An Airborne Precipitation Collector

WAYNE E. BRADLEY AND GORDON E. MARTIN[1]

Illinois State Water Survey, Urbana

(Manuscript received 13 January 1966, in revised form 2 May 1967)

ABSTRACT

A high-volume airborne precipitation collector is described. The device, installed in the nose of a twin-engine aircraft, has a 30-cm diameter intake that extends ahead of the aircraft nose. Both air and rain enter the collector where the liquid water is separated from the air by impaction and centrifugal force. Measurements of the airflow in the collector are described and the resulting collection efficiency for precipitation-size droplets is calculated and discussed.

The device is being used to determine if radioactive particles are washed from the air by precipitation between cloud base and the surface by comparing the activities of surface and airborne samples. The implications of one set of samples are summarized.

1. Introduction

The mechanisms involved in the deposition of radioactive debris and their relative importance remain factors difficult to determine in the prediction of deposition. Wet deposition is believed to account for 80–95% of the total deposition (Facy, 1962), but the relative importance of the rainout processes in the cloud and the washout of radioactive particulates beneath the cloud base by raindrops has yet to be accurately determined. Greenfield (1957) suggests the washout of radioactive particles of sub-micron size is insignificant and therefore the total washout by water droplets is very small, but this suggestion needs to be verified experimentally.

One means of assessing the efficiency of the washout process is to compare the radioactivity of precipitation samples collected simultaneously at cloud base and at the ground. An airborne water collector was designed and built to collect 500-ml precipitation samples in a relatively short period of time at aircraft flight speeds. The collector was installed on a Twin-Beechcraft airplane and several airborne water samples were collected. Tests were run in an effort to determine the water collection efficiency of the device.

2. Collector design

In order to obtain water samples in undisturbed air the collector is installed in the aircraft nose, and the intake duct, 30 cm in diameter, is extended 42 cm beyond the nose of the plane as shown in Fig. 1c. Inside the water collector the intake duct opens radially into six centrifuge compartments and terminates in the rear compartment, a cylinder 61 cm in diameter, for the impaction and removal of water. The front compartment, shown in Fig. 2a, is an empty cylinder designed to contain a door if it had proven necessary to close the collector during flight to prevent contamination. A spray nozzle for washing the device in flight has proved satisfactory and the door was not installed.

The six interior compartments shown in Figs. 1 and 2 are identical. Air is exhausted from the collector through these circular ducts and small droplets within the collector are removed from the exhaust air by centrifugal force. In order to prevent a build-up of pressure in the nose compartment from the exhaust air of the collector, a reverse exhaust scoop or vent is built around the nose of the aircraft. Thus, air enters the device at the front of the inner duct, travels along the inner duct to one of the six centrifuges, passes around a centrifuge out of the device into the nose of the aircraft and is then evacuated from the plane through the reverse scoop arrangement.

Water that impacts on the rear wall of the device drains through holes at the bottom into the collector pan. Water impacted on the centrifuge dividers or outer cylinder wall is blown by the air stream nearly to the air exit, where it is removed from the walls by a series of gutters and water scoops into the collector pans (Fig. 2). Positive drainage of water through the holes and scoops is assured by the flow of air with the water. The final separation of air and water takes place through baffles and a perforated plate in the bottom collector pan. The collected water is continuously pumped to the airplane cabin. The entire device is constructed of 22-gage stainless steel.

Between flights, a dust cover is kept over the collector entrance and exit to reduce contamination. Before each flight the collector is sprayed with a hose to

---

[1] Present affiliation: General Engineering Department, University of Illinois, Urbana.

remove contamination and the built-in sprayer is then used to clean it again in flight.

3. Instrumentation and testing

In order to obtain a better understanding of the airflow in the water collector, a pitot-static tube was installed in the center of the intake duct, and four static pressure taps were made along the central cylinder of the device, as shown in Fig. 2. Water manometers in the cabin of the plane were connected to the pitot-static tube and the static pressure taps, so that all pressures could be read continuously. A flight was made to determine the pressure distribution within the collector at indicated air speeds (IAS) of approximately 45, 54 and 62 m sec^{-1}, and at an altitude of 1500 m MSL.

A portion of the data obtained from the pitot-static tube in the nose of the collector are included in Table 1. The velocity pressure measured in the collector intake of 13.4 cm H_2O is in good agreement with the aircraft velocity pressure of 13.0 cm, as calculated from aircraft IAS. However, the static pressure in the collector intake was 8.7 cm H_2O. Therefore, the IAS within the collector as calculated from the velocity pressure minus the static pressure, or 4.7 cm H_2O, was 27.0 m sec^{-1}.

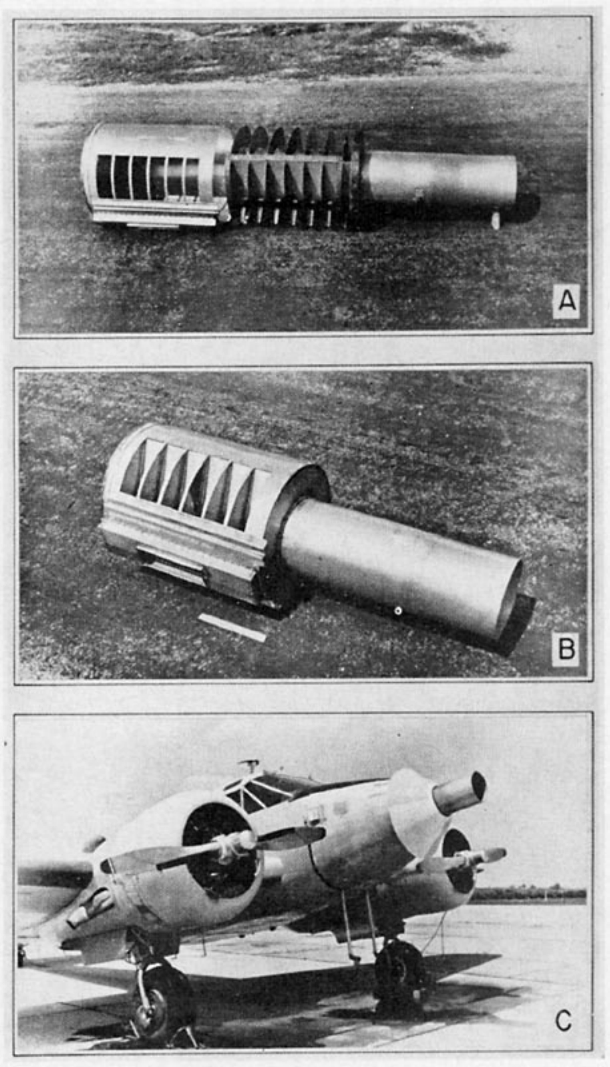

FIG. 1. Expanded (a), assembled (b), and installed (c) views of precipitation collector.

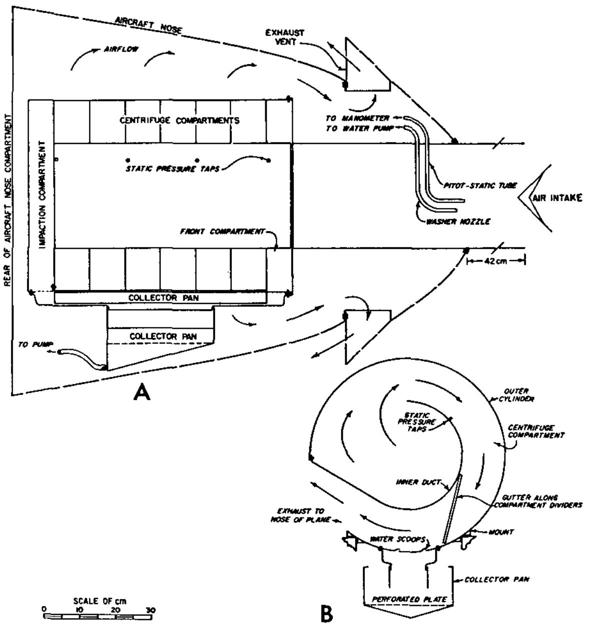

FIG. 2. Side and end view cross sections of the precipitation collector.

A static pressure increase occurs between static pressure taps 2 and 3, as shown in Fig. 3, as the air suddenly expands into the larger compartment consisting of the inner duct and the upper left-hand portion of the centrifuge shown in Fig. 2. The pressure increase in the inner duct is characteristic of that which occurs at an abrupt transition between a small and large pipe as kinetic energy is converted to potential energy. Fig. 3 also shows similar pressure data taken at 54 and 62 m sec^{-1}. The pressure distribution within the collector at 3000 m and 54 m sec^{-1} was identical to that at 1500 m.

A static pressure measurement was also taken in the nose of the aircraft about 8 cm beneath the collector exhaust. The pressure there did not differ significantly from atmospheric at any air speed, indicating that the reverse exhaust scoop did not create a significant partial vacuum within the aircraft nose. Fig. 4 gives the aircraft IAS vs. air collection efficiency and intake air speed

TABLE 1. Aircraft and water collector pitot-static tube measurements at an IAS of 44.7 m sec^{-1} and 1500 m MSL.

	Aircraft	Water collector
Velocity pressure (cm H_2O)	13.0	13.4
Static pressure (cm H_2O)	0.0	8.7
IAS (m sec^{-1})	44.7	27.0

relative to the aircraft, assuming a uniform flow through the intake. The air collection efficiency is defined as the ratio of the air speed inside the intake duct to the air speed outside the duct, multiplied by 100.

4. Collector efficiency

The pitot-static tube measurements in the intake duct indicate that the IAS there varies from 27 to 33 m sec^{-1} as the plane IAS changes from 45 to 62 m sec^{-1}. The air collection efficiency thus varies from 60 to 52%, respectively. Therefore, nearly half of the air directly in front of the collector diverges around it. The matter of concern, however, is the water collection efficiency defined as the volume of water that enters the collector tube per unit time divided by the volume of water that would enter the collector if there were no divergence of air around the intake, multiplied by 100. While nearly 50% of the air may diverge around the collector intake, much of the water in that air is carried into the collector because of the inertia of the drops.

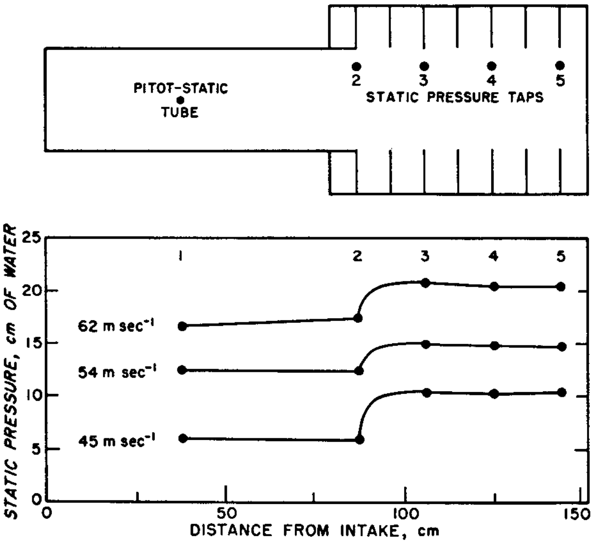

Fig. 3. Static pressure distributions within the collector for three airspeeds.

The exact airflow around the collector intake is not readily described, but a crude approximation to the flow will be hypothesized. Initially, it will be assumed that the drops remain intact until collected. The problem of drop breakup prior to collection will be discussed later. The reference coordinate system is considered moving with the plane, and the terminal velocity of the precipitation is initially considered negligible compared with the aircraft velocity. Fig. 5 illustrates the hypothesized streamlines around the collector nose. Raindrops in the volume ABCD necessarily enter the collector because the air in which they are embedded is collected, but the fate of the drops in volume AEFD exclusive of volume ABCD must be determined.

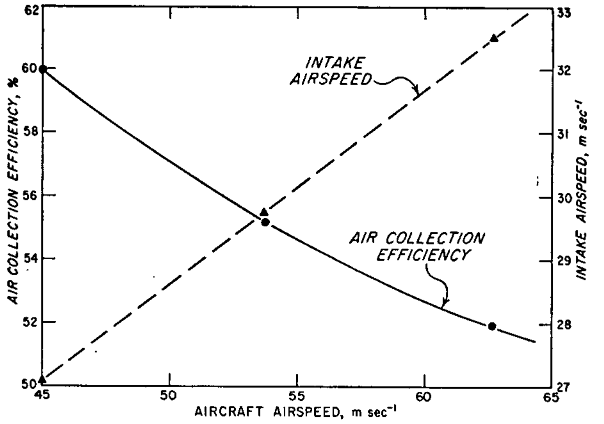

Fig. 4. Relationship between the aircraft airspeed, air collection efficiency and intake airspeed.

Consider a raindrop in the streamline AB with incompressible flow. When the drop reaches G, it is subjected to a divergent air flow with a radial component of velocity that will be assumed constant between G and A. The air is assumed to begin diverging at a distance AG in front of the collector, a distance equal to one intake duct diameter. It was shown by Dorsch *et al.* (1955) that at one diameter in front of a sphere, the maximum radial component of velocity is only 5.3% of the undisturbed axial component. In the case considered here, the obstacle is a hollow cylinder rather than a sphere, but the streamlines of the two are similar, one diameter ahead, indicating very little divergence beyond that distance. In a similar manner, the intake of the collector is about one vent diameter in front of the outer edge of the reverse exhaust scoop, or vent, as seen in Fig. 1c of the installed collector. Therefore, the vent also adds very little to the divergence of air ahead of the intake.

At an IAS of 53 m sec^{-1} and air collection efficiency of 56%, the air divergence around the intake results in EB equaling 3.78 cm. If the air begins to diverge one intake duct diameter, or 30 cm ahead of the collector intake, it moves radially 3.78 cm while traveling 30 cm

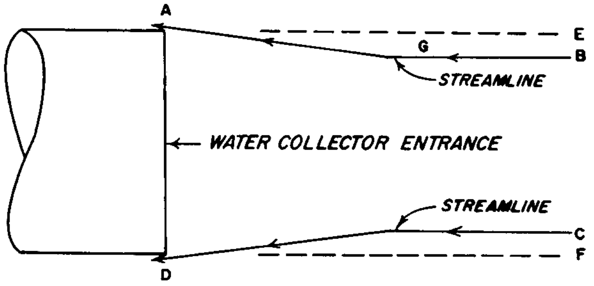

Fig. 5. Diagram of the hypothesized streamlines at the collector entrance.

in 5.68×10^{-3} sec, giving it a radial component of velocity of 6.67 m $\sec^{-1}$.

The initial drag force on the drop that causes it to accelerate radially is given by the expression (Schlichting, 1955),

$$F=C_d 5\rho v^2 A,$$

where C_d is the drag coefficient, ρ the density of air in gm ml^{-1} (STP), v the radial air velocity relative to the drop in cm $\sec^{-1}$, and A the cross-sectional area of the drop in cm^2. C_d is determined with a curve given by Schlichting (1955) using the Reynolds number Re where

$$\mathrm{Re}=\rho dv/\mu=(1.21\times10^{-3}\times4.00\times10^{-2}\times667)/(1.83\times10^{-4})=176,$$

with d the diameter of the drop and μ the viscosity of air in poises at STP. Then,

$$F=0.85\times0.5\times1.21\times10^{-3}\times(667)^2\times\pi\times(2\times10^{-2})^2=0.286 \text{ dyne}$$

for a 0.04-cm diameter drop.

The force F is the initial and maximum force on the drop. As the drop accelerates radially, its radial velocity with respect to the radial velocity of the air decreases and consequently v decreases in the above expression, and the accelerating force F becomes less. However, for the purpose of this calculation, F will be considered constant as this assumption does not materially affect the result other than making it conservative. The acceleration on the drop is thus

$$a=F/M=0.286/(0.355\times10^{-4})=8.05\times10^{3} \text{ cm sec}^{-2},$$

where M is the mass of the drop. The radial distance X traversed in the time that it takes the drop to travel from G to the collector inlet is thus

$$X=0.5at^2=0.5\times8.05\times10^{3}(5.68\times10^{-3})^2=0.130 \text{ cm},$$

where t is the time that the drop is influenced by force F.

By excluding the drops that fall outside volume AEFD after traveling radially 0.130 cm, the collection efficiency for a 0.4-mm drop is found to be over 98%. In a similar manner the efficiency for a 2-mm drop can be shown to be over 99%. Since nearly 100% of the liquid water content of rainfall is contained in drops of 0.4 mm diameter or greater (Best, 1950), the calculated collector efficiency is near 100% for precipitation-size particles. If the divergence distance AG had been assumed to be 5 diameters, the collection efficiencies for 0.4-mm drops would have been 95%. If the divergence distance AG had been assumed to be less than one diameter, a higher efficiency would have been obtained.

Since the effect of the terminal velocity of the water droplets was neglected in the previous calculation, further computations were made in which the terminal velocities of the water droplets were added vectorially to the radial air velocity, and new values were obtained for the Reynolds number, drag coefficient, force and acceleration. Computations were made for drops falling through the center of the collection volumes, and averages were taken of water collection efficiency values obtained at the top and at the bottom of the collection area at the duct entrance. Values at the sides of this area lie between these extremes and were not computed. Average water collection efficiencies obtained using the terminal velocities are within 1% of the values obtained by disregarding terminal velocities for all sizes of rainwater droplets. Fig. 6 shows the rain collection rate vs. rainfall rate and liquid water content for the collector, assuming 100% collection efficiency.

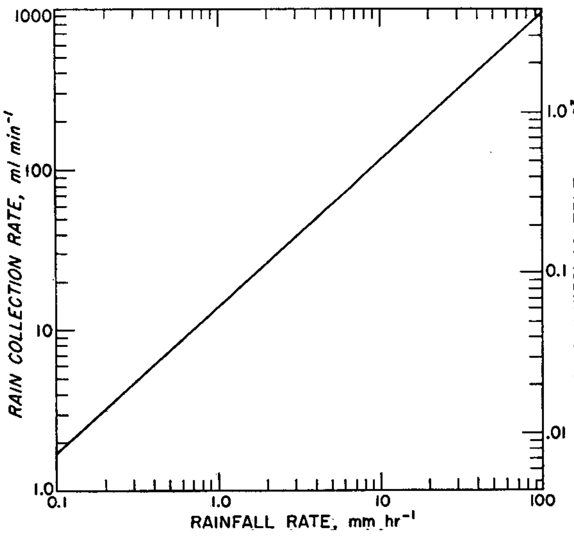

FIG. 6. Relationship between the rain collection rate, rainfall rate, and liquid water content.

In the above discussion the effect of the sudden differences in the relative velocity of the raindrops with respect to the environmental air just in front of, and within, the collector was not discussed. This problem of drop breakup resulting from transient air blasts was studied by Lane (1951) who reported that drops of 4.0 mm diameter are shattered with an air blast of 12 m $\sec^{-1}$ or greater. A 0.5 mm drop requires twice the velocity or 24.0 m $\sec^{-1}$ to be shattered. At an aircraft IAS of 54 m $\sec^{-1}$, raindrops entering the collector are exposed to a relative air velocity of 24 m $\sec^{-1}$. This blast will cause all drops over 0.5 mm in diameter to bag and shatter, and it is probable that many fragments of the shattered drops pass through the collector uncaptured.

The effect on the drops of radial airflow is not as clearly defined. The average radial velocity of 6.67 m $\sec^{-1}$ as calculated above is too small to disrupt the drops, but actual maximum velocities will be greater. Some of these drops may be shattered and a portion of their fragments carried around the collector intake uncollected.

Finally, once the water enters the collector, it must be retained by centrifugal force and impaction. The smallest fragments of drops are probably capable of escaping capture; hence, the collector does not retain all the water that enters the intake. Some sorting by drop size may also occur as a result of the possible breakup and loss of drops from the air diverging around the collector intake, as raindrop sizes above 1mm are more easily shattered than the smaller drops.

In a further effort to determine the collector efficiency, the amounts of water collected aloft were compared with those collected simultaneously at the surface. The average liquid water contents (LWC) for the rainfall rates measured at the ground were calculated with LWC vs. rainfall rate data from Best (1950). The calculated LWC was then compared with the amount of water collected aloft. The comparison was made with data taken on 5 June 1964 in very uniform rain. The amount of water collected varied from 51 to 97% of that predicted for several samples. However, the LWC varies considerably for any given low rainfall rate (Best, 1950), so that variations in calculated collector efficiency could be partially caused by the difference between the calculated and actual LWC, as well as collector loss.

It is concluded that nearly all of the raindrops enter the intake, but that the different air velocity within the collector may disrupt most of the drops. Some of the resulting fragments are too small to be captured and pass out the exhaust vent uncollected.

5. Data collection

Flights to evaluate the utility of the collector were made in east central Illinois on four occasions. A brief description of one case study follows.

A flight was made on 5 June 1964 over the East Central Illinois Raingage Network collectors, and over the University of Illinois-Willard Airport collector (Huff and Stout, 1964), starting at 0815 CST. These surface collectors have a 3-m^2 collecting surface and automatically change sample bottles every 1 mm of rain. On this flight, stratus and light rain were encountered over the entire route. The flight over the rain collector network was made at the base of broken cumulus clouds at about 1980 m MSL. Precipitation samples were taken above specific surface rainwater collectors so that a comparison could be made between the surface and airborne precipitation radioactivities. The terrain in this area is level and averages about 230 m MSL.

Fig. 7 shows the beta concentration vs. time for the airborne and surface samples taken. It is apparent that there is fairly good agreement between the time variation of beta activity aloft and at the surface. The airplane circled over surface samplers 24, 25 and 26 for 21 min, while climbing from 1340 to 1920 m MSL altitude. At the same time, samplers 24, 25 and 26 along a 9-km line were automatically collecting samples, but their sampling time was considerably longer than the airborne sample. The rainfall rate at the ground at that time was very light, ranging from 0.3 to 0.5 mm hr^{-1}. As Fig. 7 shows, the beta concentration at the surface, ranging from 375 to 870 $\mu\mu$Ci liter^{-1}, was considerably higher than the count aloft which was 265 $\mu\mu$Ci liter^{-1}.

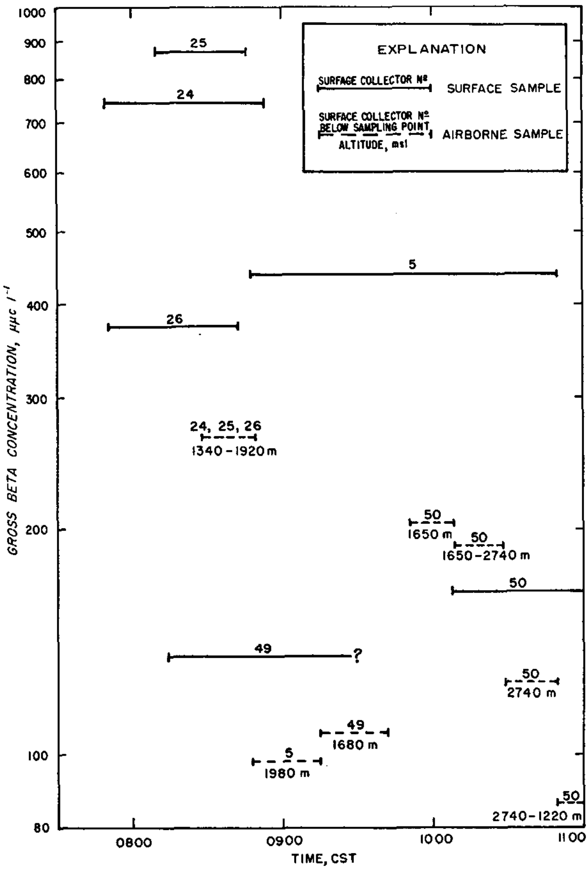

FIG. 7. A comparison between the surface and airborne gross beta concentrations and collection times on 5 June 1964.

A second airborne sample was taken over collector No. 5 at 1980 m MSL with a beta concentration 4½ times less than the surface sample, but the surface sample was collected over a longer time than the airborne sample. Airborne samples taken over collector No. 49 did not differ greatly from the surface sample, but the termination time of the ground sample is unknown. The four airborne samples taken over sampler No. 50, at the airport, do not vary much from that collected at the ground, although the sampling altitudes varied from 1220 to 2750 m MSL. The airborne samples were taken in circular pattern within 1 km of collectors 5 and 49 and within 2 km of No. 50.

Huff and Stout (1964) have shown that the beta activity in precipitation at the beginning of a storm usually rapidly decreases by a factor of 2 during the initial 20% of the rainfall. The four network samplers that took more than one sample for this storm had beta count ratios of sample No. 1 to sample No. 2 of 2.2, 2.5, 2.8 and 5.7, indicating a considerable decrease in radioactivity with time at the beginning of the storm. This was followed by a much smaller change between sample No. 2 and No. 3. The airborne sample taken above samplers 24, 25 and 26 had a gross beta concentration considerably lower than the surface samples, as previously mentioned. However, the airborne samples were taken during the latter half of the time period during which the ground samples were taken. Consequently, the beta count differences between the air and ground samples may have been the result of a general decrease in precipitation radioactivity with time. The same might be said of the samples at No. 49.

The airborne sample taken at 1980 m MSL above collector No. 5 had a gross beta count of only 22% of the surface sample. Both were initiated simultaneously but the surface sample was collected several times longer than the airborne samples. Most likely, the precipitation radioactivity was decreasing with time at the surface collectors so that the surface sampler with the longer collection period should have had a lower beta count than the airborne sample unless washout or evaporation occurred between flight level and the surface.

The samples taken from 1220 to 2750 m MSL over collector No. 50 do not vary greatly in activity from those taken at the surface. The rainfall rate at the surface was a steady 0.075 mm hr^{-1}. Most of the first airborne sample was taken at 1650 m MSL and had a gross beta concentration of 203 $\mu\mu$Ci liter^{-1}. The second sample with a concentration of 190 $\mu\mu$Ci liter^{-1} was collected on the ascent from 1650 to 2750 m MSL, but most of the water was collected near the top where higher collection rates were encountered.

The third sample was collected at 2750 m MSL at the freezing level in clear air. At this altitude, the water collection rate was 23 ml min^{-1}, 6 times greater than at lower levels, although no corresponding change in the rainfall rate was observed at the ground. The ambient temperature was 0C and a TPS-10 RHI radar showed a radar brightband at approximately flight level. Precipitation could not be seen impacting on the windshield, but what appeared to be snowflakes were observed passing against the darker background of the earth. The high water content (frozen) at 2750 m MSL is attributed to the lower terminal velocity of snow compared with the velocity of the rain below the freezing level. The terminal velocities of snow crystals vary, depending upon their shape; however, data reported by Byers (1965) support the indication that terminal velocities of hydrometeors may be increased by a factor of 6 upon melting. The number of hydrometeors per unit volume therefore decreases by a factor of 6 beneath the freezing level, or more accurately, the melting level.

The fourth sample over the airport was taken during the descent, and had a beta concentration of 86 $\mu\mu$Ci liter^{-1}. There was no apparent relationship between beta concentration and altitude, with the samples at all altitudes not varying to a large degree from that at the ground. The airborne sample counts decrease with time, and the ground sample appears to be an average of the airborne samples with time. This would indicate very little washout between 2750 m MSL and the surface.

It is not possible to draw definite conclusions concerning the presence or absence of washout from the few data available, but several implications are presented. On the samples taken directly over the network surface collectors, lower beta counts were found aloft than on the ground for most samples. The difference in activity might have been caused by washout or by the expected variation with time of the precipitation radioactivity. A portion of the increase in concentration might also have been the result of partial raindrop evaporation between sampling altitude and the surface. Dingle and Gatz (1966) calculated the changes in concentration of radioactivity in rain with humidity, ceiling height, and rainfall rate. Using the 1962 U. S. Standard Atmosphere, and a relative humidity of 90%, they found that for a drop fall distance of 1400 m, typical for this day, the radioactivity would increase by a factor of approximately 1.5. Some of the differences in activities were of this order of magnitude but others were larger. The surface relative humidity for the day under consideration actually varied from 80 to 90%, so evaporation may have been higher than 33%. The samples taken over the airport, however, indicate very little scrubbing from rain falling from 2750 m MSL. It is concluded that while the data suggest the presence of a washout mechanism or drop evaporation in the atmosphere on some occasions, they also imply that at other times the radioactive concentration present in precipitation at the surface was also present at the time the precipitation left the cloud base, as high as 2750 m MSL.

6. Summary

The airborne precipitation collector continuously samples air and rainwater through a 30-cm diameter tube extending 42 cm ahead of the aircraft nose. The water collection efficiency at the entrance of the collector has been calculated to be nearly 100% for raindrops over 0.4 mm diameter. However, drop breakup resulting from the different velocities of the drops and the air within the collector may reduce the water retention efficiency to as low as 50%. Flights have been made in light stratified and convective showers with water collection rates up to 100 ml min^{-1}. Snow samples taken in the vicinity of a radar brightband gave a liquid water content six times greater than in the rain beneath.

Preliminary data taken with the device in very light rainfall suggest that on some occasions there may be washout of radioactive debris between cloud base and the ground. The collector has numerous applications in the atmospheric sciences where airborne water samples of a moderate size are required.

Acknowledgments. Appreciation is expressed to Glenn E. Stout, Head of the Atmospheric Sciences Section, and Floyd A. Huff, both of the Illinois State Water Survey, for encouraging the construction of the collector. This study is one phase of a project being supported by the U. S. Atomic Energy Commission as report no. C00-1199-11.

REFERENCES

Best, A. C., 1950: The size distribution of raindrops. *Quart. J. Roy. Meteor. Soc.*, **76**, 16–36.

Byers, H. R., 1965: *Elements of Cloud Physics*. University of Chicago Press, 191 pp.

Dingle, A. N., and D. F. Gatz, 1966: Rain scavenging studies—data analysis, synthesis, and interpretation. Progress Rept. No. 2, AEC Contract No. AT(11-1)-1407, 34 pp.

Dorsch, R. G. *et al.*, 1955: Impingement of water droplets on a sphere. Tech. Note 3587, National Advisory Committee for Aeronautics (NASA, NACA TN 3587), 29 pp.

Facy, L., 1962: Radioactive precipitation and fallout. *Nuclear Radiation in Geophysics*, Berlin, Springer-Verlag, 202–240.

Greenfield, S. M., 1957: Rain scavenging of radioactive particulate matter from the atmosphere. *J. Meteor.*, **14**, 115–155.

Huff, F. A., and G. E. Stout, 1964: Distribution of radioactive rainout in convective rainfall. *J. Appl. Meteor.*, **3**, 707–717.

Lane, W. R., 1951: Shatter of drops in streams of air. *Ind. Chem. Eng. Chem.*, **43**, 1312–1317.

Schlichting, H., 1955: *Boundary Layer Theory*. New York, McGraw-Hill Book Co., 535 pp.