOSPHERE

A. Nelson Dingle

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Concluded)

ABSTRACT

The design and construction of an Aerodynamic Raindrop Sorter is reported. Calibration and testing of this device remains to be done.

An effort was made, by the use of expedient measures, to obtain samples of rain more or less discriminated according to drop size. Experimentation with such measures was conducted, and the nylon-net technique proved most practical although it was only partially successful. Some results of this effort are presented. Raindrop-size distributions are presented and related to raingauge records.

Coordination of research plans with other research groups and efforts has progressed, and the results are discussed.

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INTRODUCTION

The objectives of the present research have been set forth as follows:

1. To construct a full-scale aerodynamic raindrop sorter along the lines of the present pilot model, and incorporating additional features of design suggested by experimental tests.

2. To collect, for radiochemical analysis, drop-size-defined aliquots of naturally falling rain, by means of the aerodynamic raindrop sorter, and to coordinate with these collections detailed raindrop-size spectra obtained using the photoelectric raindrop-size spectrometer, together with other pertinent information, with a view toward detailed evaluation of the natural scavenging function of rain.

3. To coordinate the activities under this project with those of other concerned units, and in particular, to arrange for joint field experiments with the unit under Mr. Fuquay's direction.

Progress toward the realization of each of these objectives is reported in the first three chapters of the report. Chapter 4 contains a discussion of additional sub-projects which have been undertaken but which were not anticipated when the proposal of research was prepared.

CHAPTER 1

Aerodynamic Raindrop Sorter Design and Construction

The problem of sampling rain according to raindrop-size defined categories was studied in some detail during the first year of the present project. The results of these studies are contained in Technical Progress Report No. 1.[1] The engineering design of a full scale aerodynamic raindrop sorter was projected upon the basis of those findings, compromised as favorably as possible to meet practical considerations. Working drawings are included herewith as Plate I.

General Design Criteria

The analysis showed that reasonably useful impingement patterns should be obtained by the use of an upward-tilted wind-tunnel, and that flaring of the tunnel should also be beneficial. However, the degree of flare required to produce a substantial effect is too great to preserve laminar flow, hence the decision was made to use a constant cross-section design for the raindrop sorter.

The upward tilt of 45° was retained in the basic design for the reasons set forth earlier.[1]

The unevenness of flow observed in the pilot model had been attributed largely to inadequacies of the intake design and of the fan arrangement in that model. Practice in wind tunnel design[2,3] has led to criteria for a contraction section and straightening screens at the intake as a means of attaining laminar flow in the test section. The intake of the aerodynamic raindrop sorter was designed according to these criteria.

Study of the air flow in the light of wind tunnel experience also led to the decision to place the fan downstream from the laminar-flow section. This largely prevents the vorticity generated by the fan from entering the test (or raindrop-sorting) section.

It was necessary to consider the relative merits of closed-circuit versus open-end wind tunnel design for the present purpose. Whereas the closed-circuit design would serve to isolate the wind tunnel as completely as possible from dynamic influences of the free wind field, and would make possible the maintenance of a clean and saturated condition of the wind tunnel air, it would require a much more bulky structure, and rather elaborate temperature control apparatus would be needed to prevent evaporation or condensation from occurring in the tunnel. Aside from wind-tunnel design, for the moment, the requirement that raindrops fall vertically through the entrance slit into the sorting section, requires some means of eliminating horizontal momentum from the falling rain above the entrance slit. In the field situation, this may be done by providing a settling column, open at the top to receive a representative rain sample, and sheltered from horizontal motion of air. Considering that the raindrop sorter must be located in such a settling column for these reasons, the additional isolation of a closed-circuit wind tunnel appeared to be superfluous. It was therefore concluded that an open-end wind tunnel should more simply serve the desired purpose.

Because it is anticipated that the unit will be used at various sites separated by appreciable distance, and because the unit can conveniently be divided into structurally independent sections, a final general design criterion was that of convenient disassembly for packing and shipping.

Design Features

A 4 to 1 ratio was finally used in the specification of the contraction section. Four screen sections of .015 in. wire spaced at .062 in. centers in both directions are used in the contraction section. These are designed to be assembled separately and to bolt to the entrance fillet.

The sections of the unit are so designed that each part weighs less than one hundred pounds. This allows for ease of dismantling, moving and reassembly by a crew of two men.

Consideration of the speed of flow desired (4 m per sec maximum) and the pressure losses in the system led to the specification of a six-blade vane axial fan driven by a 1/3 hp, 1750 rpm, single phase, 110 v motor. Turning vanes were designed to prevent flow separation and turbulence in the test section.

The physical aspect of the unit together with the basic requirement of adequate sample size led to the preliminary specification of a 2 cm x 50 cm entrance slit for the rain sample. Studies of the drop trajectories in the test section then indicated that, with a 4 m per sec air speed, sufficient separation of the largest drops would be obtained within a tunnel depth of 43 cm, and 0.6 mm diameter drops would strike the floor of such a wind tunnel 1.41 m downstream from the impaction point of an undeflected drop. These considerations are shown graphically in Figure 1. In the case of a 2 m per sec air speed, the separation of the largest drops is poorer, but the smaller drops do not move so far downstream before impaction (Figure 2).

In either case, the smallest drops are carried out of the tunnel unless special provision is made to collect them. For this purpose turning vanes and collecting screens are to be used. The turning vanes will collect the larger sized drops in this size category by inertial impaction, and the collecting screens (e.g., see Twomey[4]) will intercept a proportion of the smallest drops. There appears no simple means to avoid a considerable evaporative loss from this smallest drop category. Independent data on the drop-size distribution will be used to estimate the error and to make allowance for the evaporation.

Construction

Upon completion of the design (see Plate I), estimates were obtained of the cost of constructing the unit. The Plant Department, The University of Michigan, was selected as the best bidder, and the job was placed there. Construction was completed on January 20, 1961, and photographs of the assembly are shown in Figures 3 and 4.

Experimental tests of the performance of this unit will be performed in the laboratory. Refinements of design will be derived from these tests and incorporated into the instrument in the next phase of this work. Every effort will be made to prepare the unit for field operations by mid-March.

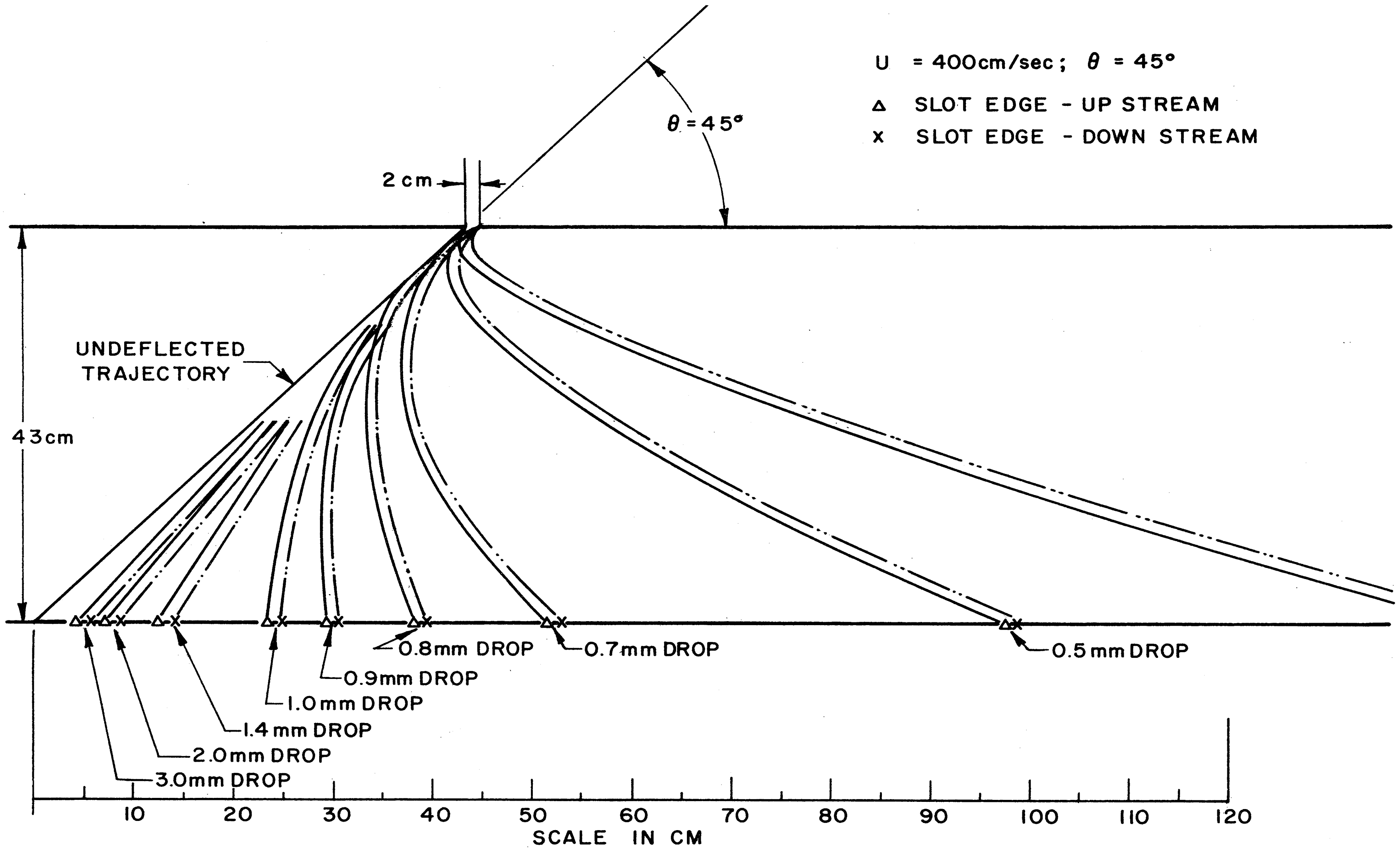


Figure 1. Design criteria for depth and length of drop-sorting section, and estimation of errors of resolution, for 4 m per sec air speed.

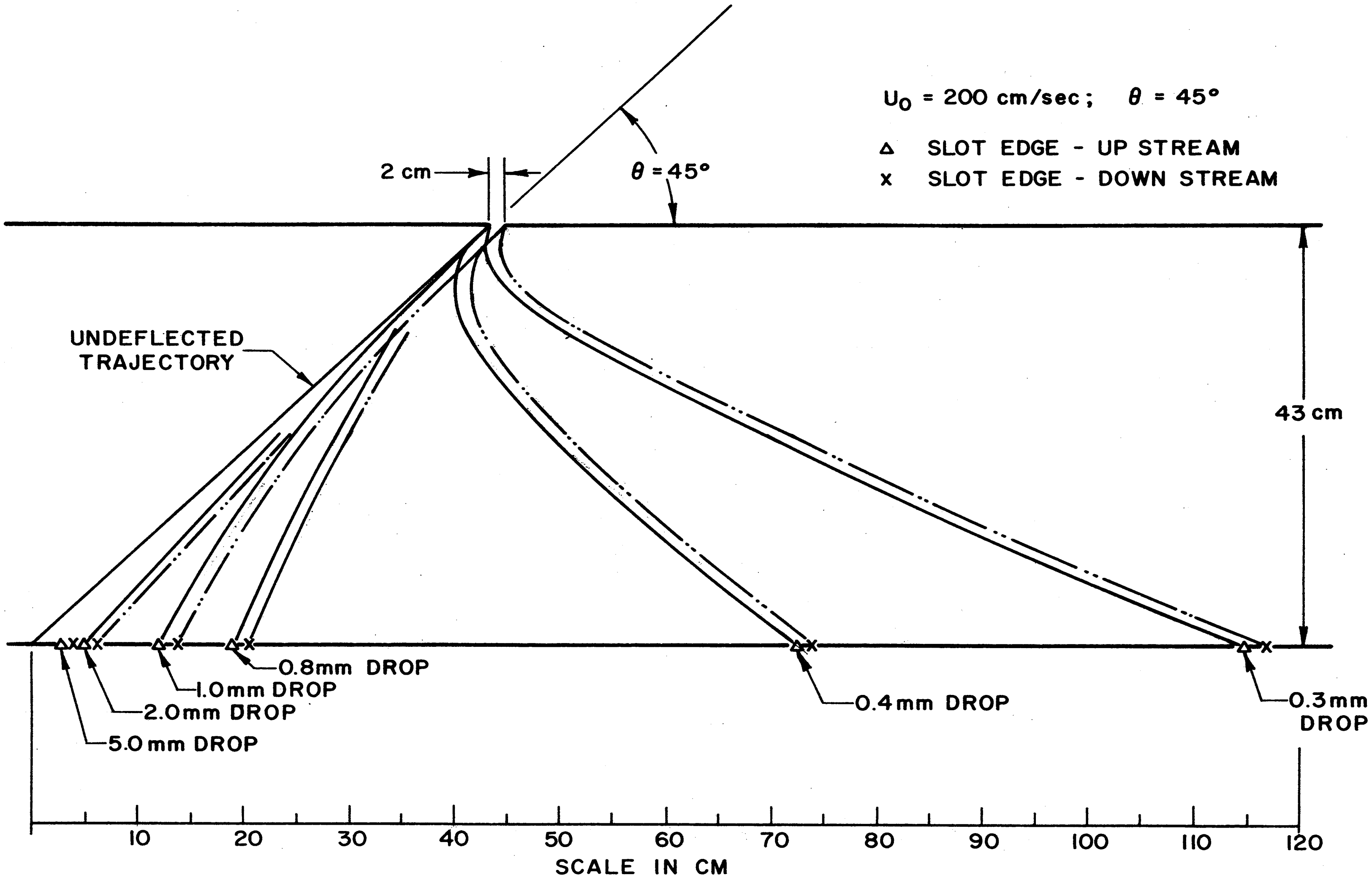


Figure 2. Design criteria for depth and length of drop-sorting section, and estimation of errors of resolution, for 2 m per sec air speed.

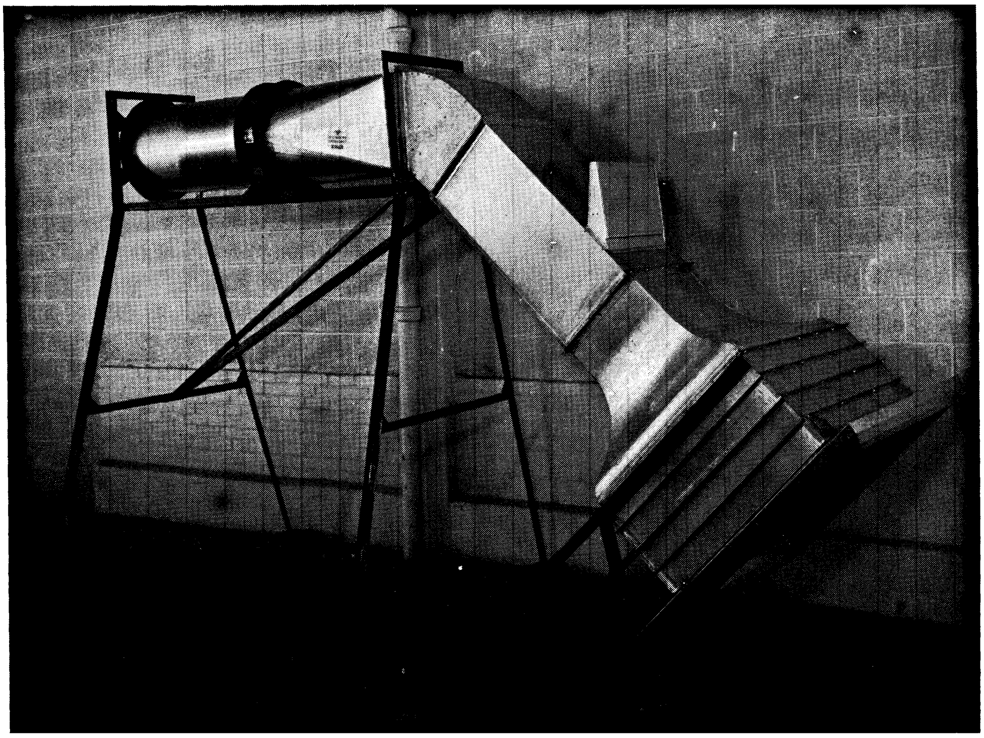


Figure 3. Photograph of the aerodynamic raindrop sorter showing, entrance fillet, straightening screens, contraction section, and rain sampling slit assembly.

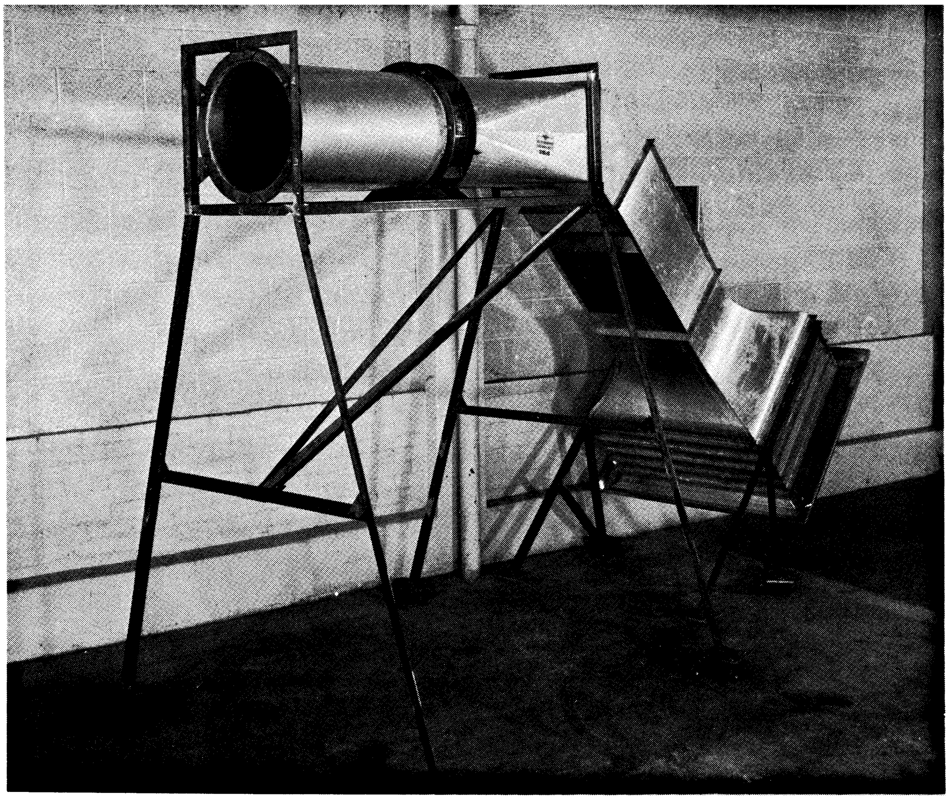


Figure 4. Photograph of the aerodynamic raindrop sorter showing tunnel exhaust, working section (floor removed), and support structure.

CHAPTER 2

Collection and Analysis of Drop-Size-Defined Aliquots of Rain

Preliminary Rain Sampling Program

To gain experience with the problems of sampling rain, of handling the samples and analyzing them, and of managing all the details that go with such experimental procedures, and also to gain some initial information on scavenging effectiveness of large versus small drops, a preliminary program of rain sampling was established early in the summer of 1960. In this program experiments have been conducted with several different, relatively crude, methods of separating drops according to size in the sampling procedure.

The nylon net method. One such method is to stretch a net of nylon over the mouth of a standard rain gauge and to hang a weight from the center of it thus forming a conical shaped net surface (Figure 5). Drainage from the lower point of the net cone is then caught in the inner container of the rain gauge and the part of the rain water which does not flow along the net cone to its center is caught in the outer portion of the rain gauge. It is supposed that the portion of the rain caught in the inner part of the rain gauge is biased toward the small-drop fraction of the rain, and that that collected in the outer part of the rain gauge mainly represents the large-drop portion of the rain. Beyond this statement it is very difficult to tell just exactly how the rain is divided by such a net. Our experience assures us that some division is accomplished.

The rapid freezing method. Recognizing the extreme crudeness of the nylon net method, we considered whether some other techniques might not work. One idea which came forward was that of freezing the raindrops very quickly upon impact and separating the resulting ice pellets by means of a set of standard aggregate sieves. The samples resulting from this method should then be quite precisely separated according to drop size. An added attraction of this method was that using liquid nitrogen, as we did, in a rather wide-mouthed container (Figure 6), we could expand the area of sampling some ten-fold over that of an ordinary rain gauge, and we could do this very conveniently. Although we

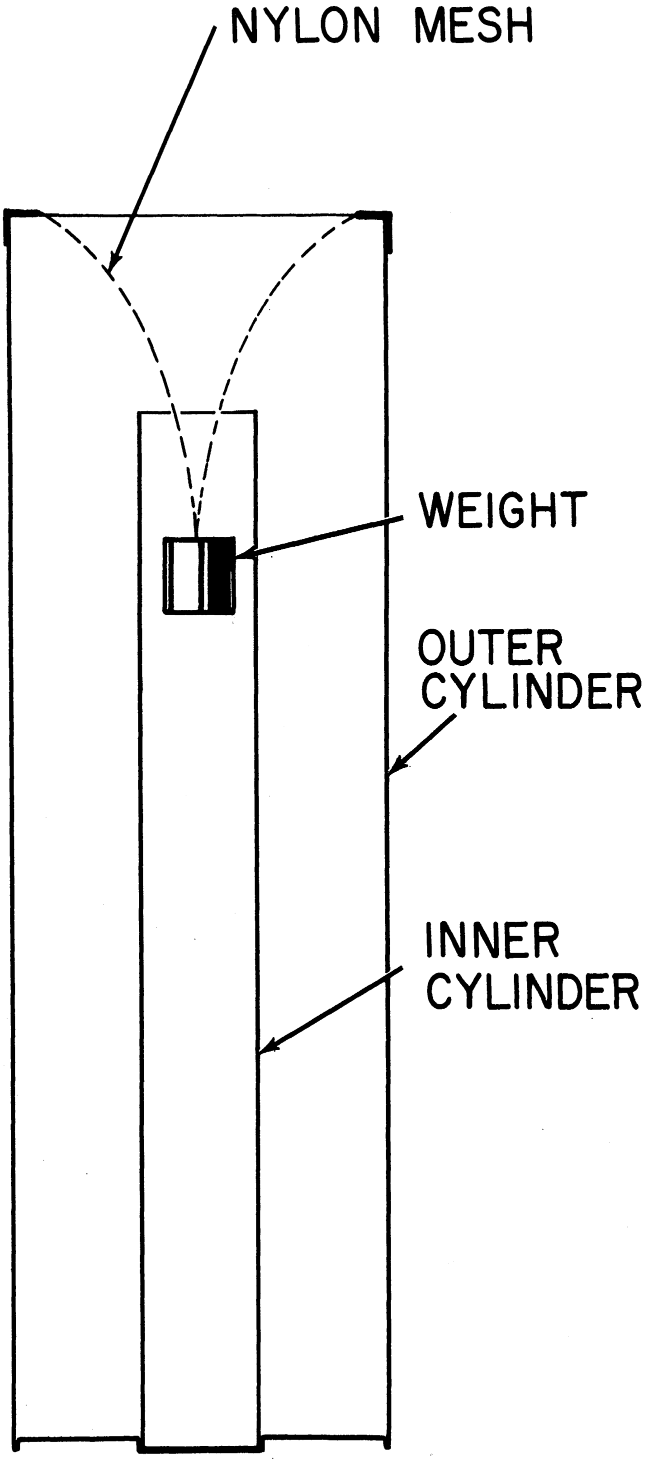


Figure 5. Cross-section of a standard rain gauge showing nylon net in place.

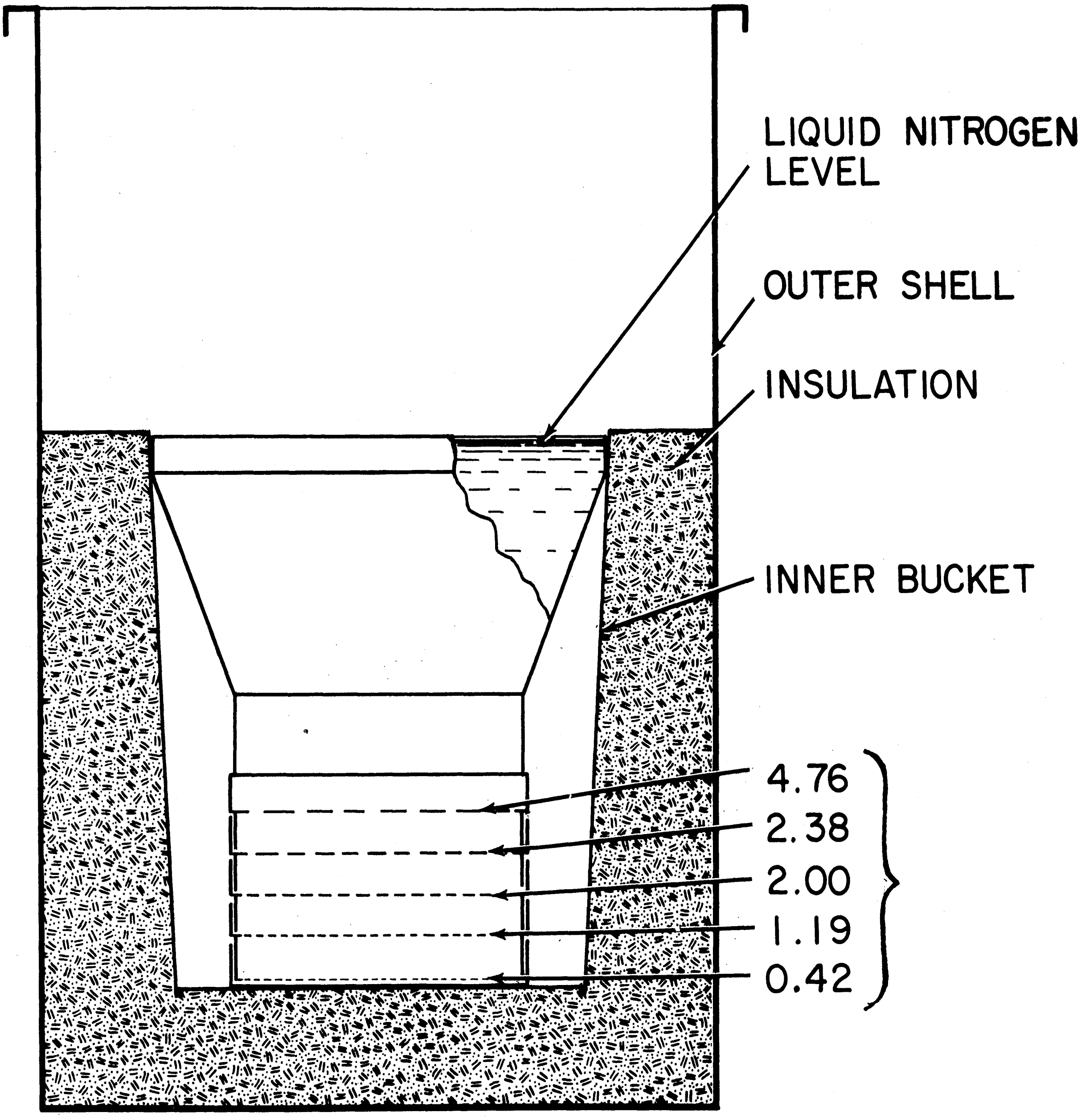


Figure 6. Cross-section of liquid nitrogen rain-collecting apparatus.

had misgivings about this method because of the likelihood of drop shatter upon impact, and because of the extreme thermal stresses which must be present in a rapidly freezing ice pellet, we were not entirely prepared for what we observed.

Among other things, we found that the ice pellets tended to form clusters, that is, a number of small very nearly spherical ice pellets would be found stuck together. Because the specific gravities of water and of ice are nearly 25 per cent larger than that of liquid nitrogen, we had assumed that gravity would prevail, and that the water substance would fall below the surface of the nitrogen and remain there throughout the freezing phase. What we found out upon dripping water drops into a container of liquid nitrogen was that the drop, if dropped from a relatively low elevation, would fall down into the liquid nitrogen pool as a single particle, but would immediately emerge again on the surface of the liquid nitrogen. There it would scoot about the surface causing the nitrogen below it to boil until thermal equilibrium was reached between the ice and the nitrogen, at which time it would sink down into the liquid, and onto the sieves. This activity on the surface of the liquid nitrogen was most fascinating, but of course it defeated our purpose because of the clustering it produced.

The freezing technique still had a number of attractive features about it. We therefore considered that if we could find a fluid of low surface tension which would not be soluble in water and which would remain fluid to quite low temperatures, that we might arrange a cooling system to maintain such a liquid at temperatures well below freezing, and thus salvage some of the benefits of this technique. Table 1 gives pertinent data on fluids that appear to meet these physical requirements. Of the various materials tried, the most nearly successful was Dow Corning 200 Fluid. This was placed in a container and chilled to about -78°C, using dry ice. Drops were dripped into the container from an eyedropper. In this case the behavior of the drops was still somewhat similar to that in the liquid nitrogen. First they sank, then they came back to the surface and moved about making a sound somewhat similar to that made by a flat knife blade held on a piece of dry ice. Finally the respective ice pellets formed an equatorial-plane split as the freezing went to completion and the noise stopped.

Obviously, the hemispheres thus produced are nicely related to the size and number of the drops from which they are formed and from this point of view, they are quite satisfactory. However, it was still necessary to examine the impact shattering problem.

TABLE 1

Properties of materials that might be used in the cold sampling method

Compound	Surface Tension dyne/cm	Density gm/ml	Freezing Pt °C	Boiling Pt °C	Solubility gm/100 gm H_2O	Remarks
Anyl benzene		0.860(4-22°C)	-78.25	202.1	i	
Butyl benzene		0.860(20°C)	-81.2	183.2	i	
Propyl benzene	30.6(4.5°C)	0.862(20°C)	-101.6	159.2	.006(15°C)	
2, 2 Dimethyl butane	18.2(0°C)	0.649(4-20°C)	-98.2	49.7	i	Flammable, boiling pt too low
2, 3 Dimethyl butane	19.4(0°C)	0.668(17°C)	-135.1	58.1	i	Flammable
2 Methyl butane	19.4(-20°C)	0.621(19°C)	-160.5	28	i	Very flammable
Cumene		0.862(20°C)	-96.9	152.4	i	Tried
Cyclohexene		0.810(20°C)	-103.7	83	i	Too expensive
Dow Corning "200 Fluid"	16.8(25°C)	0.818(25°C)	-123(°F)	100(°F)	i	Tried
Buthyl ethyl ether		0.752	-124	91.4	i	
2-5 Dimethyl; 2-4 Hexadiene		0.716(4-21°C)	-91.3	102.5	i	
1 Chlorohexane		0.872(4-20°C)	-83	132.4	i	
2-5 Dimethyl hexane		0.699(4-20°C)	-91	108.2	i	
2 Methyl hexane		0.679(4-20°C)	-119.1	90.0	i	
3 Methyl hexane		0.687(20°C)	-119.4	91.8	i	
1 Hexene		0.673(4-20°C)	-98.5	63.5	i	
1 Hexyne		0.736(0-4°C)	-150	71.5	i	
Octylene		0.722(17°C)	-104	123	i	
2, 2 Dimethyl pentane		0.674(20°C)	-125	79.2	i	
2, 4 Dimethyl pentane		0.673(20°C)	-123.4	80.5	i	
Ethyl methyl sulfide		0.837	-104.8	66	i	
Valeronitrile		0.801	-96.0	141	i	

Serious shattering was observed when the drops were released from 3 ft and higher elevations. At this point, the freezing method was set aside. The suggestion has been made that a braking layer of a viscous gas, or a freezing process that precedes impaction or shatter-producing braking might overcome the difficulty. These possibilities are under study.

Vertical air flow method. Still a third method of separating out a certain drop-size fraction of the rain was considered. This was to be accomplished by means of a small vertical wind tunnel in which the air speed would determine the drop sizes rejected from the entrance (Figure 7). After some consideration of this method and of the problems involved in getting a uniform air stream at the mouth of the sampler, of wall wetting, and so forth, this scheme was abandoned because of (a) the excessive costs of activating it and (b) its relatively low yield of information.

Analysis of the Rain Samples

The preliminary rain sampling program was begun in June 1960.

The liquid nitrogen method. Four storms were sampled using the liquid nitrogen method before that particular technique was given up. In the first of these, on June 16, a total rainfall of 1.24 in. was sampled, and 118 gm of ice pellets were collected distributed in six different size samples which ranged in weight from 8.8 gm to 31.2 gm. The radioactivity counts for these samples varied from 0.6 to 1.7 μμc with counting error estimates ranging from 19 to 58 per cent and the average count was 46 μμc per kg ±45 per cent. The second of these storms, on June 22, gave a total rainfall of 0.85 in. and the samples totaled 47.8 gm. The size fractions for this rain were mostly too small to give measurable beta counts. The third and fourth storms sampled by the liquid nitrogen method gave too little rain for analysis by the available instrument. Because of the errors of sizing and counting in this method (see above), no interpretation of the results is attempted.

The nylon net method. This technique has been used in some thirty storms. Of these, many produced rain too light to provide a sample. Experience with the method indicates that a storm must yield at least 0.4 to 0.5 in. of rain to give useful data. Information on samples collected by this method is presented in Table 2.

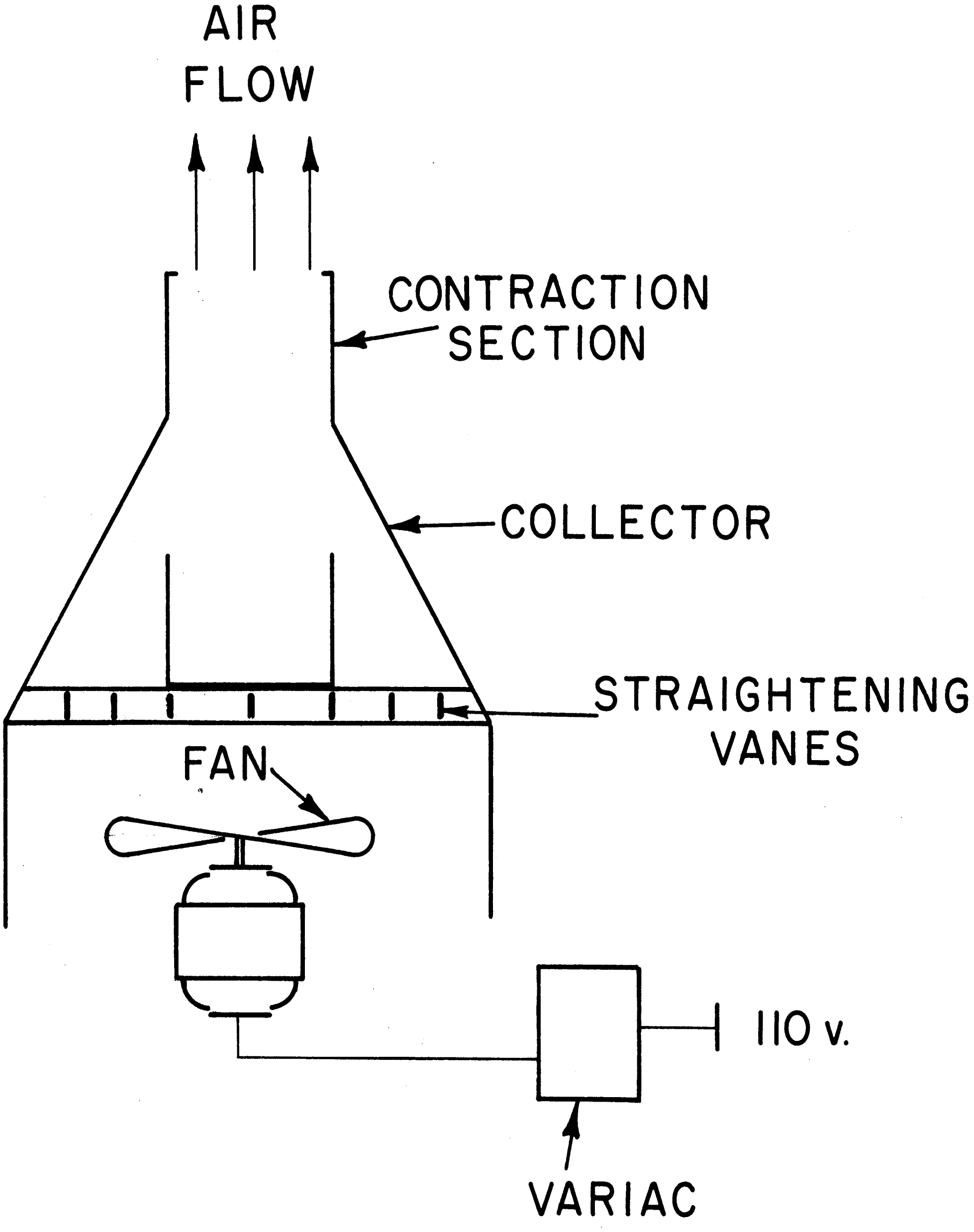


Figure 7. Cross-section of apparatus for vertical wind-tunnel separation of drops.

TABLE 2

Radioactivity of rain samples collected by nylon net method

1	2	3	4	5	6	7	8	9
				Mass	Radioactivity			
Date 1960	Sample No.	Size Category	Mass gm	Fraction %	Total μμc	Fraction %	Error %	Average μμc/kg
	1	large	627.6	32	7.7	32	13	12.1
6/12-14	3	small	365.8	18	4.7	19	18	12.8
	38	large	988.3	50	12.0	49	10	12.1
			1981.7		24.4			12.3
6/14-15	33	large	143.8	90)	Not measurable			
	35	small	16.1	10)				
			159.9					
7/2-3	2	large	*		9.5	93	12	-
	32	small	*		0.7	7	54	-
			757.7 *		10.2			13.5
8/3 a.m.	40	small	35.6	7	0.5	12	60	14.0
	41	large	464.9	93	3.6	88	20	7.7
			500.5		4.1			8.2
8/3 p.m.	42	small	24.7	10	0.1	4	80	4.0
	43	large	216.0	90	2.4	96	28	11.1
			240.7		2.5			10.4
	45	small	140.3	11	1.0	6	52	7.1
8/10	46	large	767.1	60	10.0	58	10	13.0
	47	large	379.1	29	6.1	36	15	16.1
			1286.5		17.1			13.3
8/15	48	small	53.3	11	1.7	16	36	31.9
	49	large	434.2	89	9.0	84	11	20.7
			487.5		10.7			21.9
9/19	51	small	72.3	12				
	52	large	544.6	88				
			616.9					
10/14-15	C (53	small	288.1	26				
	C (54	large	824.7	74				
			1112.8					
	D (55	small	177.5	16				
	D (56	large	922.4	84				
			1099.9					
11/15-17	61	large	127.0	62				
	63	small	78.1	38				
			205.1					

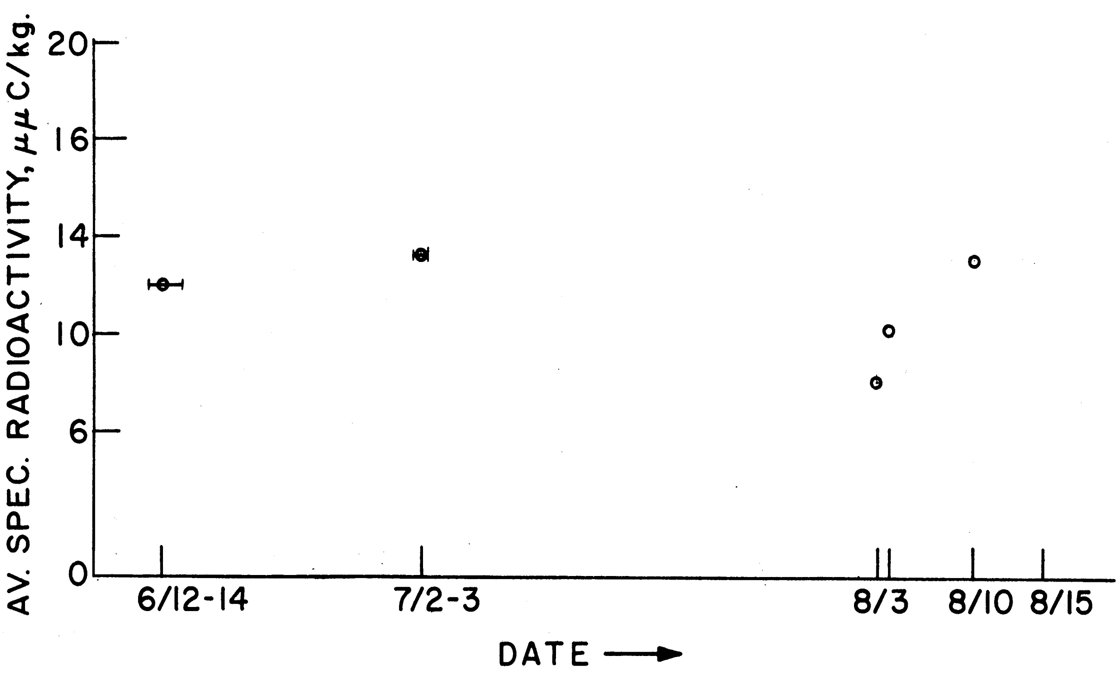
* By an oversight, these samples were not weighed. Total sample mass is estimated from independent rain gauge information.

The radiological analysis, which is performed by The National Sanitation Foundation, School of Public Health, The University of Michigan, provides a thallium-204 equivalent gross beta count (column 6) together with the 95 per cent confidence error estimate (column 8) for each sample submitted. The fraction of the radioactivity (column 7) and the specific radioactivity (column 9) for each sample are then computed.

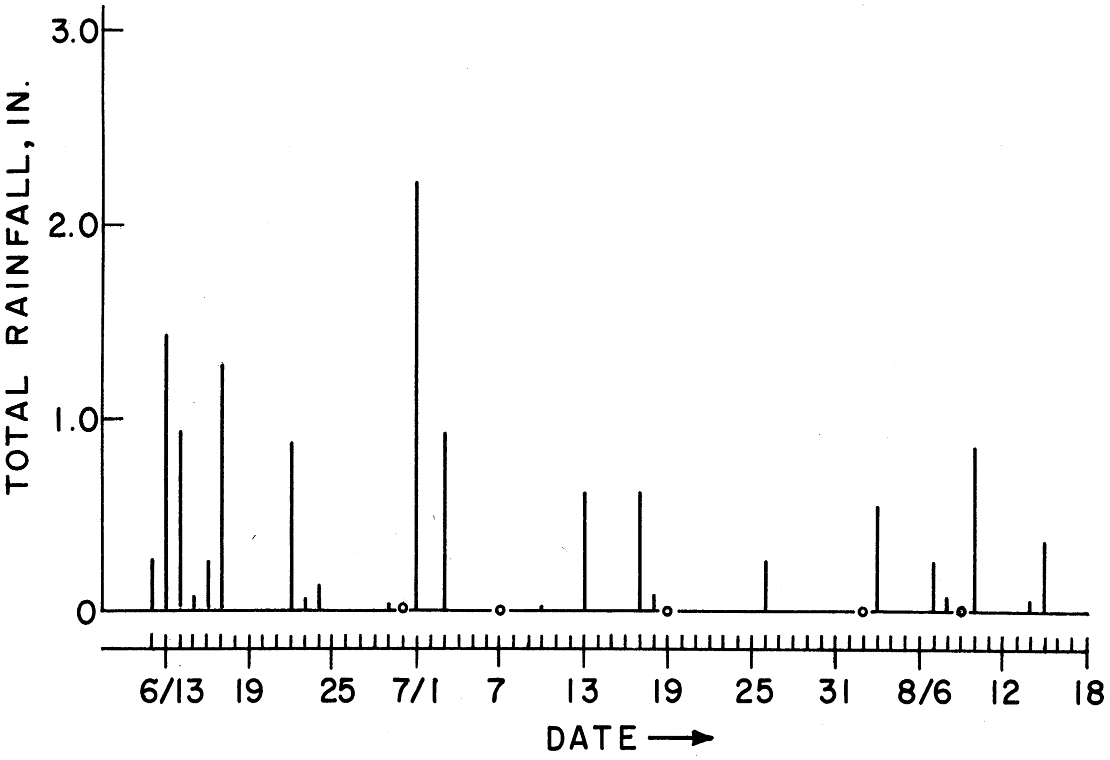
The changes of specific radioactivity between storms are of interest, particularly as they pertain to the transfer of radioactive debris from the stratosphere to the troposphere and to its dispersion within the troposphere. Figure 8 shows the average specific radioactivity levels for rains sampled by the nylon net method, and also the rainfall amounts recorded for all rains at Ann Arbor during the period June 12 to August 15, 1960. There appears a general level of radioactivity near 12 to 13 μμc per kg of rain. The samples of August 3 gave counts below, and those of August 15 gave counts considerably above this value. The rain of August 3 essentially terminated a hot dry period of eight days' duration, at the end of which unirrigated lawns were completely brown. That of August 15, however had been preceded more closely by substantial rain on the 10th (of 13 μμc per kg specific activity) and a light rain on the 14th. The implications of the synoptic situations are not clear, and considerable compilation and study are needed to clarify them. The large counting error associated with these samples strongly suggests that such a study on these data is not justifiable; nonetheless, it is appropriate to consider whether the excess of radioactive materials present on August 15, and the relative deficit on August 3 might be explained in terms of stratosphere-troposphere exchange.

Bleichrodt, et al[5] have reported a dramatic change of radioactivity associated with a cold frontal passage on October 31, 1958. This change is related through the air trajectories traced in the respective air masses to the high-latitude tests conducted in the earlier part of October.

Dyer and Yeo[6] infer from their observations of radioactivity levels in weekly samples of rain that the original cloud of contamination injected at low latitude remains discrete in the lower stratosphere for six to nine months. They cite evidence that suggests a poleward drift of the debris cloud at a mean rate of about 1.1 m per sec from near the equator to 38°S accompanied by a lateral spread of about 180° of longitude seven months after its introduction into the stratosphere. These authors do not attempt to postulate a mechanism whereby the contamination enters the troposphere from the stratosphere.



(a) Average specific activity ($\mu\mu$c per kg) of rain collected at Ann Arbor, Michigan, June-August, 1960. Horizontal bar indicates time of accumulation of rain sample.



(b) Total rainfall at Ann Arbor, June-August, 1960.

Figure 8

Most speculation on the question of the synoptic distribution of radioactive contaminants in the atmosphere tends to the notion that in the absence of renewed nuclear tests, the distribution of radioactive contaminants should in time become quite uniform as the concentration diminishes. Although it is likely in the present case that sampling and counting errors contribute effectively to the observed variations of concentration between storms, the possibility remains that real changes may occur and may be related to irregular stratosphere-troposphere exchanges. The hypothesis in this case would be that irregular injections of radioactive material from the stratosphere into the troposphere may produce a non-uniform distribution of the materials in the troposphere, and result in changes of the type shown by our data. A rather low general background level of radioactivity should then prevail, and relatively infrequent and brief increases above this level should be associated with such localized injections of stratospheric air as suggested by Reed.[7] The occurrence of such an intrusion of stratospheric air into the troposphere in the formation of a katafront may or may not place this air directly into a rain-generating situation in the troposphere. A substantial synoptic investigation, such as Reed's, would be necessary to establish this point, and of course this will be justified for those cases in which the radiochemical data are sufficiently accurate.

<u>The differences of radioactivity levels within storms</u>, as shown by the values for the respective drop-size fractions (columns 6 and 9, Table 2) also deserve some discussion. Initially it is necessary to consider the role of the nylon net in separating the drop size fractions. Since the inner cylinder of the rain gauge has a cross-sectional area one tenth as large as the outer container, ten per cent of the rain should enter the inner container without benefit of any biasing effect of the conical net. In addition, small drops that impinge upon the net without penetrating it contribute water which tends to flow along the net surface to the inner cylinder. Laboratory tests indicate that about 50 per cent of the 0.8 mm diameter drops which strike the net at their terminal speed penetrate it. Data obtained using the raindrop-size spectrometer show that about 10 per cent of the total mass of a typical summer rain is contained in drops less than 0.8 mm diameter. If the biasing effect of the net were limited to this drop size class, depending upon the applicability of the 10 per cent mass estimate for the specific rainfall in question, 19.0 per cent of the total catch of rain should be found in the inner container. In the storms of June 12-14, October 14-15, and November 15-17 (Table 2) the small drop fractions comprise about this proportion of the total sample. The problem of explaining an

inner cylinder catch of less than 10 per cent is raised in the case of the morning rain of August 3. The most ready explanation is the possibility of a handling mistake or a weighing error. The alternative possibility of strong wind and of evaporation from the net producing this effect should not be overlooked, however. The other storms gave samples somewhat less biased than expected by the above reasoning. More complete explanation of these mass proportions is contemplated following reduction of the raindrop-size data.

The partitioning of the radioactivity among the rain fractions is of special interest. Column 9, Table 2, gives the respective specific activities for the samples that have been analyzed. Interpretation is tenuous because of the large counting errors (column 8) associated with the small samples. In the first storm (June 12-14), however, these errors are only moderate, and computation of the respective levels of radioactivity of the drop fraction smaller than 0.8 mm diameter and of the large drop fraction may be made under the assumptions discussed above. The result is a specific activity of 12.1 μμc per kg for each part of the large drop sample and 13.5 μμc per kg for the small drops. The corresponding figures for the August 15 storm are much more extreme: 20.7 and 139 μμc per kg for the large drop and small drop fractions, respectively.

There appears little point in attempting such estimates for the other higher error samples, but evidently the strongest evidence of the present data is that the small-drop fraction of the rain is characterized by higher specific radioactivity than the large-drop fraction. The most obvious mechanism available to produce this effect is evaporation from the small drops during their fall and from the surface of the collecting net. An analysis of the evaporative losses will be essayed for a future report.

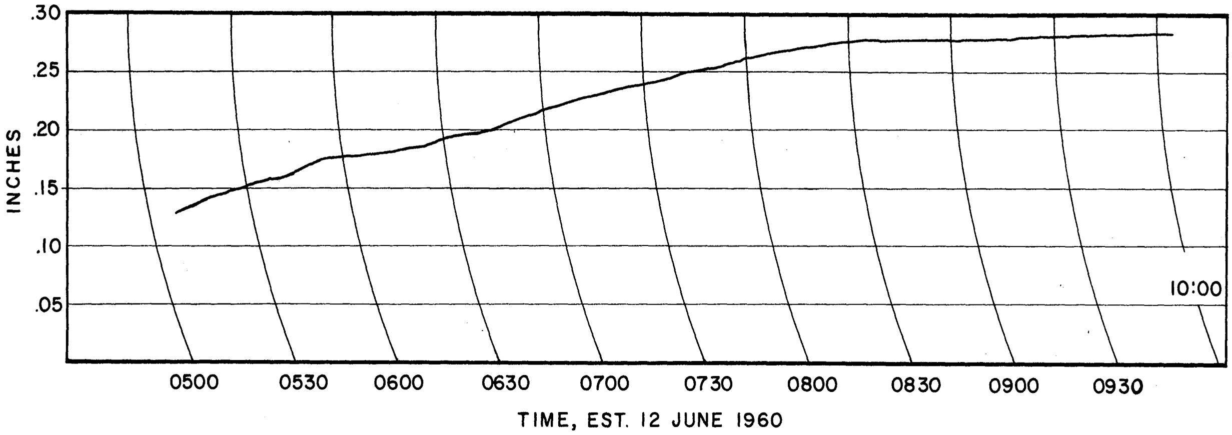
Bleichrodt, et al[8] found a negative correlation between rainfall rate and specific radioactivity of their samples of rain water. Similar observations have been made by Cowan and Steimers[9] and by Isotopes, Inc.,[10] and the latter group has pursued the question further to show an inverse climatic correlation between rainfall amount and cumulative Sr90 in soils in the latitude zone of 30° to 60°N. The possibility that the radioactive content of rain was concentrated by an evaporative process operating more effectively upon the light than the heavy rains was pointed out by Bleichrodt, et al.[8] Because they also observe that "... gross activity is usually proportional to the volume of water in the sample ..." the assumption that in these latitudes the cloud water antecedent of all rains tends to contain a relatively uniform concentration of radioactive material appears reasonable. This assumption further implies that the radioactive materials are uniformly mixed throughout the rain-forming air of middle latitudes.

The climatological evidence[10] is somewhat less amenable to direct interpretation. The variations of annual precipitation totals within the 30° to 60°N zone are definitely not primarily attributable to evaporation from falling rain. This means that another mechanism must be operative. It is possible that the leaching effects of the heavier rains may serve to reduce the soil Sr90, but this effect must also depend upon soil type. This question deserves further careful study.

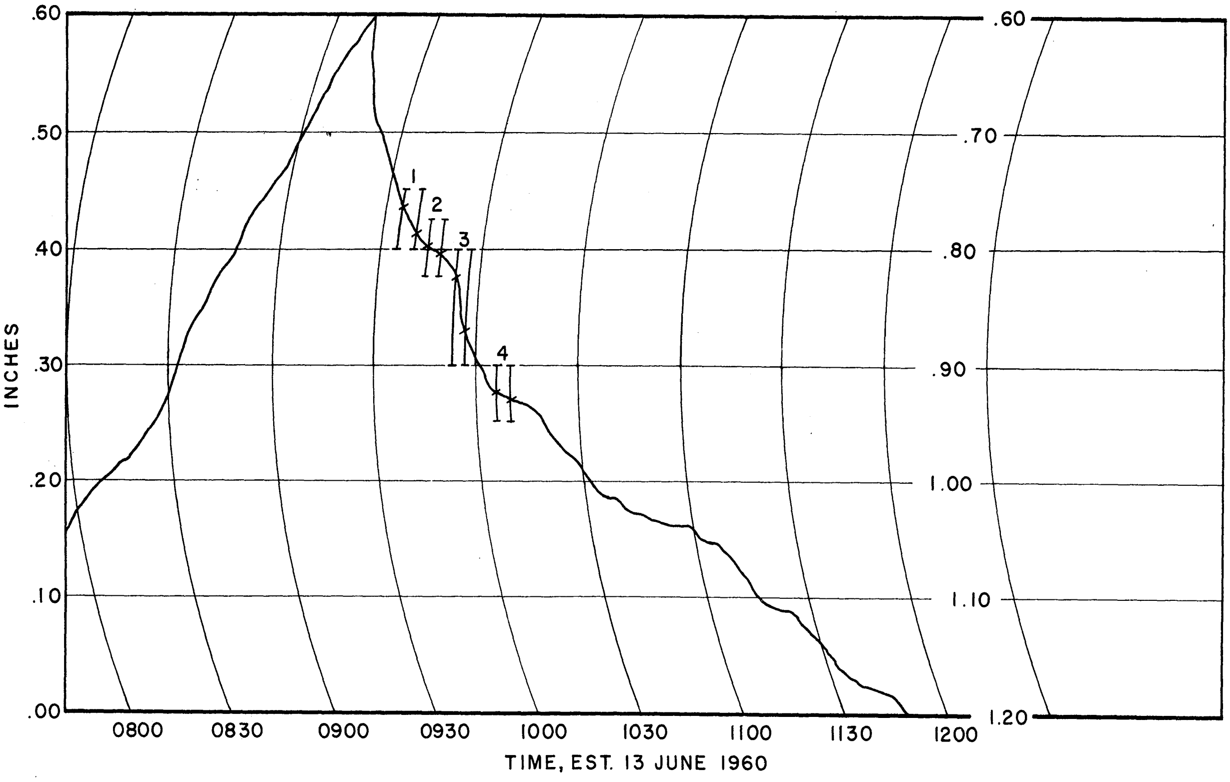
<u>Raindrop-size spectra</u>. Difficulties were encountered in getting complete coordination of raindrop size data with the nylon net sampling data. Further, the raindrop-size data have not yet been completely reduced to numerical form. Nonetheless, a few of these data are available, and brief inspection of them in relation to the rain sampling data is appropriate.

Raindrop spectra were recorded on June 12 and 13 and portions of these records were selected for analysis. The rain of June 12 was attributed to overrunning of warm air with a stationary front south of the station. This rain was light and quite constant in character, being composed entirely of drops less than 2 mm in diameter. The standard weighing rain gauge, equipped with a ten-fold-enlarged collector funnel, produced the record shown in Figure 9(a) under this condition. The rain intensity averaged about 1.0 mm per hr and accumulated to 4.07 mm (0.160 in.) during this period. In contrast, the rain on the 13th was considerably heavier as shown by the ten-fold-rain gauge chart in Figure 9(b). In this case the intensities become moderate, and are quite variable. To characterize the rain under different intensity regimes, four periods were chosen from the records of the 13th for preliminary analysis: (1) 0935-0940, (2) 0944-0948, (3) 0953-0957, and (4) 1006-1010, all EST.

The rain amounts as read from the record and as computed from the raindrop spectra for these four periods are shown in Figure 10. Raindrop-size spectra for these four periods are shown in Figure 11. Characteristically, in this range of rainfall intensities the number of drops in each size range increases, and the maximum drop size increases, as the intensity rises. There are, however, clear variations of this general tendency. Table 3 gives the minute-by-minute drop-size spectrum data in which these features are somewhat more prominent. The rain intensity contribution of each drop



(a) Weighing rain gauge chart for 12 June 1960. Amount is amplified ten-fold by means of an enlarged receiving funnel. Maximum intensity is 2.3 mm per hr.



(b) Weighing rain gauge chart for 13 June 1960. Note periods 1, 2, 3, and 4 discussed in text.

Figure 9

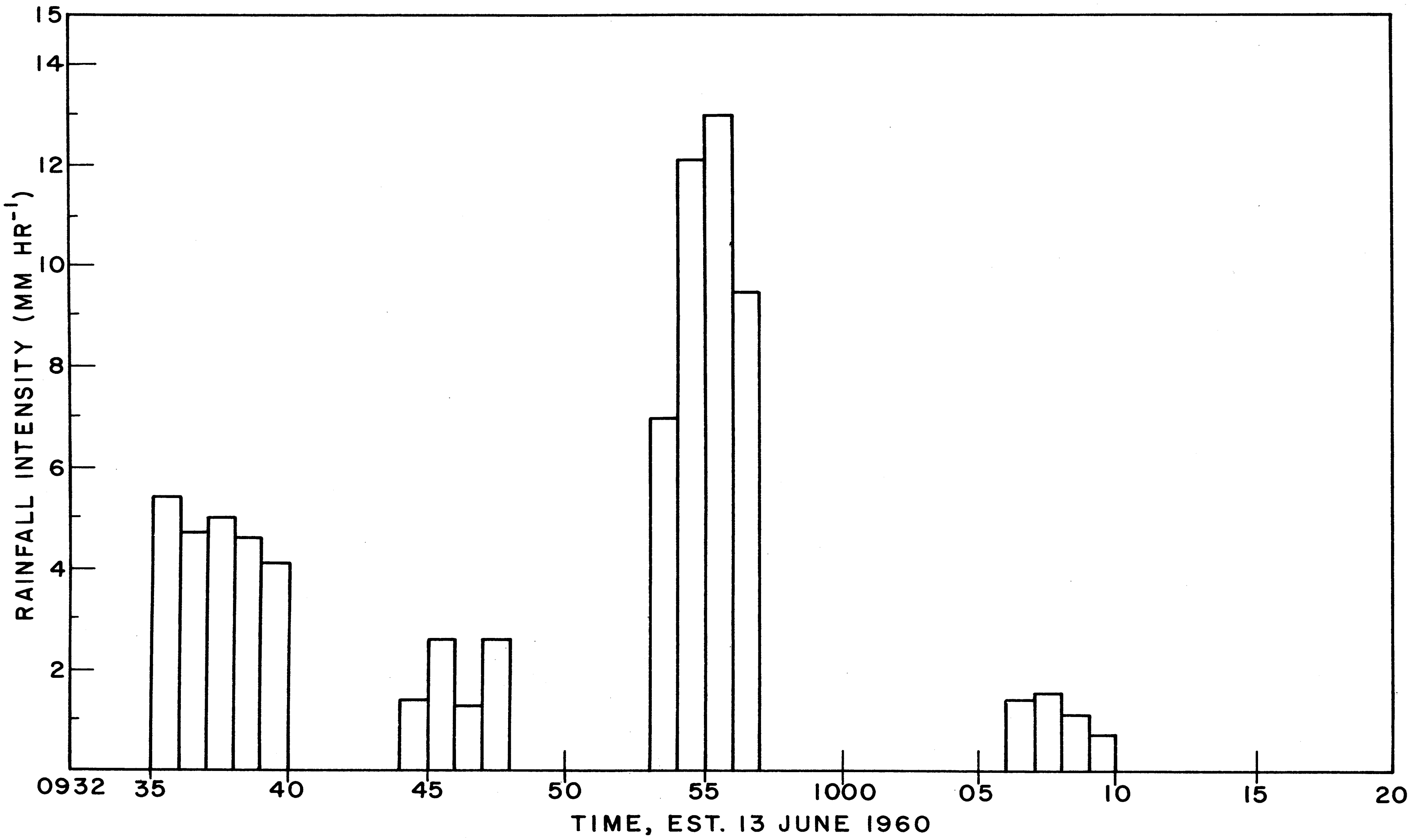


Figure 10. Rainfall intensities each minute for periods 1, 2, 3, and 4 (Figure 9b) as computed from raindrop spectra.

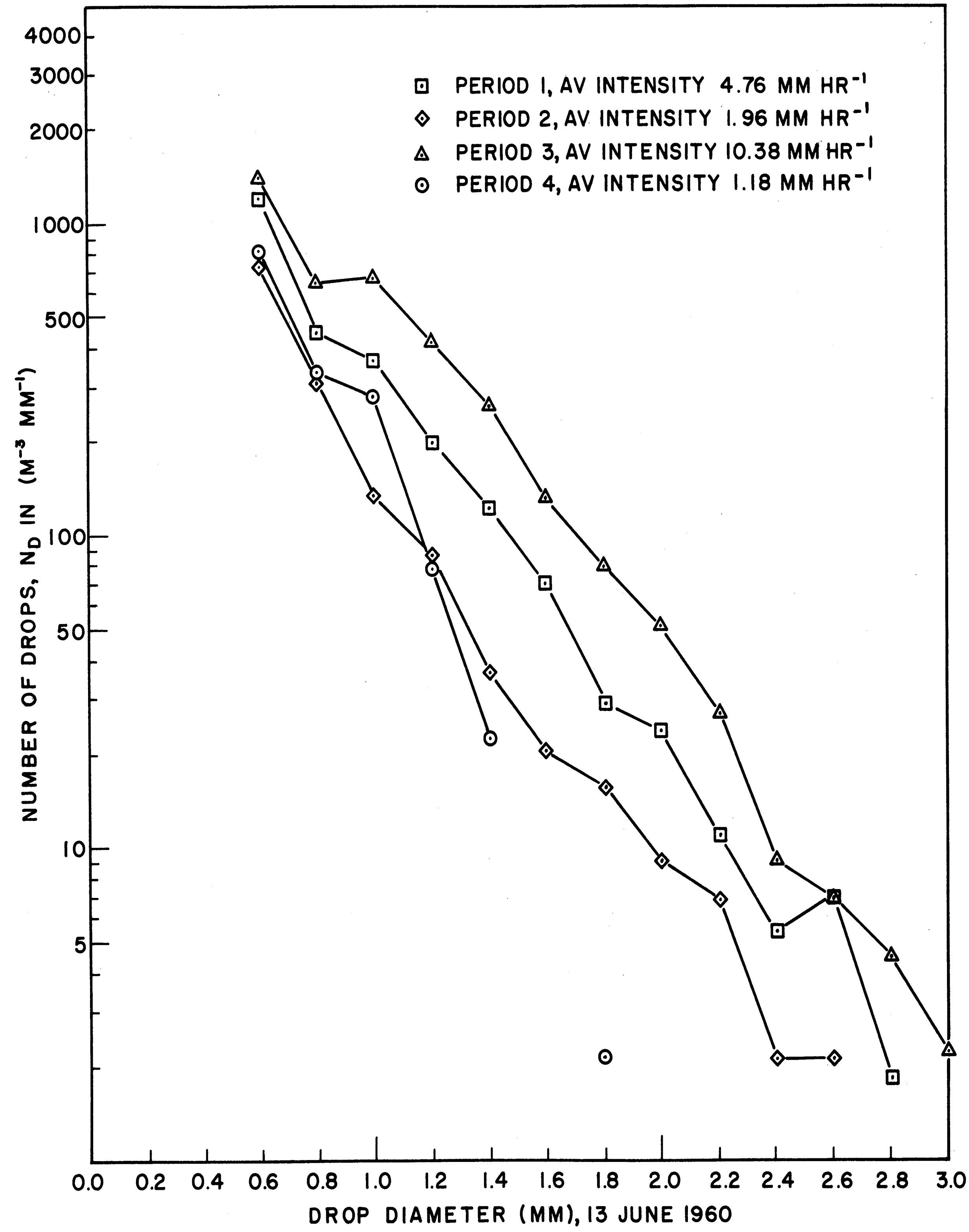


Figure 11. Raindrop-size spectra averaged for each of the periods 1, 2, 3, and 4. (Figure 9b).

TABLE 3

Raindrop-size distributions each minute for four selected periods 13 June 1960

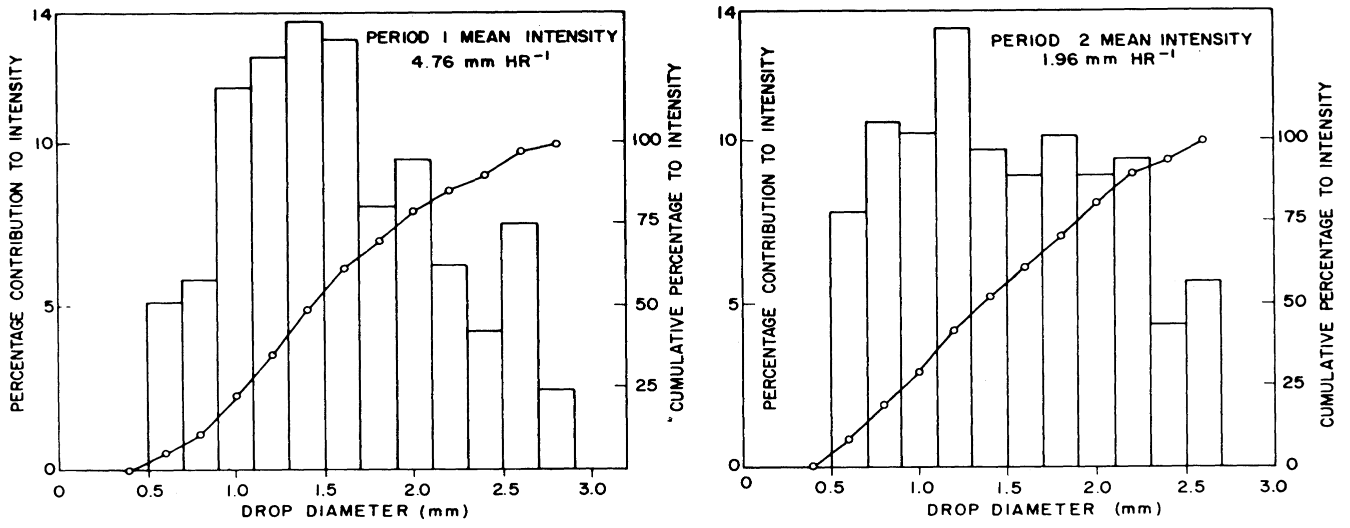
Time EST	Drop Diameter mm													Intensity mm hr^{-1}
	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0	
0935	1384	607	375	196	107	62	71	36	0	9	9			5.39
0936	1197	330	312	161	188	71	9	18	9	9	0	9		4.67
0937	1179	491	339	205	71	36	27	18	27	9	18			5.06
0938	1232	366	420	241	134	89	18	27	18					4.60
0939	1009	411	384	188	107	98	18	18	0	0	9			4.08
Average	1200	441	366	198	121	71.2	28.6	23.4	10.8	5.4	7.2	1.8		4.76
0944	777	447	116	80	18	36	9							1.38
0945	705	259	152	89	54	18	18	9	18	0	9			2.60
0946	857	268	107	89	28	9	9	9						1.29
0947	723	339	152	89	45	18	27	18	9	9				2.55
Average	766	328	132	86.8	36.3	20.2	15.8	9.0	6.8	2.2	2.2			1.96
0953	1116	518	339	259	250	134	89	18	27	9				6.98
0954	1375	643	634	411	268	152	80	89	45	9	18	18		12.10
0955	1697	732	920	697	357	107	116	98	18	18	9	0	9	12.98
0956	1358	652	822	286	170	134	36	0	18					9.46
Average	1386	636	679	413	261	132	80.2	51.2	27.0	9.0	6.8	4.5	2.2	10.38
1006	893	401	366	80	18	0	9							1.45
1007	929	295	312	125	54									1.51
1008	750	313	277	89	9									1.09
1009	679	304	170	18	9									0.69
Average	813	328	281	78	22.5	0.0	2.2							1.18

size category and the curve of accumulated rainfall against drop diameter for each of the four periods are shown in Figure 12. In these periods the percentages of water received in drops up to 0.8 mm diameter range from 6.6 to 31.3 per cent.

Although the radiochemical data for the storm of 16 June are not subject to firm interpretation because of the sampling method (liquid nitrogen) used, complete raindrop-size spectra were obtained for this storm. The type of rain in this storm was vastly different from that of the June 12-13 storm, hence the data are pertinent here to document more extreme rains. The ten-fold-rain gauge record is shown in Figure 13. Because of the extreme sharpness of the showers, it is not feasible to estimate intensities of rainfall from the record chart. The minute-by-minute intensities as computed from the drop-size data show the violently variable character of the storm (Figure 14).

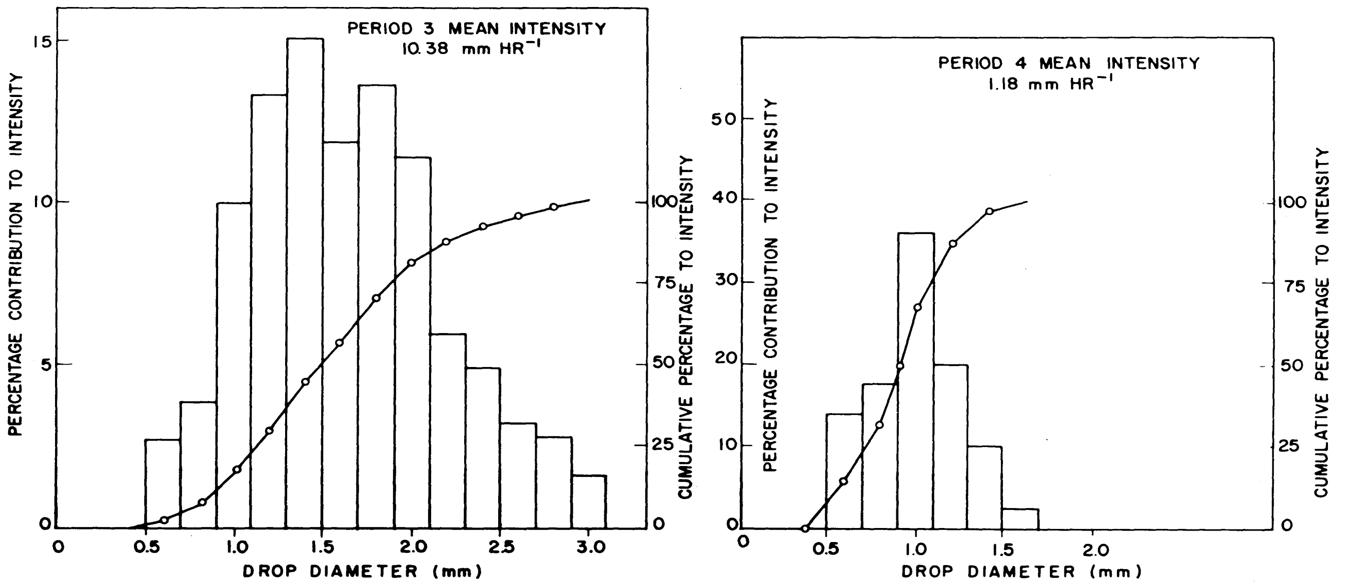
Some of the more extreme raindrop size spectra from this storm are shown in Figure 15. The intensity and the total rainfall are plotted against drop size in Figure 16.

These figures show quite clearly the degree to which, with increasing intensity of rainfall, the raindrop-size spectra depart from currently accepted empirical relations (Best,[11] Marshall and Palmer[12]). Further, it is quite evident that, as rainfall intensity increases, the variability of the drop-size spectra for any given intensity of rainfall increases. The significance of these findings as regards the various components and the total of scavenging effectiveness is under study.



(a) for period 1: 0935-0940 EST, 13 June 1960

(b) for period 2: 0944-0948 EST, 13 June 1960



(c) for period 3: 0953-0957 EST, 13 June 1960

(d) for period 4: 1006-1010 EST, 13 June 1960

Figure 12. Rain intensity and cumulative intensity as functions of drop size.

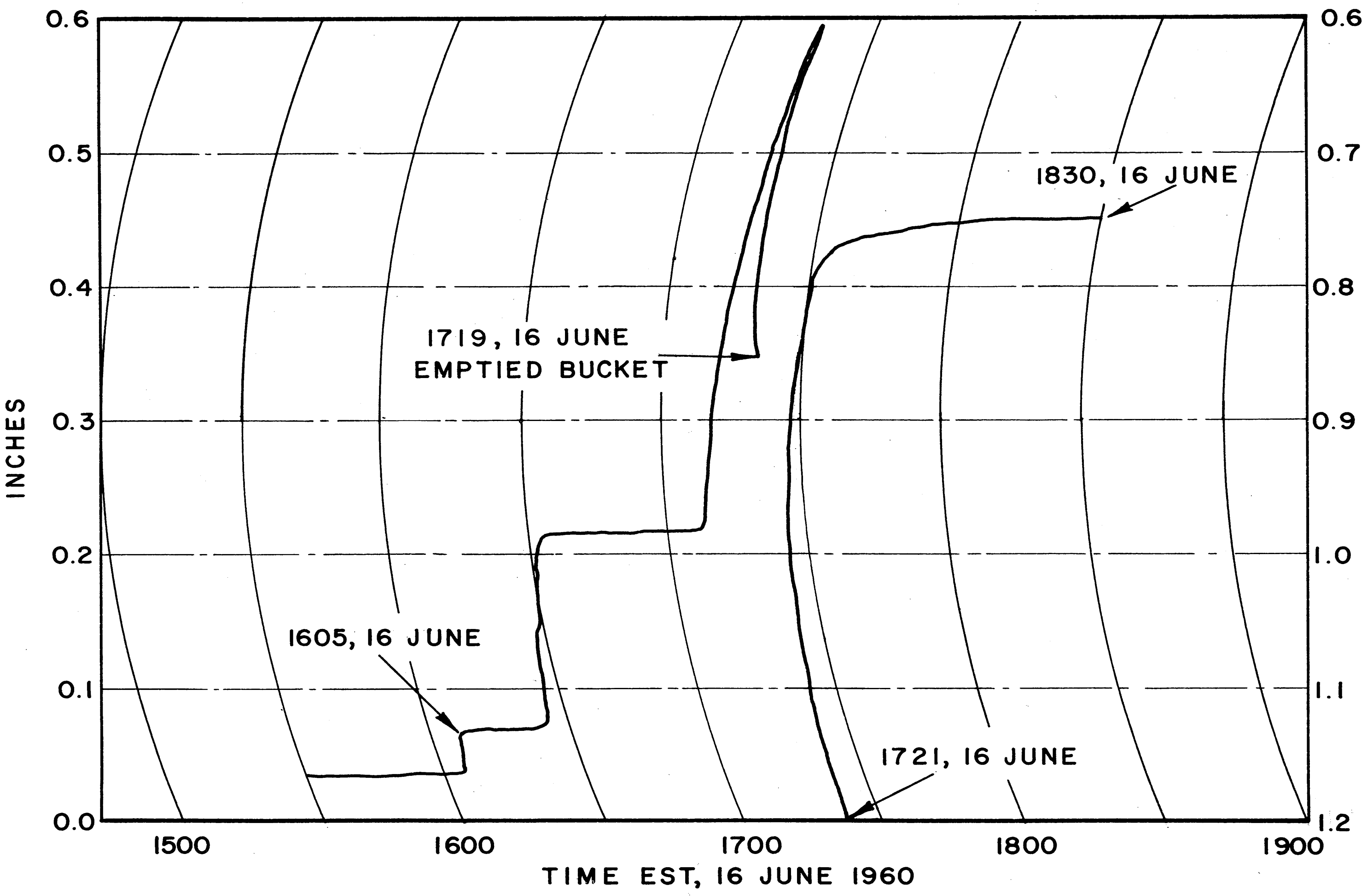


Figure 13. Weighing rain gauge chart for 16 June 1960. Same collector as described above (Figure 9).

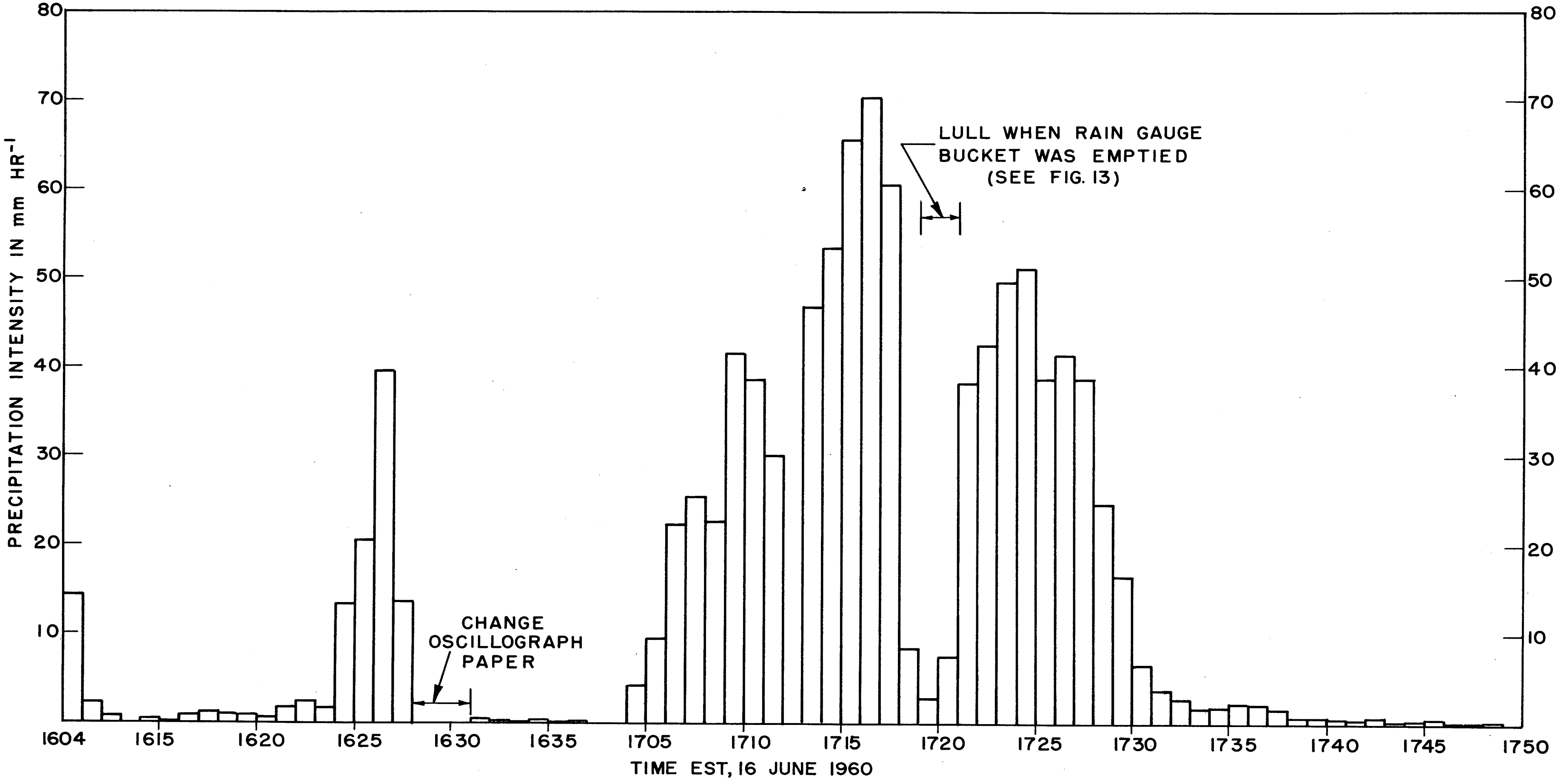


Figure 14. Rainfall intensities as a function of time, 1604-1750 EST, 16 June 1960.

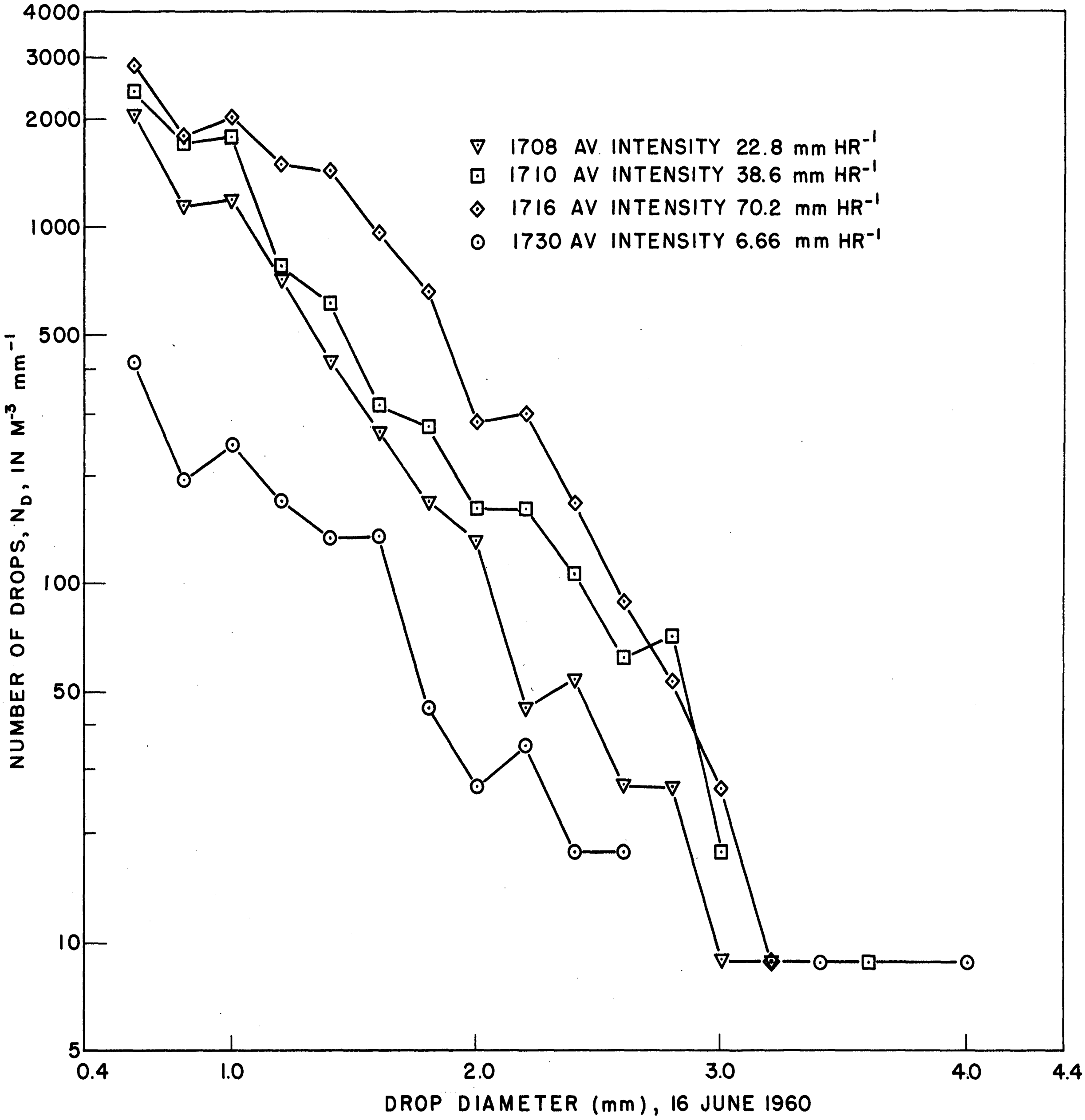


Figure 15. Typical raindrop size spectra, one-min intervals, 16 June 1960.

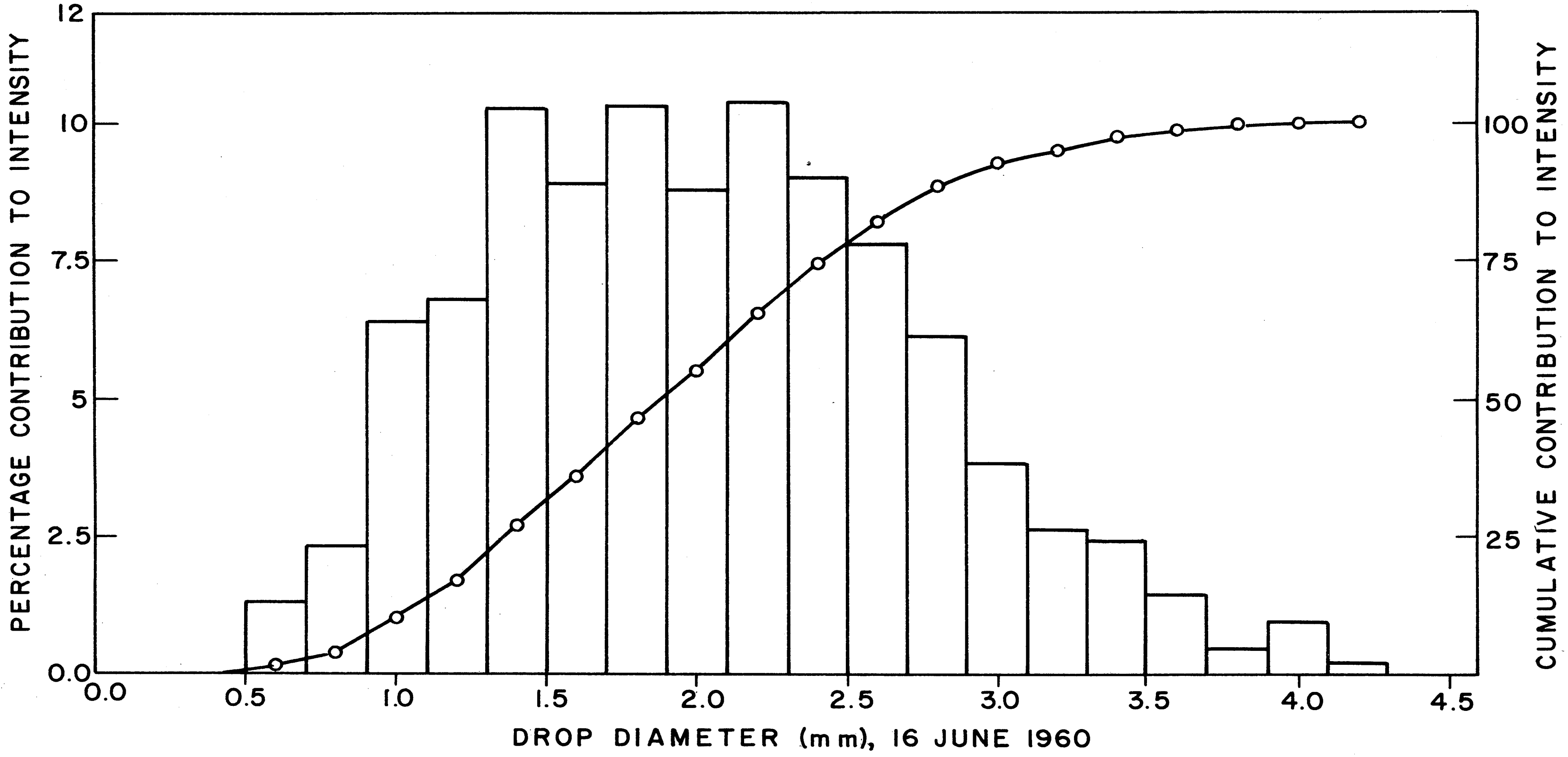


Figure 16. Rain intensity and cumulative intensity as functions of drop size, 16 June 1960.

CHAPTER 3

Coordination of Work with Other Units

Hanford Atomic Products Operation

Discussion of collaborative efforts to be undertaken with the Hanford Atomic Products Operation meteorological group has led to the planning of a series of field experiments at the Hanford site. As a preliminary step, a comprehensive climatological study of rain and fog occurrences at the Hanford site was made. The results of this study indicate that the best time to study natural rains at the Hanford site is during October and November. Fog occurrences are at a maximum in November and December. Thus it is concluded that the period October-December should prove most fruitful for field experiments on natural cloud and rain scavenging.

Several preliminary experiments designed to test the rain wash-out and the Brownian and turbulent motion scavenging mechanisms are planned for the summer period, 1961. In connection with these experiments, the feasibility of various techniques of air sampling and of rain collecting will be explored in anticipation of the fall season experiments.

An effort will be made to model the wash-out situation by using controlled sprays upon artificially generated clouds of particulate. The sampling grid at the Hanford site will provide a well-documented basis for monitoring the particulate cloud; the cloud generating equipment there will serve as source; and the towers will provide elevated mountings for spray generators to simulate rain. Samples collected at ground level will be evaluated in terms of the drop sizes involved and the number and size distribution of the particles collected.

The fogs that occur at the Hanford site offer an opportunity to study the scavenging effectiveness of the Brownian motion process combined with small scale atmospheric turbulence. In general outline, it is clear that the fog presents conditions such as prevail in stable clouds prior to the production of rain. One experimental approach requires that such a fog be contaminated with an identifiable particulate of suitable size, and that it be sampled sequentially to determine the rate at which the particulates are "captured" by fog droplets. Studies will be made to determine the practical feasibility of available techniques for performing this type of experiment.

Field experiments under natural conditions are then contemplated for the October-December period at the Hanford site. In these experiments, raindrop-size spectra and size-defined samples of rain will be collected. Additional data on the contamination of the atmosphere before, during and after rain and fog will be collected utilizing the Hanford sampling grid. The feasibility of obtaining useful data from aircraft on contamination at higher levels, and on cloud water inside and outside the rain area, etc., will be explored. These experiments will provide necessary background for the design of more comprehensive field studies of the scavenging effectiveness of rain under natural conditions.

Under the existing circumstance that the level of radioactive contamination of the atmosphere is very low and decreasing, the possibility of advancing knowledge in the field of rain cleansing of the atmosphere by working with other contaminants deserves study. Inasmuch as most atmospheric contaminants originate at the earth's surface, the problem of finding an identifiable substance, the behavior of which might simulate that of radioactive debris moving downward from the stratosphere, is complex. However, the physical behavior of tiny particulates present in the troposphere, independent of their origin, is pertinent to the scavenging function, and the study of this behavior should lead to knowledge that can be applied to the problem of radioactive contamination. Accordingly, some study of natural contaminants of the atmosphere and of rain will be undertaken in connection with the field experiments at the Hanford site.

Aeroallergen Project, The University of Michigan

The attention of the Aeroallergen Project has been focused upon plant pollens as air contaminants, and has especially dealt with ragweed (*Ambrosia artemisiifolia*) pollen. Because substantial monitoring of the atmospheric distribution of ragweed pollen is accomplished under the Aeroallergen Project, it is both logical and economical for the Rain Scavenging Project to take advantage of the opportunity thus presented to study the rain scavenging of this specific particulate.

The pollen of *A. artemisiifolia* is a sphere with small bumps on its surface having a diameter of 18 μ ±2 μ and a density of about 1.3 gm per cm^3. Its source is within about 18 in. of ground level, and by and large, it is not carried to great heights, although in strong convective currents, some pollen are carried to tropopause-level. Thus it is a large particle as air contaminants go, and it is removed from the atmosphere primarily by gravitation, turbulent impaction, and rain wash-out.

The opportunity to make evaluations of existing theories of the rain wash-out process is thus presented by the juxtaposition of the pollen-monitoring data, counts of the pollen found in the various rain samples, and drop-size distributions of the rain. Because the circulation of the pollen grains in a storm must be governed by continuity considerations, these evaluations should provide a basis for estimating the extent to which low level air is entrained in the rainstorm circulations and participates in the rain processes. The mechanics of the wash-out of particles of this size have been quite well delineated by Langmuir,[13] Chamberlain[14] and Greenfield[15] and the analysis we are doing represents a straightforward application of their equations.

Preliminary work with this approach has been undertaken under the present contract. The data from the nylon net separator are, however, considered inadequate to deal realistically with the problems we wish to attack, because of mechanical interference of the net with the falling rain. The more adequate data that will be obtained with the aerodynamic raindrop sorter will provide a basis for numerical comparisons and a complete report of this phase of the work.

CHAPTER 4

Additional Sub-Projects

The study of temporal variations within and between storms. Bleichrodt's work[5,8] shows that temporal variations of specific radioactivity of rain can be correlated with changes of the rate of rainfall on the one hand, and with changes of air mass on the other. In the first instance, the difference is attributed largely to the increasing effect of evaporation as rainfall rate decreases, whereas in the second the origin and age of the radioactive contaminants play a part. The data of Dyer and Yeo[6] are interpreted in terms of a postulated "cloud" of radioactive contamination which appears to remain distinct for an extended time. The pertinence of this kind of information to the present studies is apparent, and we have taken steps preparatory to assembling similar data.

A pair of large rain-collecting pans have been made for the purpose of procuring sequential samples in heavy rains, and measurable samples in light rains. The design was in a measure controlled by the standard size of galvanized metal sheets, i.e., 4 ft x 8 ft. Each of two such sheets is formed into a 4-in. deep pan turning up the edges and sealing the joints. A 2-in. diameter drain is made in each pan in such a way that the two can be conveniently manifolded into a single drain. Each pan thus presents a collecting area of 28.1 ft^2 (2.6 m^2).

The method of Bleichrodt, et al[8] will be adapted for obtaining sequential samples of rain within storms. The pans will be set upon a wooden platform designed to slope slightly toward the drain-corner of each pan. The bottoms will thus be maintained quite flat so that a squeegee procedure may be used in sampling light rains. This procedure is obviously superfluous under heavy rainfall. A complete record of the collecting time and time interval for all samples will be maintained, and samples of the order of 1 gal. of rain water (about 0.035 in. of rain over the total area of the collecting pans) will be taken.

Radioactive species analysis and decay-rate dating of radioactive contaminants. The instrumentation and technique required to identify radioactive species present in sufficiently large samples of rain are available to our analyst. The large collecting pans will make possible the regular collection of sufficient sample for species determinations, and it is planned that these shall be made on samples collected in 1961. In addition, in those cases in which the drop-size-discriminated samples are large enough, species determinations will be made.

The method used by Dyer and Yeo[6] to estimate the date of origin of radioactive samples is also of interest. Since we need to develop as complete information as possible about the variations in radioactivity, it is appropriate to attempt this type of identification of our samples. Accordingly, we plan to make sequential counts of representative samples over a period of months for this purpose.

<u>Deuterium and the isotopes of oxygen</u>. It has been suggested that analyses of some of our rain samples to determine the O^{18}/O^{16} ratios and the relative amounts of deuterium present may be accomplished simply, and at the same time, may contribute highly interesting additional information, particularly relating to the phase-change history of the water substance. This suggestion is under study, and will be activated if it proves feasible within the context of the project.

<u>Radar data</u>. The raindrop-size data provide all necessary details of the physical nature of each rainfall as it reaches the ground. A good deal of additional information about the processes of growth of the raindrops, and the nature of the storms in which they are generated is required to construct reasonably complete descriptions of the drop growth and scavenging processes. The means immediately available for obtaining observations within the rainforming clouds is present in weather radar.

To promote this aspect of the research, an effort was made to procure a suitable surplus radar unit. Such a unit was located in the possession of the Huron Portland Cement Company of Detroit. This unit, a Westinghouse MU-1 type marine radar, had been used on one of the company's Great Lakes ships.

The characteristics of this type of radar unit are well adapted to our needs and situation. It operates on 110 v, 60 cycle electric power. It is rated at 40 kw power output in the 3 cm (X-band) wave-length region. The pulse-length is 1/4 μ sec, and the pulse repetition rate is 1100 per sec.

Whereas these characteristics are not ideal for general weather radar work, they are well-adapted for short-range study of the structure of rainstorms, and for relatively detailed resolution of rain masses aloft. Douglas, Gunn and Marshall[16] showed that a zenith-pointing radar, capable of good resolution at close range, could add valuable information about the origins of snow to that available by means of PPI and RHI presentations and soundings. It is our opinion that, used in conjunction with other radar data and synoptic information, the raindrop-size spectra and the records obtained from a zenith-pointing radar of high resolution will provide a powerful means of penetrating the precipitation-forming processes. These, of course, are intimately involved with the rain scavenging function.

In the present instance, the MU-1 unit has been transferred gratis to our possession through the good offices of Mr. Charles M. Adams, Vice President, The Huron Portland Cement Co. We propose to modify and adapt this unit to serve as a zenith-pointing narrow-beam radar and to install it near the site of the raindrop sorter, the raindrop-size spectrometer, and the rain-collecting pans. The work of servicing and adapting the MU-1 radar is under way.

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