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IN SITU MEASUREMENT OF PARTICULATE NUMBER DENSITY AND SIZE DISTRIBUTION FROM AN AIRCRAFT

by Daniel Briehl
Lewis Research Center
Cleveland, Ohio

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Daniel Briehl

NASA - Lewis Research Center
Cleveland, Ohio

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ABSTRACT

As part of the instrument evaluation plan for the NASA Global Atmospheric Sampling Program, two different commercial particulate measuring instruments were flown aboard the NASA Convair 990. A condensation nuclei monitor was utilized to measure particles larger than approximately 0.003 μm in diameter. A specially designed pressurization system was used with this counter so that the sample could be fed into the monitor at cabin altitude pressure. A near-forward light scattering counter was used to measure the number and size distribution particles in the size range from 0.5 to 5 μm and greater in diameter.

Considerable variation in number density was encountered for both classes of particles at the test altitudes ranging from 5 to 12 km. Presence of clouds could be detected by the light scattering instrument because large numbers of particles would then be registered by the instrument, especially in the size range above 5.0 μm in diameter.

1. INTRODUCTION

At NASA the Global Atmospheric Sampling Program (GASP) is currently underway to equip several commercial Boeing 747 airliners with a system to measure, in-situ several atmospheric constituents on a global basis. The purpose of this program is to determine the possible contribution of jet aircraft to possible atmospheric contamination over the duration of the program which is expected to be several years. The air sampling system installed on these airliners must be designed to operate unattended. Also, this system may be inaccessible for periods as long as several weeks. These constraints as well as the aircraft shock, temperature and vibration environment and safety considerations for the installation on board the airplane impose severe demands on sampling instruments. The program has been limited to atmospheric measuring techniques which are already developed.

The need for obtaining reliable data on the background concentrations of a number of minor atmospheric constituents is necessitated by concern regarding the effects of present aircraft engine exhaust emission as well as the effects due to projected increased traffic due to both subsonic jets and the introduction of the supersonic transports. SMIC (1971) suggests that several aircraft engine exhaust constituents including particulates, oxides of nitrogen and water vapor may have potentially harmful effects. In order to assess the effects of these constituents it becomes necessary to have accurate atmospheric models and a knowledge of the background levels especially in areas of heavy air traffic.

This paper describes some details of flight tests of prototype instruments for the GASP system. These instruments were installed on the NASA CV-990 research aircraft based at Ames Research Center. Details of the aircraft system are described by Bader and Wagoner (1970). The installation was flown on the ASSESS and SEASAT mission during January of 1974. The data were taken over land over the west coast of the United States as well as in maritime air between San Francisco and Hawaii. This paper will present data from two particulate measuring instruments included in the installation. A condensation nuclei counter measured concentration of particles over 0.003 μm in diameter and a near forward light scattering type instrument measured the number and size of particles greater than 0.5 μm in diameter.

2. SAMPLE CONDITIONING

Special sample conditioning was required for the condensation nuclei monitor because the instrument could not tolerate any difference between the sample inlet pressure and the ambient pressure surrounding the instrument. Because the cabin of the aircraft was pressurized and because most of the data were to be taken at altitudes above 5 km the pressure within the cabin would be greater than that of the ram air entering the instrument. A pressurization system was therefore prepared which allowed the use of filtered cabin air to pressurize the incoming air sample. Referring to figure 1, an air sample taken from the atmosphere exterior to the aircraft is introduced into the pressurization system by the combined action of the difference between the total ram air pressure of the inlet probe and that of the static dump line. An air pump also aids the flow. The incoming air sample is fed alternately to each of the two sample chambers by a motor-driven rotary valve. While one chamber is being filled with a new sample, the other, already containing a sample, is pressurized with cabin air passed through a filter thus maintaining the particle count of the sample. The counter samples each chamber successively as it reaches cabin ambient pressure. The degree of pressurization is dependent on the difference between the cabin altitude pressure and the air sample pressure. Essentially, all the particles from the cabin air were removed.

In actual operation an incoming air sample at altitude pressure is drawn into one of the chambers. At the end of a timed flush period, cabin air is allowed to bring the chamber to cabin pressure through the filter. Now the counter can draw from the chamber through a check valve for the duration of the sample period. The pressure within the chamber is vented through a check valve bypass line around the pump. The phase difference between the two chambers is 180 degrees. The pressurization system was capable of providing the demand flowrate of the condensation nuclei counter which was about 3 liters per minute. Flow through the nuclei counter was monitored by a rotameter mounted on the front of the instrument. Occasional adjustments were required during the flights due to changes in cabin altitude pressure. The rotary valve was driven at 28 rpm by a motor. Losses through the pressurization system were not more than 20 percent as measured by ground tests using ambient air. The unit used only metal tubing to minimize losses due to electrostatic forces on tubing walls.

An effort was made to minimize particle losses upstream of both the pressurization system and the condensation nuclei counter. The sample residence time was minimized by locating the instruments as close as possible to the sample probe. Metal tubing (1.3 cm dia. OD) was used between the probe and the pressurization system to eliminate electrostatic losses. Bends were made with as large a radius as possible to prevent impaction losses.

3. INSTALLATION

The particle samplers were installed aboard the NASA CV-990 research aircraft based at Ames Research Center, Moffett Field, California. A schematic and photograph of the sample probe assembly are shown in figure 2. The inlet and discharge probes were mounted on the same window blank installed in the forward part of the airplane. Isolation valves and a bypass line allowed for purging of the inlet probe at altitudes below the test altitude, generally above 5 kilometers. Injestion of liquid water and large concentrations of particulates found below the test altitude could thus be avoided. The probe assembly penetraded the aircraft skin sufficiently to avoid injestion of boundary-layer air. Operational characteristics of the light scattering particle counter made it desirable to run as much flow through the instrument as possible. Therefore large size tubing (1.3 cm dia. OD) was used to lead the sample to the instrument from the inlet probe. Residence time and flow losses were reduced by locating the instrument as close to the inlet probe as possible. A small vane pump was used downstream of the instrument to provide maximum flowrate. A heat transfer mass flowmeter was used to monitor sample flowrate. The flow would vary with altitude ranging from about 21 liters per minute at 5 kilometers to a minimum of 6 liters per minute at 12 kilometers.

The condensation nuclei sample pressurization system, the condensation nuclei counter, the light scattering particle counter, recording instruments, and associated plumbing were mounted on racks supplied by Ames for use aboard the CV-990 aircraft. Racks were placed near the sample inlet probe to minimize sample residence time. The output of the condensation nuclei counter was monitored on a strip chart recorder. Output of the light scattering particle counter expressed as the number of counts in each of five size ranges were recorded manually.

4. DESCRIPTION OF INSTRUMENTS

4.1 Condensation Nuclei Counter

The counter was a commercially available unit adapted for rack mounting in the airplane. A similar system is described by Skala (1963). Operation of the counter is similar to that of a cloud chamber, i.e., water is condensed upon particles much less than 1 μm in diameter to produce droplets which can readily be detected optically. All particles above approximately 0.003 μm in diameter are detected. A constant air sample flow is periodically diverted through a humidifier which injects water into the sample then into a cloud chamber where a fixed-volume expansion of the sample occurs providing a supersaturation of about 300 percent. The supersaturation causes growth of cloud nuclei to occur very rapidly, in a matter of only a few milliseconds. A light beam was directed across the cloud chamber and focused on a photocell. The formation of the cloud attenuates the light beam reaching the photocell. The degree of light attenuation is proportional to the number of condensation nuclei present in the sample stream. After each expansion process, the cloud chamber is pressurized and flushed out. A new measurement is made every second. Several seconds are required for the instrument to respond to a step change due to the time required for the instrument to flush itself out.

A small vane type vacuum pump is used to supply a continuous air sample and a reduced pressure for the cloud chamber expansion. A portion of the vacuum pump discharge is used to actuate pneumatic valves which control the flushing of the cloud chamber. The humidifier consists of a series of baffles and wetted wicks which humidify the incoming air. The water level within the humidifier is controlled by a thermistor which activates a solenoid valve when the water level drops below the thermistor. About 0.10 liter of water is carried in a reservoir within the instrument. This supply is sufficient for at least several hundred hours of continuous operation of the counter. A motor driven rotary valve controls the timing of the flow through the expansion chamber as well as providing a vacuum on one side of a slack diaphram within the fixed volume which would cause the expansion to occur. The valve drive motor rotates at 60 rpm.

The counter was flown in the as-calibrated condition from the manufacturer. No facilities were available for the calibration of the unit at NASA Lewis. The flight data were adjusted by a correction curve supplied by the manufacturer. This correction was required because the reduced cabin pressure changed the calibration of the instrument. Cabin altitude pressure was recorded periodically during the flight series. The limit of detectability of the instrument was 30 condensation nuclei counts per cubic centimeter.

4.2 Light Scattering Particle Counter

The light scattering counter measured number, concentration and size of particles larger than 0.5 μm , although small in number, these particles represent the bulk of the mass of the particles of all sizes. A commercial light scattering counter which consisted of an electronics cabinet and a sensor was used during the flight series. Having the unit in two parts was convenient because the sensor, which was smaller and lighter than the electronics box, could more easily be located near the sample inlet probe in the aircraft installation.

The operation is similar to that of a unit described by Liu (1973). An air sample containing particles passes through a sensitive volume, illuminated by a condensed, collimated and focused light beam. Light scattering caused by the particles is detected by a photomultiplier tube with light from the main beam being absorbed by a light trap. Particle size is determined by the amount of light striking the photomultiplier. The output of the photomultiplier is fed into a multi-channel pluse height analyzer which is calibrated in terms of equivalent optical diameter based on original calibration by polystyrene latex spheres. The instrument was equipped with a plug-in unit which would automatically store the particles counted in each of five different size ranges. The unit would stop the counting after a preselected time interval had elapsed. A total counting time of either 1 or 10 minutes could be selected. One of the size ranges could be selected for viewing on the digital display on the front panel of the instrument. The five size ranges are shown in Table I.

Table I

CHANNEL NO	PARTICLE SIZE, μm
1	0.5 - 0.7
2	0.7 - 1.4
3	1.4 - 3.0
4	3.0 - 5.0
5	$>$ 5.0

Before the flight series the light scattering particle counter was calibrated using an aerosol generator. Monodispersive latex particles were used in the aerosol generator. The index of refraction of the particles was 1.6. A total of 6 different sized monodispersive particles were used. Approximately 80 percent of each size of the monodispersive particles were registered in the proper channel.

5. RESULTS AND DISCUSSION

The most useful data were obtained when an altitude profile mission was flown. An altitude profile consisted of a pattern wherein the aircraft would fly at a given low altitude long enough for a sufficient amount of data to be taken, execute a climbing turn until the next selected altitude was achieved, then fly back along the same track as the first leg. In this manner, the same vertical column of air could be sampled at each selected altitude.

The results of such a flight are shown in figure 3. The altitude profile is shown on the top portion of the figure. Condensation nuclei concentration is shown plotted versus Greenwich Mean Time (G.M.T.) in the bottom portion of the figure. This flight was made between Reno, Nevada and the Pacific coast line on 23 January 1974. The first leg of the flight was made at an altitude of 4.7 kilometers. Most of the data taken during the first half of the leg was at or below the limit of detectability of the instrument (about 30 nuclei per cubic centimeters).

During the flight series it was not unusual for the condensation nuclei counter to be reading below its limit of detectability, in fact, this occurred about 40 percent of the time.

At about 2115 G.M.T. in the first leg the nuclei count began to increase steadily until the end of the leg. A value of 1100 counts was recorded at the instant the 4.7 kilometer altitude leg ended and the aircraft began a climbing turn. The 1100 count peak was one of the highest recorded during 13 flights and approximately 65 hours of flying time. At that same instant the count rate began decreasing rapidly until it reached a value of 500 counts after which another peak of 700 counts was recorded. This indicates the layered nature of the condensation nuclei with altitude. Thereafter the count decreased steadily during the balance of the climb with the decrease continuing for the first few minutes of the next leg which was at 6.2 kilometers altitude. It can be inferred from the data immediately before, during and immediately after the first climbing turn that a region of high concentration of condensation nuclei existed inland from the California coast line where the turn started and extending to at least 6.2 kilometers.

After the initial decrease had leveled out at the beginning of the 6.2 kilometer leg, the count rate was relatively steady, however, the condensation nuclei count was rather high, about 300 per cubic centimeter, which is higher than that usually recorded during the flight series. A peak of about 40 counts above average was registered prior to 2200 G.M.T. indicating some structure in the condensation nuclei concentration at this altitude.

The next leg was an east to west run at 7.7 kilometers altitude. It is interesting to note that during the climb to 7.7 kilometers as well as for the first few minutes of the leg, the condensation nuclei count remained about the same as that seen in the previous leg. This would indicate a relatively homogeneous region of condensation nuclei concentration over a course at least 300 kilometers long and 1.5 kilometers in height. This region ended about 100 kilometers into the 7.7 kilometer altitude leg when a peak of 600 counts was achieved. This peak decayed to the original level of about 300 counts in about 5 minutes. The flight distance for this peak is broad enough, about 42 kilometers, so that aircraft traffic is not a reasonable source. However, it may not be unreasonable to attribute the peak to a large ground source. The response time of the instrument is on the order of several seconds representing a distance of about 0.1 kilometer at this altitude. About 10 minutes after the count rate had leveled off after the peak, the rate began to increase slowly but steadily until it reached about 500 counts when the leg was ended. During the climbing turn to 10.8 kilometers, a single peak was recorded of 900 counts. The width of this peak indicates the length of the high concentration course was at least 30 kilometer long and covered an altitude span of 1.5 kilometers. The possibility of a single aircraft being the source of this peak is remote unless dilution has occurred over a large area.

The leg at 10.8 kilometers altitude was a west to east run. Average condensation nuclei concentrations of about 475 per cubic centimeter at this altitude are higher than was usually encountered during the flight series. A single peak about 9 kilometers long occurred 5 minutes from the end of the leg.

The climb to 12.1 kilometers showed a generally decreasing trend in concentration. No marked peaks were encountered at this altitude. The average count level was about 50 counts below the level at the previous altitude. At the end of this run the aircraft descended quickly to the next altitude for the final run which was at 9.2 kilometers altitude.

Considerable concentration fine structure was encountered during the descent to 9.2 kilometers and during the first few minutes of the run. These peaks are narrow enough to be directly attributable to single aircraft flights. There was a general decreasing trend to the data at this altitude indicating considerable non-homogeneity in the condensation nuclei concentration.

Figure 4 presents a portion of figure 3 with an expanded time scale. It shows some of the detail which was omitted from figure 3 for clarity. Because of the repetition of the basic pattern of the peaks and valleys, the detail shown in figure 4 does not represent real changes in condensation nuclei count. Instead, these data are probably indicative of a pneumatic coupling problem between the condensation nuclei counter and the pressurization system. The phenomenon of peaks and valleys in the condensation nuclei output has been demonstrated in the laboratory under simulated flight conditions. The period of a half sine wave has been measured to be slightly over two minutes. Each one of the two chambers located in the pressurization system is pressurized 28 times per mintue. The basic cycle time of the condensation nuclei counter is once per second. Thus, the cycle times of the pressurization system and the condensation nuclei counter are slightly mismatched. Inserting a ballast volume between the pressurization and the condensation nuclei counter did not eliminate the pulsations. A larger ballast volume might be tried, but a disadvantage would be a delay in response time. More work needs to be done to eliminate this problem.

The results of 5 separate size distribution measurements of light scattering data are shown plotted on figure 5. These data were taken during the flight on 23 January 1974. The symbols of figure 3 show when the data on figure 5 were taken. Each measurement was gathered over a ten minute time period. There were two reasons for selecting a ten minute sampling period instead of a one minute sampling period. First, better statistical data can be expected from the larger sample and second, with the longer sample period less time needed to be spent recording the data since each size distribution had to be recorded manually. Trends in the data shown in figure 5 show a good correlation with those of figure 3. With the exception of the distribution which started at 2249 G.M.T., the distributions follow the trend in increasing concentration shown in the condensation nuclei plot. The other exception is that the peak shown at 2231 G.M.T. on the condensation nuclei data is ignored in the hierarchy of the first four distributions. At the top of figure 5, the distribution which starts at 2249 G.M.T. deserves special mention. All the other distributions are proven low distribution (slope 3-3.5), typical of aged atmospheric aerosols, while the particle size distribution obtained from the data at 2249 G.M.T. show large quantities of atypical large particles that indicate recent material formations. Note that not only is the concentration higher than the other distributions, but if a line were to be drawn through the points, its slope would be much shallower than lines drawn through the other distributions. This shallow slope indicates presence of water droplets or ice crystals being registered by the counter. At the time this measurement was taken, no clouds were visible at the aircraft altitude (7.7 km), although thin cirrus were visible above at about 12 km. Thus, the light scattering particle counter could detect the presence of "invisible" clouds or droplets or ice crystals in concentrations below that required for observation. Cloud detection data cannot be separated from particle data after the size distribution has been completed. However, if during the ten minute sample period one would observe the digital display for one of the larger size ranges, a very rapid counting rate would indicate the aircraft was flying through clouds.

Figure 6 presents condensation nuclei concentration versus G.M.T. for a flight between San Francisco and Hawaii on 30 January 1974. Note that the bulk of the flight was spent at constant altitude. Considerable structure in the condensation nuclei concentration was encountered during the climb from 5.5 to 10.8 kilometers. When cruise altitude was reached, the count slowly decayed to the limit of detectability of the instrument. The reading then slowly increased until a peak of 480 nuclei per cubic centimeter was obtained which was followed by a further slow decay. The decay reached a minimum, then the counting rate climbed rapidly and leveled off at 420 nuclei per cubic centimeter. During the next hour of flying the concentration was relatively constant. Data were lost for several minutes beginning at 2325 G.M.T. while the ballast volume was adjusted. In general, the condensation nuclei data from this flight indicated fairly homogeneous air once cruise altitude was obtained.

Results of 5 separate size distributions of light scattering data are shown plotted on figure 7. These distributions were taken during the flight on 30 January 1974. The symbols on figure 6 show when the data on figure 7 were taken. The distributions with start times of 2101 and 2136 both show shallow slope indicating they are containing large numbers of water droplets or ice crystals. Note that the relative concentrations of each of the 5 size ranges is the same for both distributions indicating clearing or diluted air without preferential removal or evaporation of any particular droplet (or ice crystal) size. Visual observations taken from the aircraft at the time these distributions were taken confirmed the presence of cirrus clouds. The remaining distributions show steep slopes. Visual observations confirmed the absence of clouds when these distributions were taken.

6. CONCLUDING REMARKS

Flight tests have been made with two particle measuring instruments and their respective sample conditioning systems proposed for installation in commercial Boeing 747 airliners. The instruments were flight tested for approximately 65 hours up to altitudes of 12.2 kilometers in the NASA CV-990.

Results of two typical flights show that the concentration of condensation nuclei can range from the limit of detectability of the instrument to 1100 particles per cubic centimeters. Considerable fine structure was usually registered as the aircraft climbed indicating that the distribution of condensation nuclei was nonhomogeneous. Several peak concentrations were encountered at constant altitude with the possibility that the cause was the crossing of an individual dispersed aircraft wake. The instrument performed well during the flight series although more work needs to be done to integrate the pressurization system with the condensation nuclei counter in order to eliminate a pneumatic coupling problem between the two instruments.

For the two flights selected for analysis, concentrations of light scattering particles ranged from 2.5×10^5 per cubic meter in the smallest size range to about 3 particles per cubic meter in the largest size range with the size distribution in clean air typifying the Junge (1963) power law distribution with an exponent of 3 to 3.5. Considerable variation in concentration occurred with altitude although the highest concentrations were not always found at the lowest altitudes. When the aircraft flew through clouds, very large numbers of particles would be registered especially in the larger size ranges. The presence of clouds could thus be detected by the slope of the size distribution curve.

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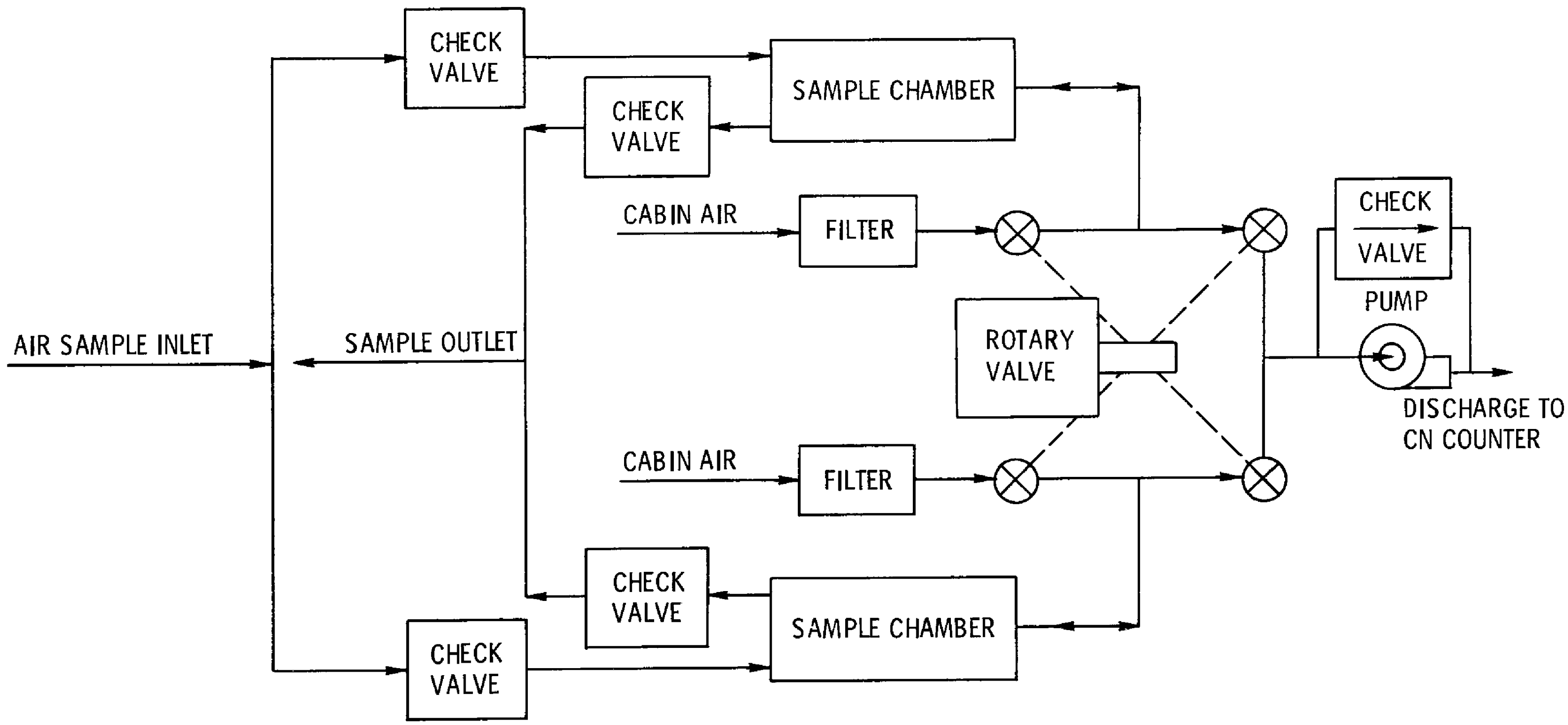

Figure 1. - Condensation nuclei monitor pressurization system.

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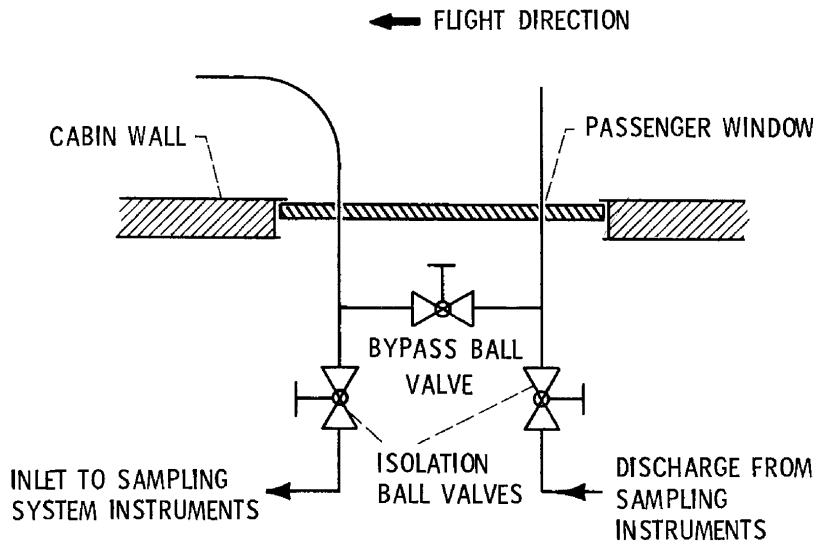
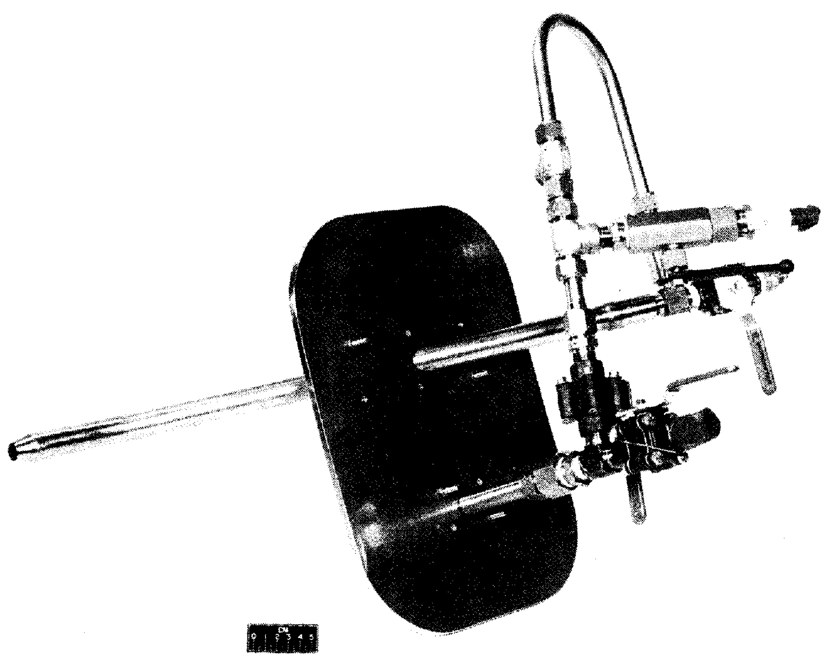


(a) SAMPLE PROBE SCHEMATIC.



(b) SAMPLE PROBE ASSEMBLY.

Figure 2. - Sample probe assembly for CV-990 installation.

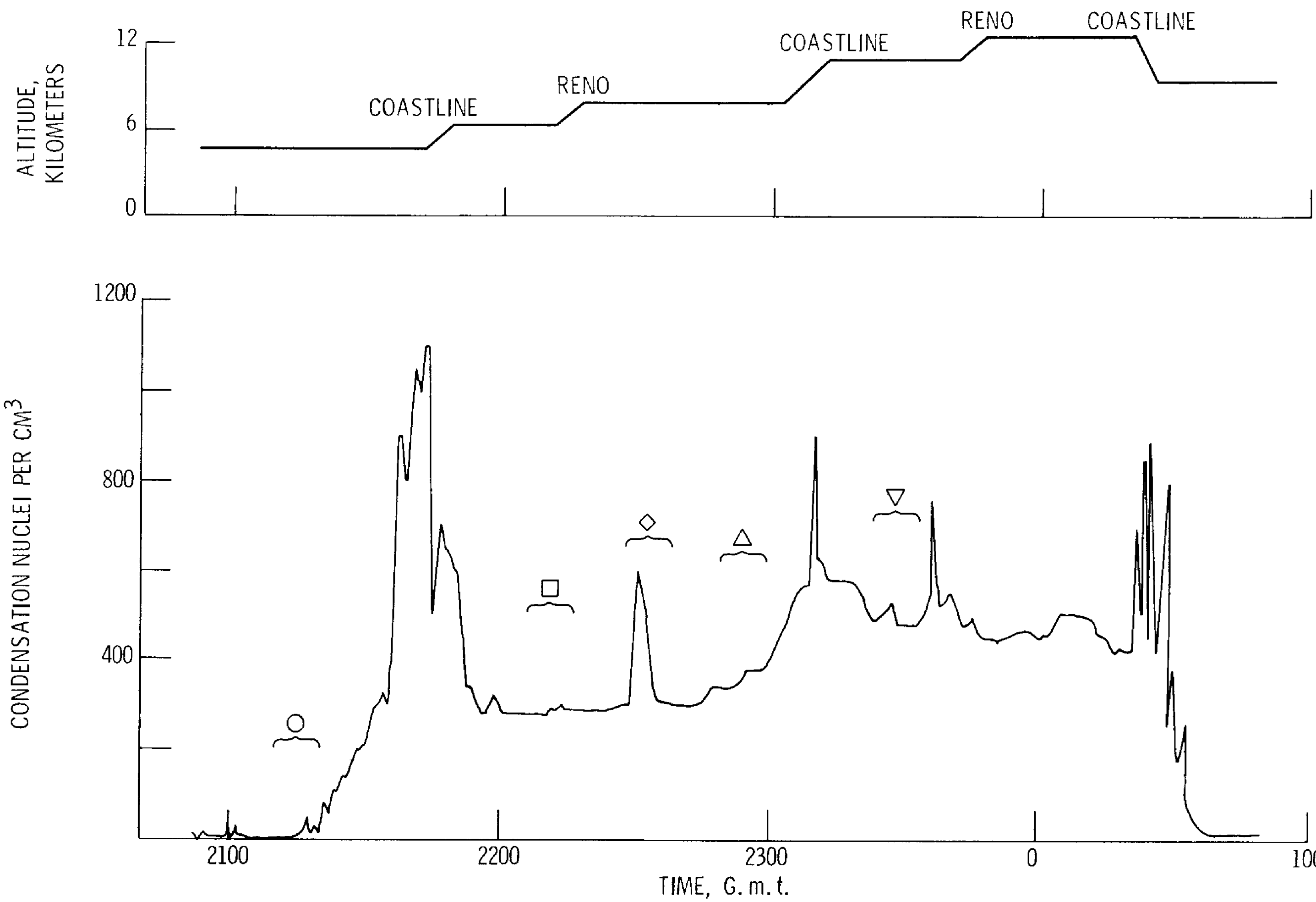


Figure 3. - Concentration of condensation nuclei vs time for flight on January 23, 1974.

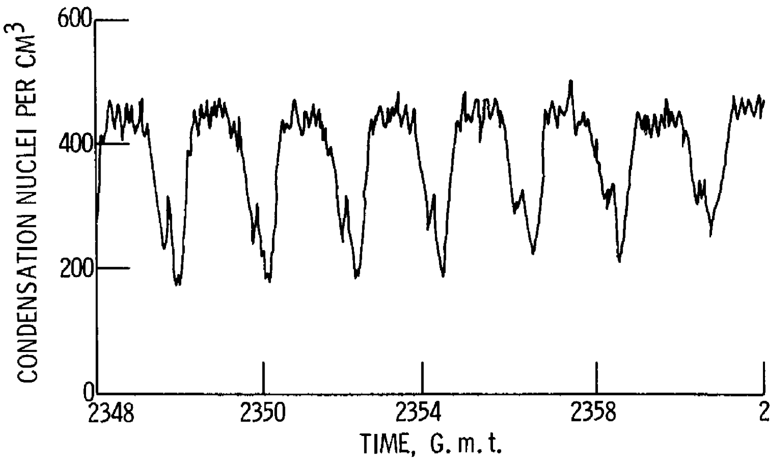


Figure 4. - Section of figure 3 with expanded time scale showing detail of CN output.

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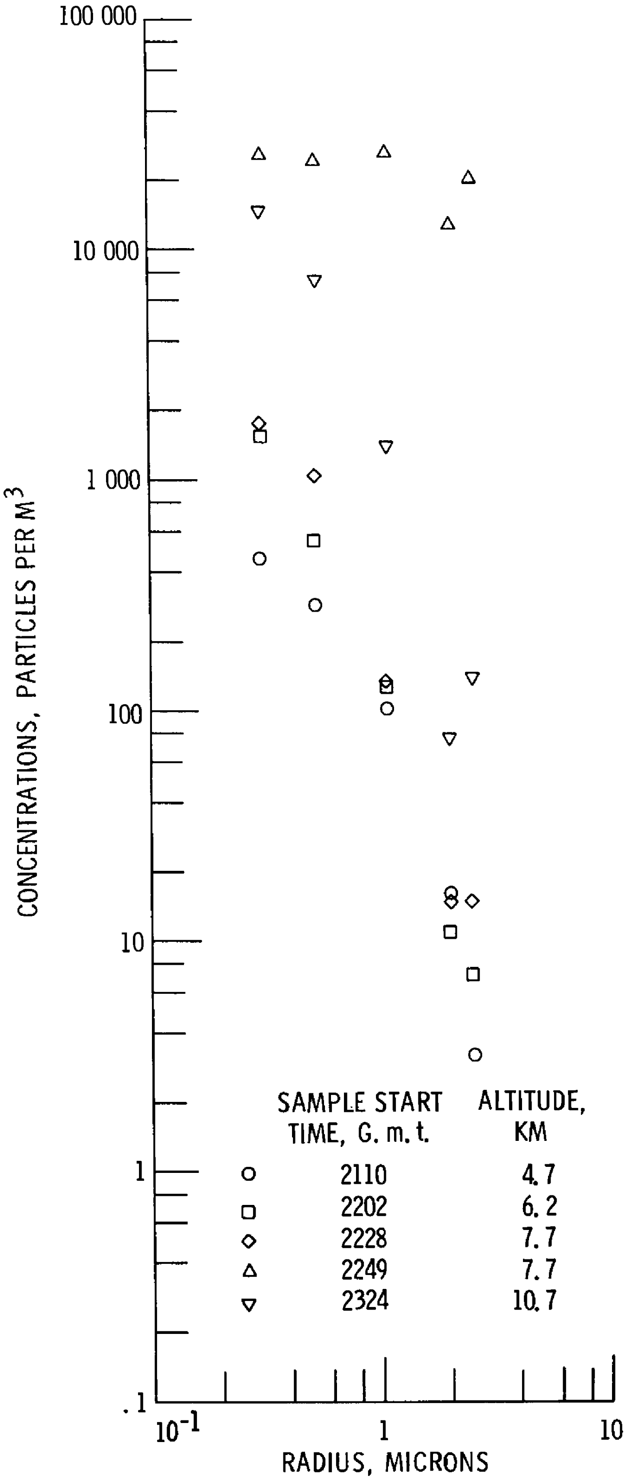

Figure 5. - Concentration and size distribution of light scattering particles taken at various altitude on January 23, 1974.

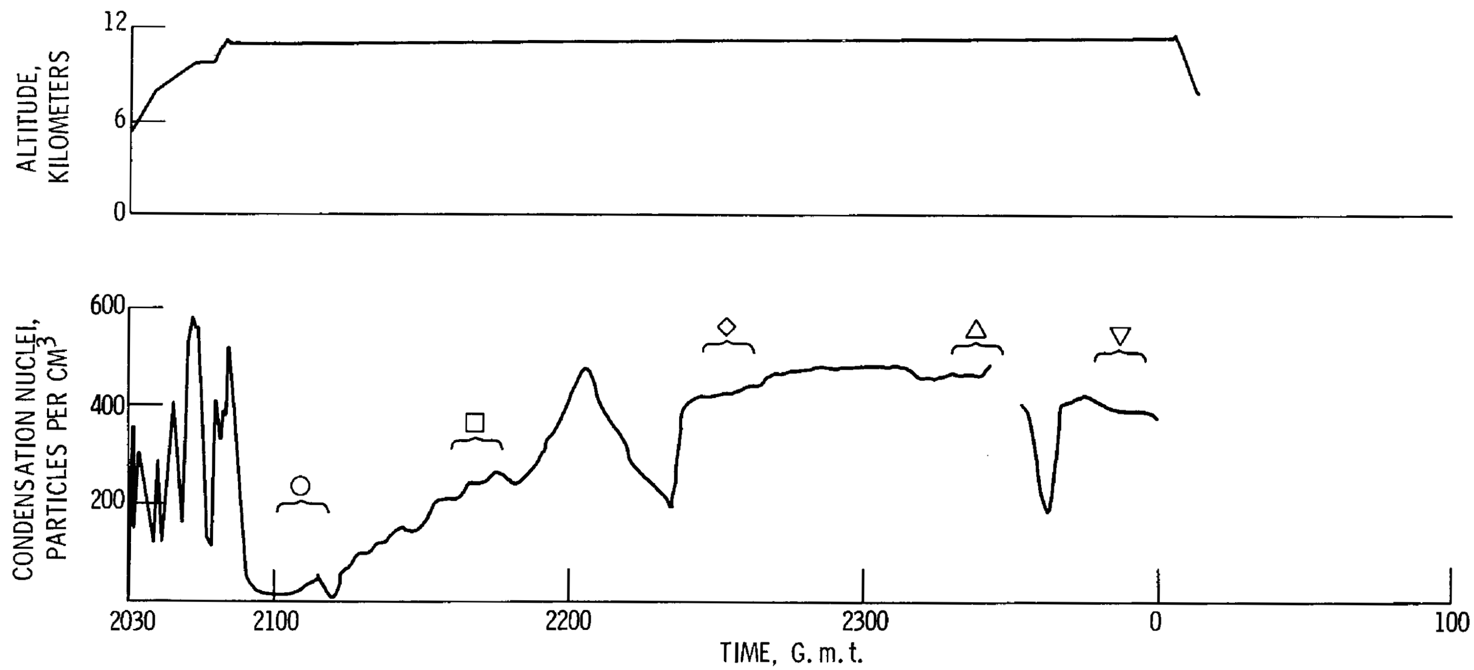

Figure 6. - Condensation nuclei concentration during flight from San Francisco to Hawaii, January 30, 1974.

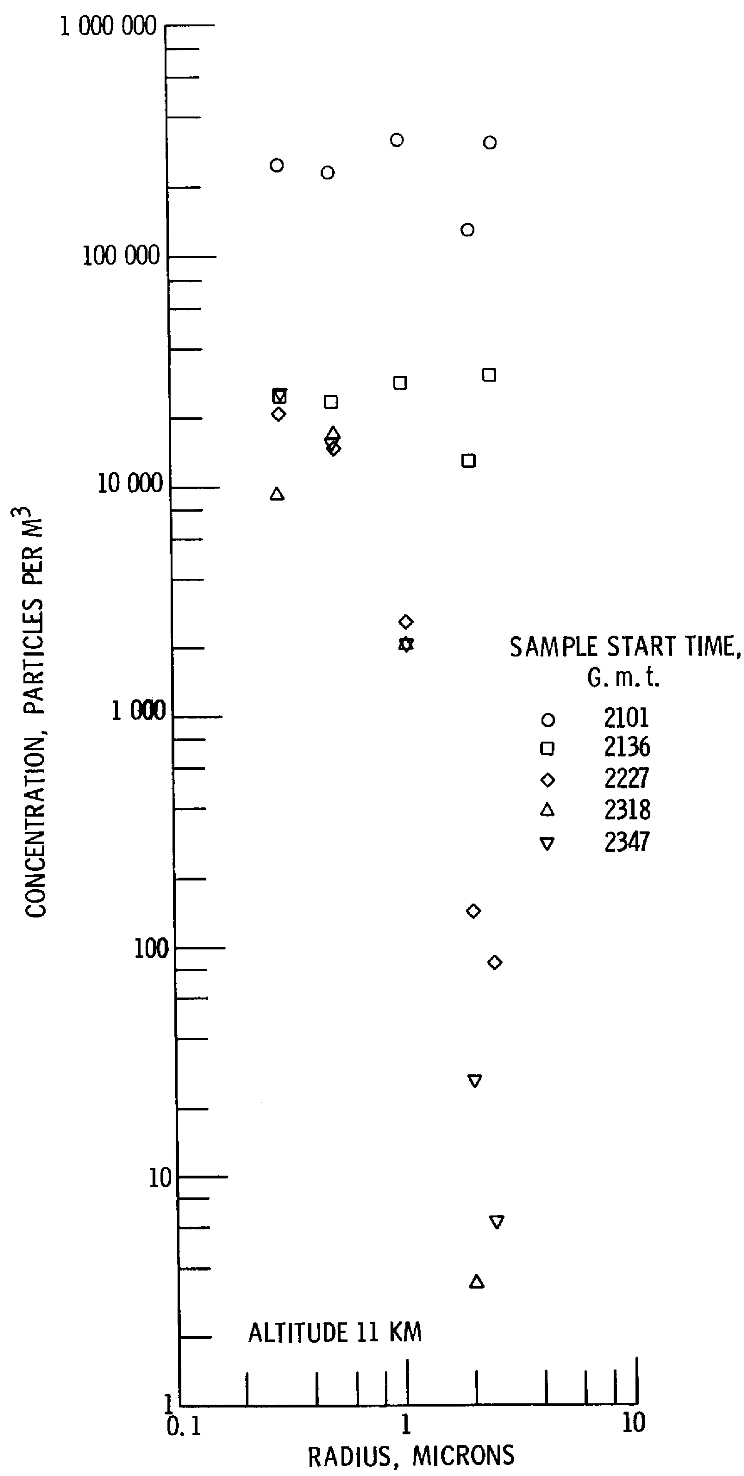

Figure 7. - Concentration and size distribution of light scattering particles taken on flight from San Francisco to Hawaii, January 30, 1974.