

## A Continuous Ice Nucleus Counter and its Application to Tracking in the Troposphere

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### ABSTRACT

A continuous, automatic, and portable instrument was developed for detecting and counting ice nuclei in the field and laboratory. The nuclei are activated in a cloud chamber and the resulting ice crystals are counted by an acoustic particle sensor while the water drops are ignored. The instrument is used in aircraft, trucks, and at fixed sites to track silver iodide and natural ice nuclei.

### 1. Introduction

The ability to detect and count ice nuclei is essential to many studies in cloud physics. We are interested in the origin and transport of natural ice nuclei. Of particular interest is the theory that in some cases these nuclei arrive from the stratosphere by way of a jet stream extrusion process which, as shown by Danielsen (1964), brings radioactive debris from the stratosphere into the troposphere (Dingle, 1965; Kroenig, 1965; Reiter, E. R., 1965; Reiter, R., 1964). Exploratory flights by the National Center for Atmospheric Research (NCAR) as well as other work (Bigg, 1957, 1963a, 1964; Droessler, 1965; Georgii, 1959; Kellner, 1963; Soulage, 1963), indicate that such a process may exist for ice nuclei.

In 1965 NCAR conducted a series of aircraft flights near jet streams using the membrane technique of Bigg (1963b) to detect ice nuclei. Typical results are shown in Fig. 1. The profile in Fig. 1a was most common and normally present in flights parallel to the jet stream.

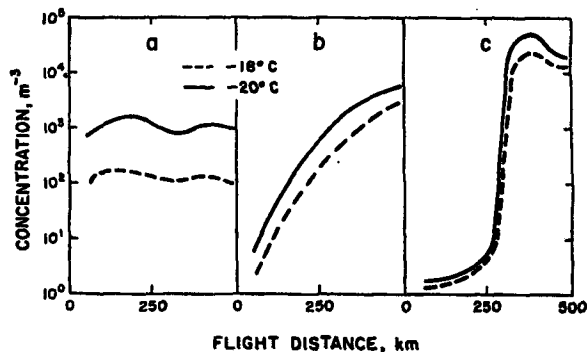


FIG. 1. Natural ice nuclei concentration profiles at constant altitude vs. flight distance in the vicinity of a jet stream.

The profile in Fig. 1b was found in several flights perpendicular to and below the jet streams, and in Fig. 1c, near the core of the stream. These preliminary results raise interesting implications regarding the origin and transport of the nuclei. However, the membrane filter method (Bigg, 1963b) used to detect the nuclei proved to be inadequate for the task at hand. It is necessary to track the nuclei in real time, automatically, and, in many cases, from an aircraft. Such equipment was not available and a program was initiated to provide the necessary apparatus. The only available equipment was the Meteorological Research, Inc., cold chamber and Bigg's (1959) continuous counter; neither are adequate for this work.

The nucleus detector developed at NCAR for the above needs is based on the acoustic particle counter (Langer, 1965, 1966<sup>1</sup>) as a detector. The air sample is humidified and cooled to form a supercooled cloud. Ice nuclei active at this temperature produce ice crystals, which grow to a much larger size than the cloud drops. The acoustic sensor only detects particles larger than 20–30  $\mu$ , and is thus insensitive to the tremendous number of cloud drops present but not to the much larger ice crystals. The ice nuclei detector developed on this principle is described below along with test results demonstrating its feasibility.

### 2. Design and operation of the continuous ice nuclei counter based on the acoustic sensor

The details of the acoustic sensor operation are described in the literature (Langer, 1965, 1966<sup>1</sup>). In brief, it consists of a glass tube (Fig. 2) that tapers gradually from a diameter of 2.5 cm to a 1.5- or 3.0-mm capillary

<sup>1</sup> Langer, G., 1966: A further development of an acoustic particle counter. Fifth Annual Meeting of the American Association for Contamination Control, Houston, Tex.

that is 6 cm long. The capillary then enters a 2.5-cm diameter glass tube. Airborne particles passing through the counter at 50–100 m sec<sup>-1</sup> give a loud, audible click if one particle dimension is above 20–30 μ. With a signal-to-noise ratio better than 20:1 and a several hundred millivolt signal, the 2-msec pulse can easily be counted by conventional electronic circuits.

To form ice crystals from the nuclei, a mixing-type cold chamber produces a supercooled cloud at a desired temperature. Ice crystals nucleated at that temperature are allowed to grow for 1 min before being pulled through the acoustic sensor.

Schematic drawings of a typical unit are shown in Figs. 3 and 4, while a photograph of the unit installed in the NCAR Beech Queen Air plane is shown in Fig. 5. The chamber allows a flow of 10 liter min<sup>-1</sup> for about a 1-min hold up. The complete assembly, with electronics, weighs 140 lb. It consumes 7.0 A maximum at 120 V, 60 cycles. The compressor is a 1/5-ton hermetically sealed model controlled with a handset automatic

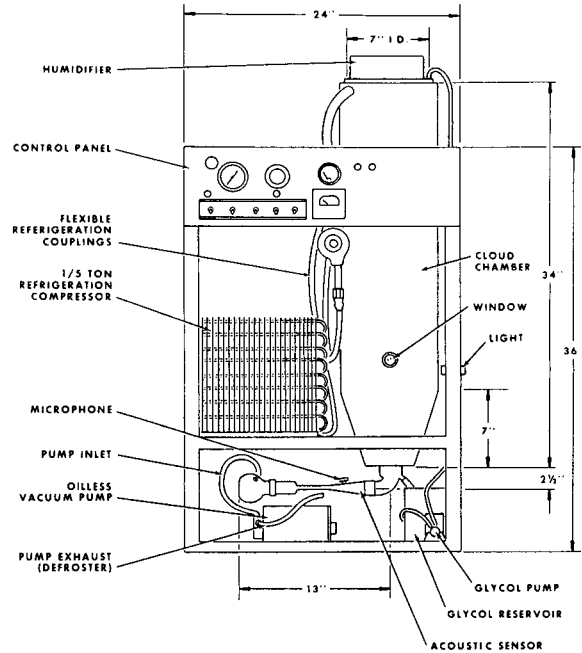


FIG. 3. Schematic drawing of ice nucleus counter.

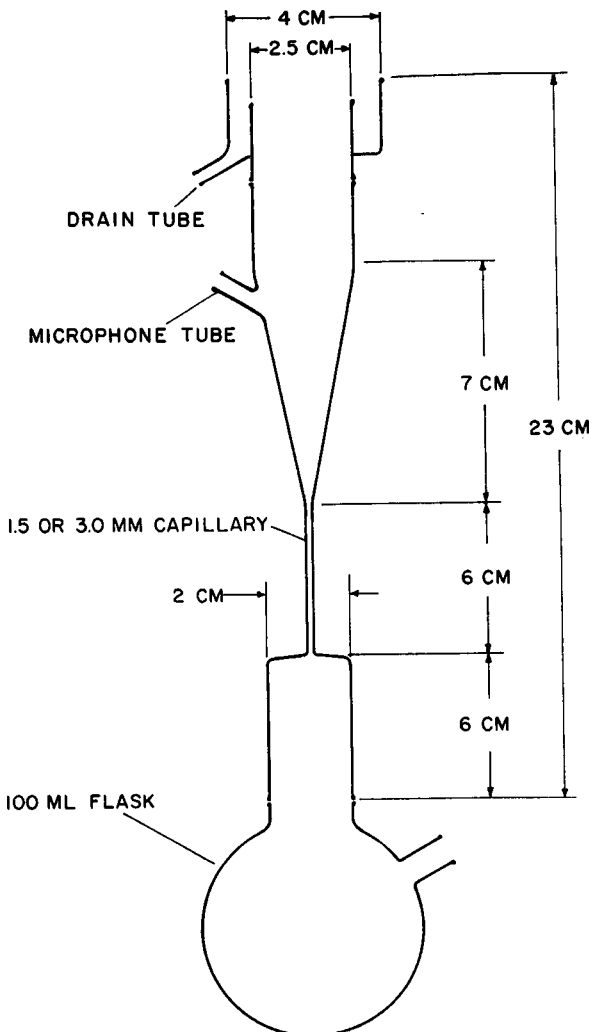


FIG. 2. Acoustic sensor design used for counting ice crystals.

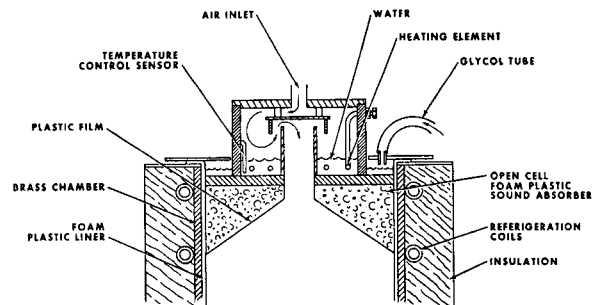


FIG. 4. Details of lid and glycol distribution system of ice nucleus counter.

expansion value. The lowest working temperature available is -25C. The instrument can be ready for operation at -21C in 30 min. A bypass on the compressor coil to equalize the pressure across the compressor itself makes it possible to restart the unit quickly once it has been in operation. Even then, however, the current surge is in excess of 10 A and is borderline for the 8 A ac system on the plane. The compressor is therefore started on ground power and then shifted with an electric relay to the aircraft system to prevent possible damage to the inverter by the starting surge. A Venturi can be used to provide suction. This will reduce current consumption to less than 5 A.

It is essential to prevent the formation of frost on the walls of the chamber. Otherwise, spurious counts result from nucleation initiated by the frost crystals. The frost crystals apparently induce freezing in droplets that pass in close proximity. Without a cloud in the chamber, counts are not recorded in the presence of frost, i.e., the frost crystals do not fall off the wall. Either

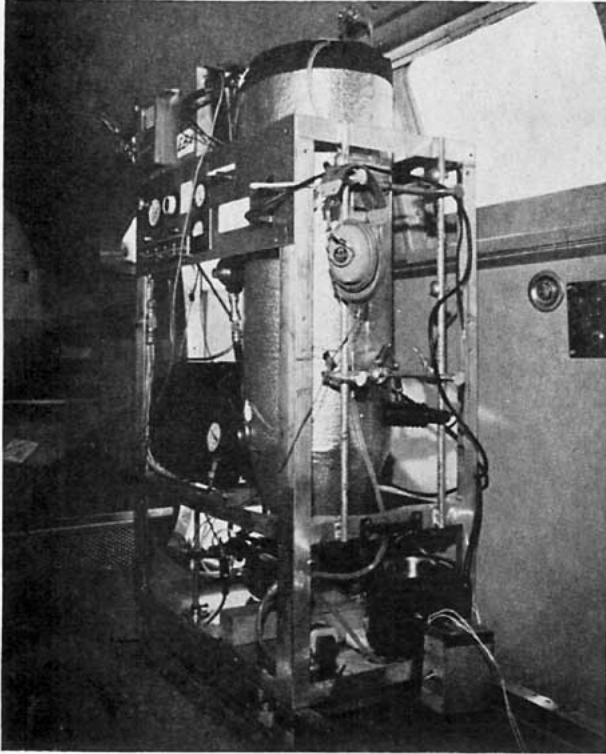


FIG. 5. Ice nucleus counter installed in aircraft.

very small ice crystals splinter off the wall and grow larger when a cloud is present or, more likely, freezing is induced suddenly on drops that closely approach or touch the frost crystals. In this process some splintering may occur. Splintering of natural ice crystals in this manner may be significant in glaciating clouds.

The frost control system consists of a polyurethane foam lining on the walls along which glycol is wicked. This is accomplished by extending the lining at the top into a trough filled with glycol. A 75-95 per cent glycol-water mixture is used. A satisfactory foam is a 1/8-inch felt of firmness #3 made by the Scott Paper Company. The felt extends into a bottom trough which collects the glycol runoff and directs it into a reservoir where it is either intermittently or continuously pumped back to the top. In the unit shown in Fig. 2 the glycol volume is adjusted so that the pump, actuated by a flow switch, goes on every 2-4 min. No frost was formed during the longest operational time of 4 weeks.

The lid of the chamber (Fig. 4) serves to distribute the glycol, humidify the air, and trap large dust particles. A thick plastic foam lining on the bottom of the lid absorbs the sound from the sensor signal to prevent echoes. The foam is covered with Saran Wrap (Dow Chemical Company) which acts as a moisture barrier. Otherwise the foam would fill with condensing moisture and lose its sound-absorbing properties. If a continuous water film formed on the Saran, it would reflect sound. The foam is therefore cut into a "cone" shape so the drops forming on the Saran will run off to the side.

The humidifier exposes a warm water surface to the incoming air to warm and humidify the air. The water temperature is usually kept between 40 and 50C and the humidified air temperature is approximately 32C. When the natural humidity is high, humidification is accordingly reduced. The object is to produce a uniform and fairly dense cloud so that ice crystals can grow to a large enough size in the time available. If the number of cloud condensation nuclei is low, some of the droplets become sufficiently large to set off the sensor, producing

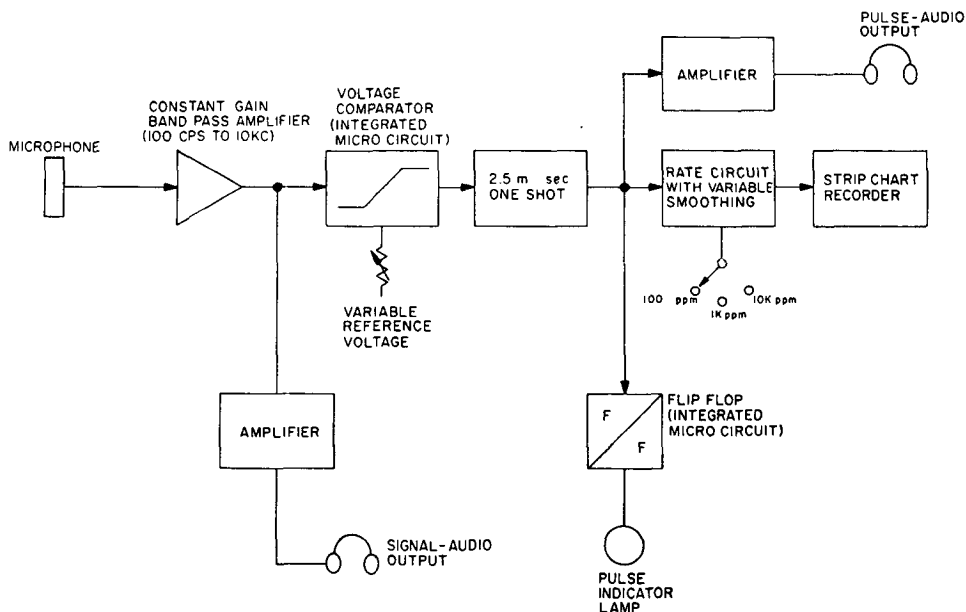


FIG. 6. Simple electronic counting circuit for ice nucleus counter.

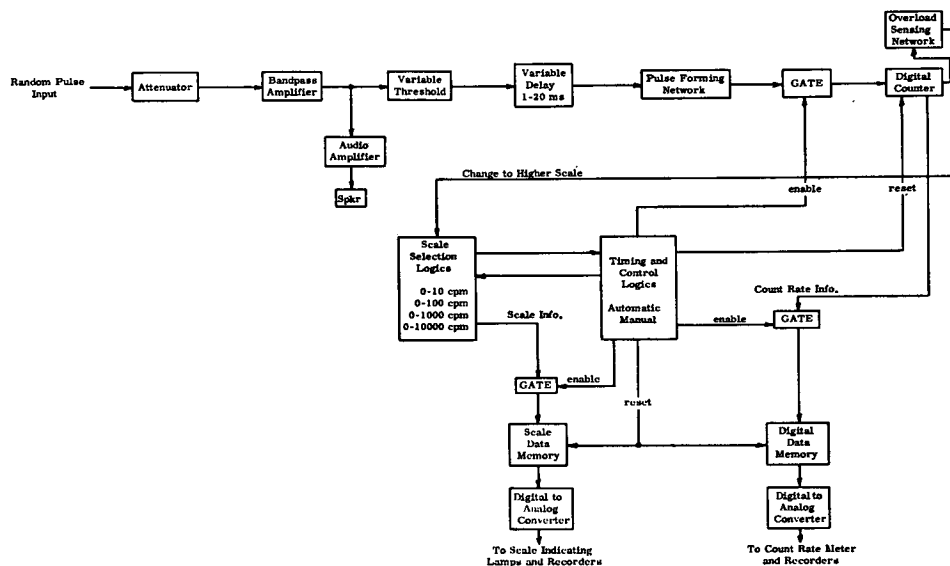


Fig. 7. Advanced electronic counting system for ice nucleus counter.

a low-level, interfering background signal. In this case, cloud condensation nuclei must be provided artificially, which is seldom necessary at ground levels. However, artificial cloud condensation nuclei are often a must in aircraft tracking, especially at several thousand feet above the ground. Cloud condensation nuclei are provided by the hot ceramic surface of a heating element from a small soldering iron. The element is placed in a shroud at the air inlet of the humidifier. As an alternative, a cloud can be generated by introducing finely atomized water into the sampling stream.

The entrance tube to the humidifier is faced by a baffle plate. It serves to impart turbulence to the air for efficient humidification. In addition, larger particles (above approximately  $20 \mu$  diameter) that could set the sensor off are impacted on the plate and collected.

The acoustic sensor that counts the ice crystals can be seen at the bottom of Fig. 3 and its details in Fig. 2. It is a unit with a 1.5-mm capillary to give a flow of about  $10 \text{ liter min}^{-1}$  at 105 mm Hg suction. Note that it is arranged horizontally. This arrangement causes some loss of ice crystals in the elbow but makes it possible to lower the chamber bottom so that it can be sufficiently long for the cramped quarters in an aircraft or carryall vehicle. The sensor tends to fog on the outside and can frost on the inside. These effects are counteracted by letting the pump exhaust pass over the sensor on the outside as shown in Fig. 3. The flask at the end of the sensor prevents ice from building up in the outlet line. The flask has enough surface area to warm the air and evaporate all drops.

The instrument described above is now available commercially.<sup>2</sup> This version is heavier than the NCAR model, has a larger compressor and is fully automatic. This commercial unit can be operated in an aircraft of

<sup>2</sup> E. Bollay Associates, Inc., Boulder, Colo.

the Beech Queen Air type, providing 10 A at 120 V ac, 60 cycles, is available. If the sensor pump is replaced by a Venturi, only 8 A are needed.

Fig. 6 shows a simple electronic circuit<sup>2</sup> to count the ice crystals. A delay of 2.5 msec between counts is built into the system to prevent two counts for one particle. The signal is of a rapidly decaying oscillating form, but for a loud click from a particle, the second oscillation could still be larger than the threshold value. For practical purposes this limits the count to about  $10,000 \text{ counts min}^{-1}$ . Three counting ranges (0-10, 0-1000, and 0-10,000) are available and must be set by the observer.

This counter (with a Rustrak recorder) will give a mark for each ice crystal at concentrations below  $20 \text{ min}^{-1}$ . When counting natural nuclei it was noted often that counts occur in groups of 2-6 counts. This grouping indicates the possibility of splintering. As a drop freezes it may break into several small ice fragments, which then grow to larger crystals by the time the sensor is reached.

A much more sophisticated electronic recording system was developed by E. Bollay Associates, Inc.,<sup>3</sup> to process the data as it is collected for easier data reduction. Fig. 7 gives the basic features of this system. The counter measures true rates of random events by counting the total number of events that occur in a sampling period. The sampling period can be controlled in four decade (120 through 0.12 sec) steps. The output of the counter is converted into an analog presentation that is calibrated over a full scale range from 10 through  $10,000 \text{ counts min}^{-1}$ . The counter output is stored in memory so that the rate reading is from the last sample period. An auto-ranging feature automatically adjusts

<sup>3</sup> Under subcontract with the University Committee for Atmospheric Research to work with NCAR.

the sampling period so that the analog output is between 10 and 95 per cent full scale. This feature permits long sampling periods to be used to obtain meaningful readings at slow event rates, with subsequent immediate sampling for shorter periods if the rate of events suddenly increases. In this manner, an optimum sampling rate (for the given accuracy of the instrument) is automatically selected. The input signal is preconditioned by a variable threshold, 1 mV to 1 V, control that excludes all events whose amplitude is below threshold and by a variable delay, 1 to 20 msec, which excludes all but the first event occurring in the delay period.

The NCAR Ice Nucleus Counter has proven to be a reliable instrument up to 15,000 ft. Above this altitude, the signal-to-noise ratio, which falls off with altitude, is not adequate with the 1.5-mm sensor in the noisy aircraft environment. The 3-mm sensor gives a good signal up to 20,000 ft when sampling ice crystals in mixed clouds. However, the flow rate is too high for the small compressor used on the NCAR unit. The model equipped with the larger compressor has not been flown over 10,000 ft.

Over 15,000 ft the counter gives a lower concentration of ice nuclei than are actually present in the air because the low density of the air causes some ice crystals to settle out of the air stream to the bottom of

the chamber and so they are not counted. This deficiency will require a more advanced chamber design.

We cannot tell at present how accurately the NCAR Ice Nucleus Counter determines ice nuclei in the atmosphere because we do not sufficiently understand the nature and interaction of the nuclei in natural clouds. In other words, we do not know precisely what we are looking for. In fact, one motive for developing the counter was to help answer this question. Comparison runs were made by Dr. Bigg with the Bigg-Warner chamber (Warner, 1957) and Bigg's (1965) bubble technique. The correlation was good within the limitations of these two techniques, which allow a determination to be made only every 15 min. The best that could be done was to compare the slope of the nuclei count vs. temperature.

### 3. Ground and aircraft tracking of silver iodide and natural nuclei

The primary effort has been concerned with demonstrating the feasibility of this new counter for aircraft use and making it available for various field projects. Also, it was deemed desirable to show that the device is practical for following the diffusion of silver iodide in cloud-seeding experiments. A system for doing this is essential for engineering-type weather modification

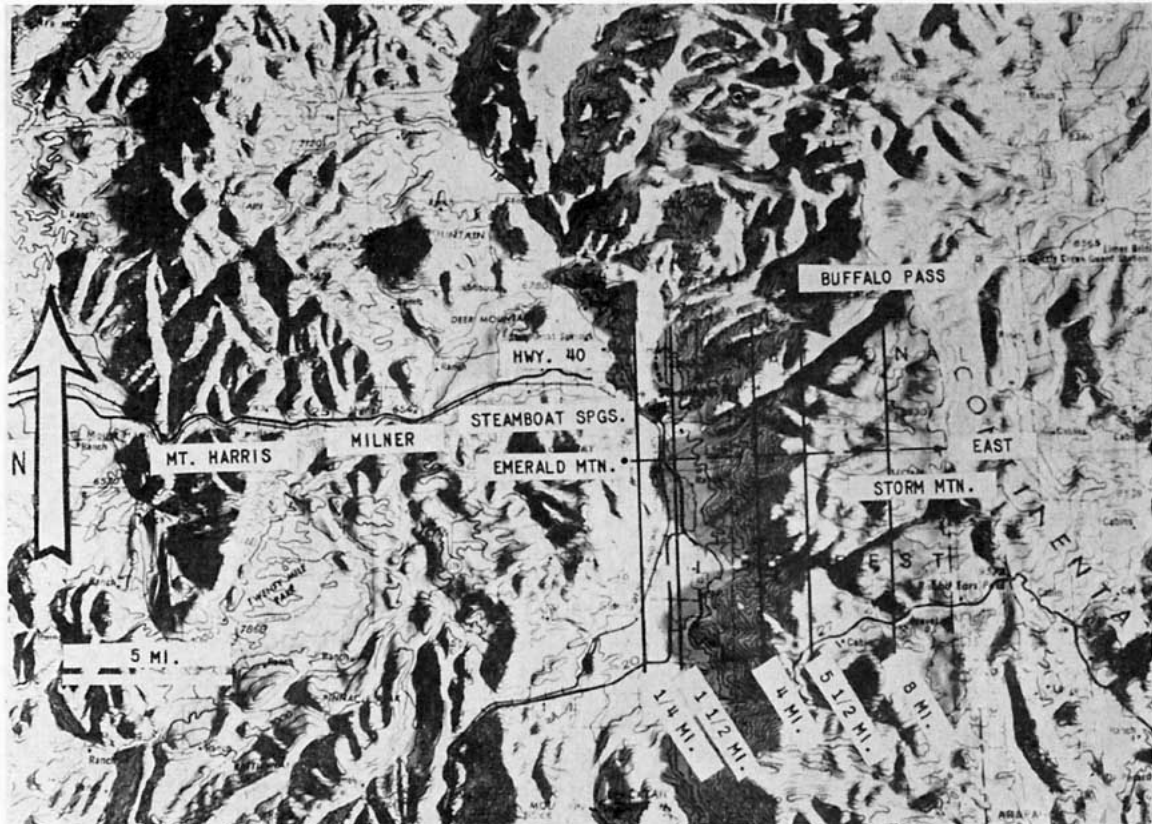


FIG. 8. Relief map of Steamboat Springs area.

studies. The field evaluation of the counter is described below.

As a first step in the development of the airborne counter, tests were made with a truck-mounted unit. Electricity was supplied with a gasoline generator. A silver iodide generator served as the source of nuclei. The results are described below.

The work was conducted near Steamboat Springs, Colorado (6800 ft), in cooperation with E. Bollay Associates, Inc., which maintains a weather modification test area along the Park Range for the Bureau of Reclamation.<sup>4</sup> Fig. 8 shows the test area for following the path taken by the truck- and aircraft-mounted counter.

Silver iodide nuclei were produced with two Skyfire generators at the Emerald Mountain (8200 ft) site south-southeast of Steamboat Springs (Fig. 8). Low-lift balloons were released from Emerald Mountain during the morning. The first of these showed that the nuclei should be carried rather close to Buffalo Pass, east of town. The instrument was dispatched by truck toward that point. By the time it was in position (about 1400 local time) and had established radio contact, a second balloon had been released and had headed 40 deg to the south of the first position. The instrument was turned on to verify that the plume was absent and then was trucked back toward the valley to intercept the plume. When the base of the Buffalo Pass road was reached, a third balloon was tracked overhead. The detector was turned on and detected concentrations significantly above natural background (180 counts  $\text{min}^{-1}$  versus 10 counts  $\text{min}^{-1}$ ). Very high concentrations were detected at the north edge of town and at the beginning of the road to Storm Mountain, both points some 1500 ft below the generators. The equipment was then driven up to about 8000 ft on Storm Mountain where it detected concentrations above background.

This trial demonstrates the futility of tracking silver iodide plume patterns on the ground in mountainous terrain with a single unit, because of the lack of accessible roads. The tests made it clear that any useful tracking in a diversified terrain must be carried out by airplane. The tests also showed that much of the generator's output is dissipated in the valley, even though the smoke was released 1500 ft above on a peak.

Fig. 5 is a photograph of the aircraft installation in the NCAR Beech Queen Air. A 1-inch intake extending above the boundary layer from the roof of the plane serves as a ram-air intake. A fraction of this air is used by the counter. The first tests were made over the plains of eastern Colorado with a ground-based charcoal silver iodide burner as a source. The site, near Longmont (5000 ft), was circled close in to locate the plume. Then straight passes were made at right angles to the plume at increasingly longer distances. The flight altitude was usually 5500 ft to stay beneath the inver-

sion. In some flights no plume was detected at 500 ft above the ground. Presumably, meteorological conditions kept the smoke from rising.

Typical test results for a 6000-ft inversion, up to 10-mph gusty winds from the SSE, and clear sky conditions were as follows. At a distance of 5 mi at 5500 ft, the plume was 4.5 mi wide for four repeated passes with an average concentration of 10 nuclei  $\text{liter}^{-1}$  tested at  $-18\text{C}$ . This plume width correlates roughly with a source strength of  $10^{13}$  nuclei  $\text{min}^{-1}$ , which is reasonable for a charcoal burner.<sup>5</sup>

Tracking studies were then carried out in the mountains at the E. Bollay Associates, Inc., test area near Steamboat Springs. Two skyfire generators (E. Bollay Associates, 1965, pp. 58, 97-102) on Emerald Mountain produced the nuclei at a rate of about  $10^{14}$   $\text{sec}^{-1}$  at  $-21\text{C}$ . Also, a zinc sulfide generator was turned on intermittently to serve as a second means of tracking. A fluorescent particle detector (E. Bollay Associates, 1965, pp. 24-33) was installed on the aircraft along with the NCAR counter to permit simultaneous tracking.

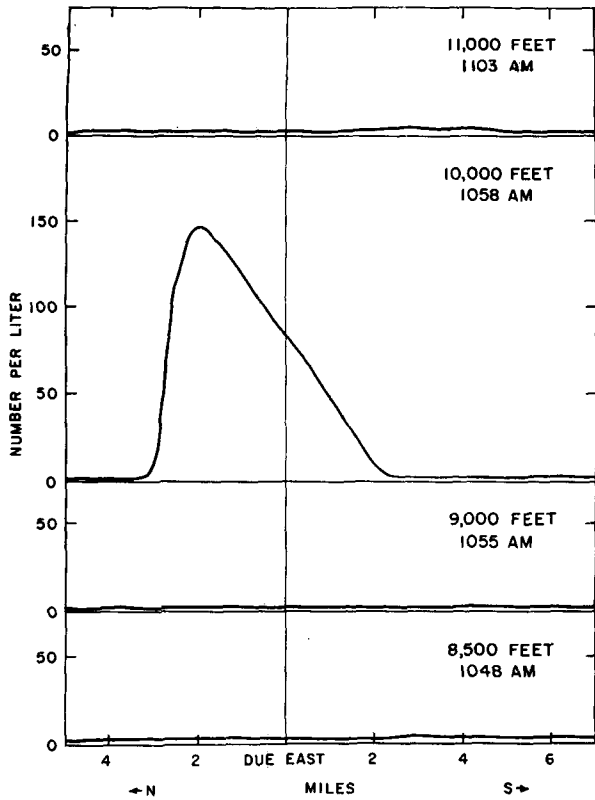
Because of aircraft scheduling and flight limitations, the tests were not carried out during seeding operations; as pointed out below, however, meteorological conditions approximated seeding conditions.

In interpreting the results, the following should be kept in mind. The zinc sulfide detector, which counts the particles individually while airborne, responds almost instantaneously while the ice nucleus counter has a delay of 20 sec before the first crystals are counted. The hold up of the chamber is actually about a minute but some of the crystals are transported through the chamber faster than that because of turbulent mixing and settling of the crystals. As a result, the actual plume structure is blurred to some extent, but this is not critical for this application. The flight data for the Steamboat Springs tests were corrected for an effective delay of 1 min as derived from simultaneous counts with the ice nucleus and zinc sulfide counters as described later. The nuclei were counted at  $-21\text{C}$ .

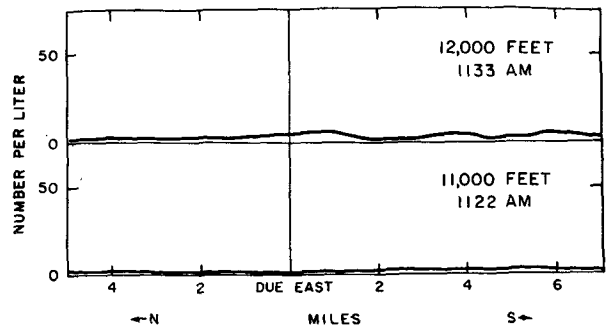
The test area was approached from Craig along Highway 40 via Mt. Harris and Milner on 11 May 1966. A nuclei count of 20  $\text{liter}^{-1}$  was noted at 1030 over Milner (8000 ft) in the Yampa Valley. Another puff was found upon turning east toward Emerald Mountain and starting into a counterclockwise, 1/2-mi radius circle around the mountain at 8500 ft. This count was at 40  $\text{liter}^{-1}$  and in both cases the cloud was about 4 mi across. The site for the generators was then circled to locate the plume direction at that time. The wind was steady from the south at 5-10 mph on the ground at the site, but a balloon release went to the east a few thousand feet and then traveled over the valley to the north. Cloud cover was low and broken initially; at the end of the tracking period the clouds closed in and

<sup>4</sup> Contract No. 14-06-5281.

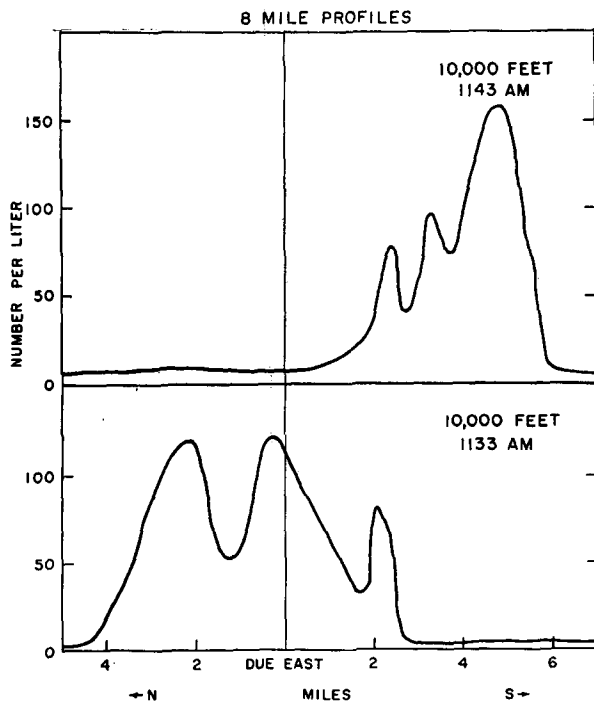
<sup>5</sup> Private communication, L. Grant, Colorado State University, Fort Collins, 1966.



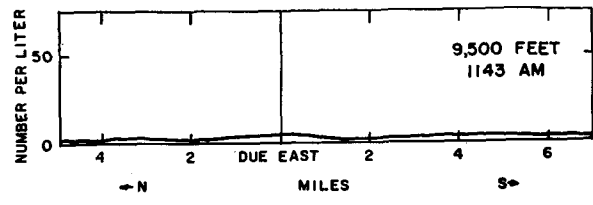
a.



b.

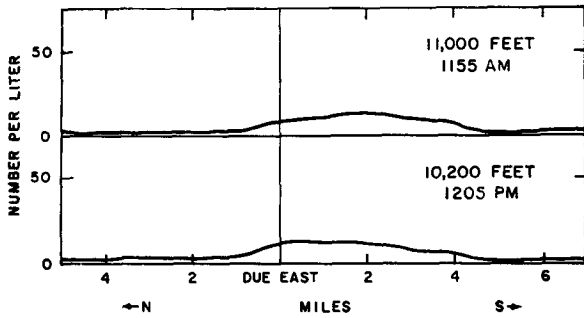


c.

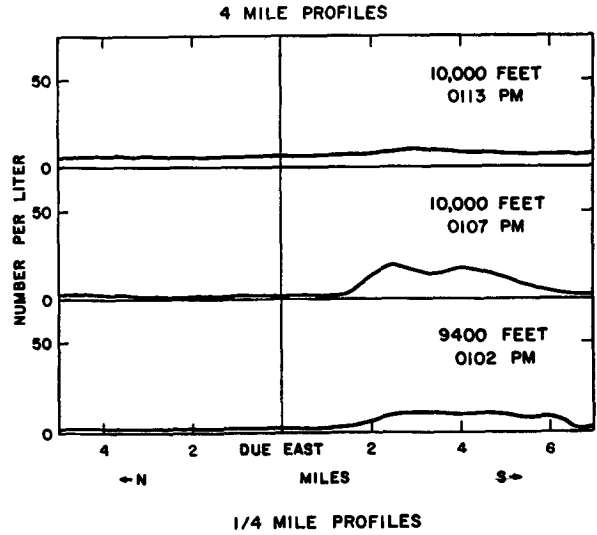


d.

FIG. 9. Ice nuclei concentration profiles on a north-south course at various distances due east of generator site. See text for discussion.



e.



f.

FIG. 9. (continued).

snow flurries started in the area. Some virga were observed during the test.

A series of N-S flights was begun at 1040 a.m. at a speed of 140 mph and a horizontal distance of 1.5 mi when due east of the site. Fig. 9a shows profiles of nuclei detected for successively-higher flights over the valley with the time given when due east of the site. The plume was found only at 10,000 ft. The graph gives the nucleus counts and cloud width. The next step was a series of flights 8 mi from the site, near the Continental Divide at 11,000 and 12,000 ft (Fig. 9b). No cloud was found and the flights were resumed on the original course 1.5 mi from the site (Fig. 9c). The cloud was still at 10,000 ft but had shifted south on the second pass. Later, a released balloon traveled east off the mountain and then south over the valley.

It was desirable to determine the distance to which the cloud extended across the valley. Therefore, passes were made 5.5 mi east along the edge of the range, which is about 10,000 ft high. The plane was at 9,500 ft and a weak pattern of counts was detected, as shown in Fig. 9d. The search was then shifted to 4 mi east above the edge of the valley (8000 ft) at 10,200 and 11,000 ft flight altitude. Fig. 9e shows that counts increased somewhat. Finally, tracking 1.5 mi away at 10,000 and 11,000 ft showed the cloud in the previous position, but somewhat weaker. However, nuclei were now found at 11,000 ft as well, so the cloud had extended vertically. By this time, the wind speed had dropped to <5 mph at the ground.

From these tests it appears that the nuclei were trapped in the Yampa Valley east of Emerald Mountain and simply did not rise over the first mountain range. As the plume from the site extended toward the east it apparently broke up into separate clouds traveling up or down the valley. The approach flight revealed

such puffs in the valley to the west of Steamboat Springs. On the return flight to Craig at 1340 another such cloud was found where the valley widens at Mt. Harris. The cloud gave a count of 40 liter<sup>-1</sup> and extended 5 mi to the west from Mt. Harris. The background count in the area at -21C was less than 0.5 liter<sup>-1</sup>.

Before returning, the site was circled on a 3-mi radius to compare the ice nucleus counter and the zinc sulfide detector. This test was preceded by a few passes (Fig. 9f) along the edge of Emerald Mountain, 1/4 mile east at 9400 and 10,000 ft to locate the plume. The wind had become quite weak and some time elapsed before the zinc sulfide traveled an appreciable distance from the site. The comparison flights were then begun, and a typical pass is shown in Fig. 10. It shows a 1-min delay between the time that the ZnS detector first saw the cloud and when the nucleus counter responded. The nucleus counter does not show the fine detail that the zinc sulfide detector presents, but the main features

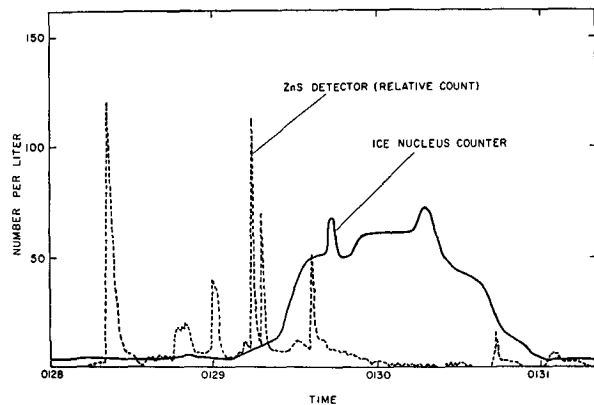


FIG. 10. Zinc sulfide detector vs. ice nucleus counter, 3 mi east of generator at 8000 ft.

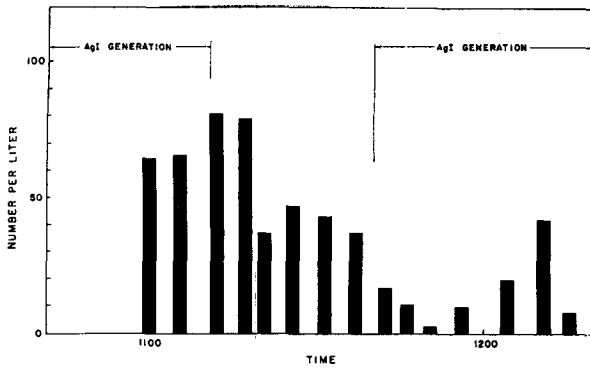


FIG. 11. Average ice nuclei concentration per 10-mile track on north-south course 1½ mi east of generator.

of the plume are reproduced. More detail could have been obtained by the nucleus counter, but the chart speed was too low.

On 14 May another test series was undertaken in the same area under high cloud cover. This time the weather conditions were quite different. At 11,000 ft the wind was averaging 22 mph from the southwest and was very turbulent. A north-south course was selected at 10,000 and 11,000 ft. The flights were made 1.5 mi east of the site at 140 mph. No clear plume pattern emerged at either altitude, but random fluctuations (around 60 nuclei liter<sup>-1</sup>) indicated that the silver iodide was intensely mixed by the turbulence. The generators had been on 15 min when an 80-min period of regular passes was started. Generation was discontinued 15 min after the start of tracking and resumed 30 min later. Fig. 11 shows clearly how the silver iodide gradually dissipated over a period of 40 min after the generator shut down.

The start of the second release period can be noted on the graph. It shows the presence of a plume pattern

at the start, so flights were initiated to see how far the nuclei traveled. On a north-south course, 8 mi due east of the site, at 11,000-ft altitude, a plume was detected about 3 mi wide, averaging 10 nuclei liter<sup>-1</sup>. At 12,000 ft the plume was found again, but was one and one-half times as strong. Still further out on an 11,000-ft pass 15 mi ESE of the site, an 8 mi wide plume was located. The plume showed no peak, but averaged 10 nuclei liter<sup>-1</sup> rather evenly. At that time the second silver iodide release had been going for 1 hr. On turning back, a strong plume was detected 6 mi from the site, east-southeast, off Storm Mountain at 11,000 ft. The plume extended 7 mi on a north-south track and reached a maximum concentration of 70 nuclei liter<sup>-1</sup> with an average of 30 nuclei liter<sup>-1</sup>.

It is evident that under these conditions of strong turbulence the plume from Emerald Mountain was lifted over the mountain range forming the valley to the east of Steamboat Springs. It traveled to the Continental Divide with a noticeable concentration. Much of the generator output, however, was dissipated in the Yampa Valley. Also, neither of the flights showed that the silver iodide rose above the ground more than 1500 ft.

4. Industrial contaminations

The principal aim of NCAR's development of this ice nucleus counter is to study the origin and transport of natural ice nuclei. The work at Steamboat Springs gave us experience with the sensor's response to known nuclei, which has been useful in studying the more complex behavior of naturally occurring ice nuclei. Unfortunately, such studies are complicated by the fact that industrial activity also creates ice nuclei with no intent toward weather modification. Flight with membrane filters have indicated several such sources along

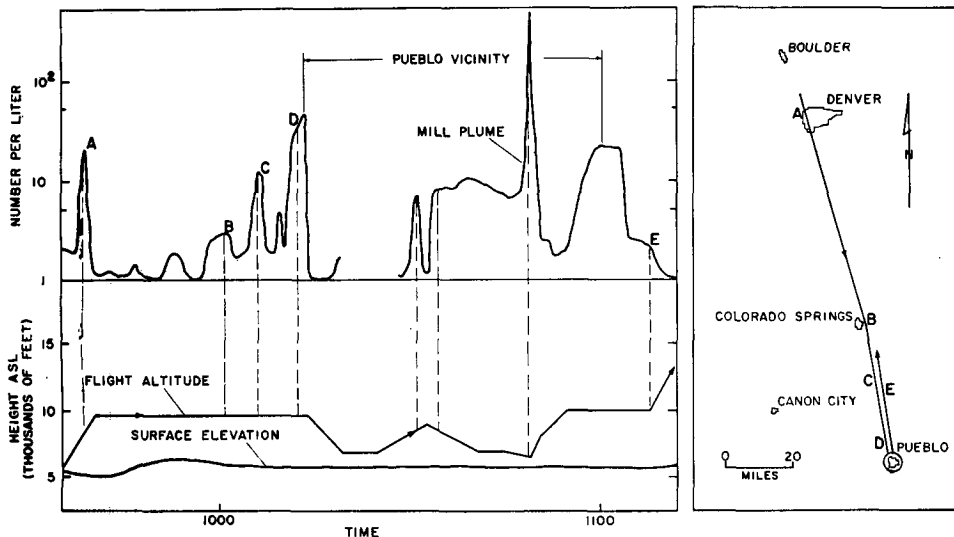


FIG. 12. Ice nucleus profile, Denver-Pueblo-Denver, 26 May 1966.

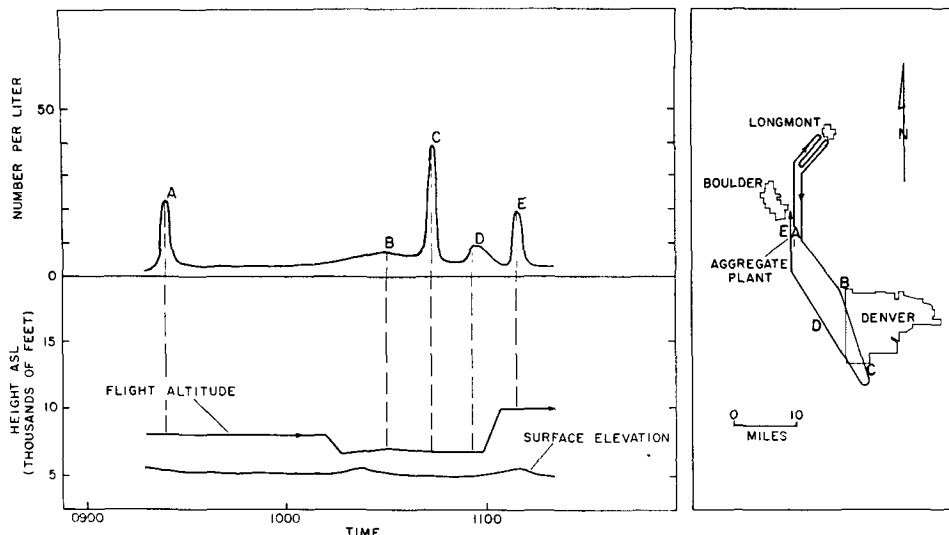


FIG. 13. Ice nucleus profile, Denver and vicinity, 25 May 1966.

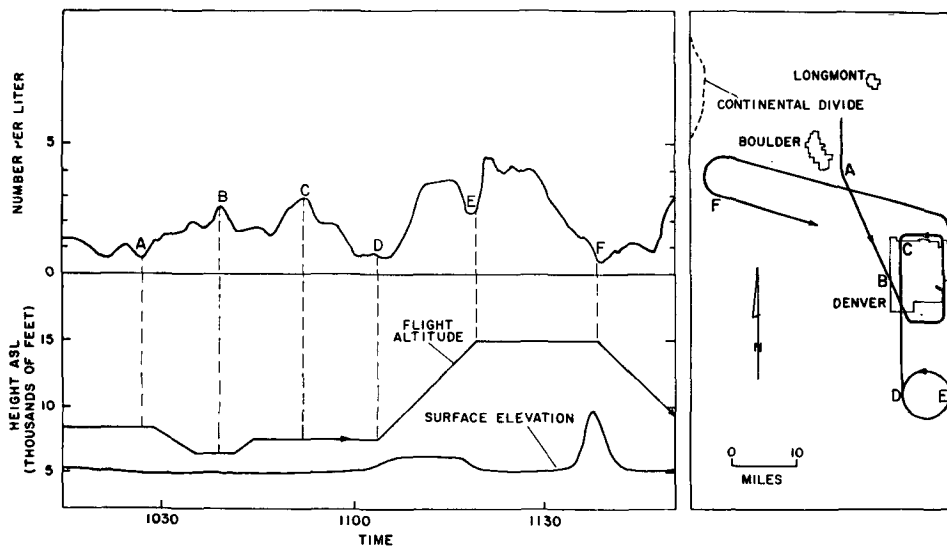


FIG. 14. Ice nucleus profile, Denver and vicinity, 3 June 1966.

one of the major flight paths used to search for nuclei in the vicinity of jet streams. Flight surveys were carried out to locate these sources in eastern Colorado. The resulting data are for  $-21^{\circ}\text{C}$  and are not corrected for the chamber hold up of 1 min.

A strong source near Pueblo was identified as the smoke plume from the steel mill. Other investigators have shown similar results (Soulage, 1958; Telford, 1960; MacCready, 1955). Fig. 12 shows the flight pattern and nucleus count. The plume count over the plant approached that of a silver iodide burner at the same distance. A little south of Denver occasional puffs of nuclei were encountered, which may have originated from Pueblo. Such a prolific and continuously emitting source can cause confusion when tracking natural

nuclei from soil or stratospheric origin. It is interesting to speculate if it can affect local climate.

Nuclei sources around Denver, and their extent, were investigated in the flights shown in Figs. 13 and 14. The map serves as reference for the geographical locations. On one occasion a strong local plume was noted (Fig. 13) over southwest Denver near the race-track. This plume may have been from a foundry, but attempts to pin down the location were not successful. Fig. 13 shows only a small increase when passing over the area a second time. Another point source was noted near an aggregate plant at the start and end of the flight on 25 May (Fig. 13). An attempt to relate it to the plume of the plant proved negative. A cement plant

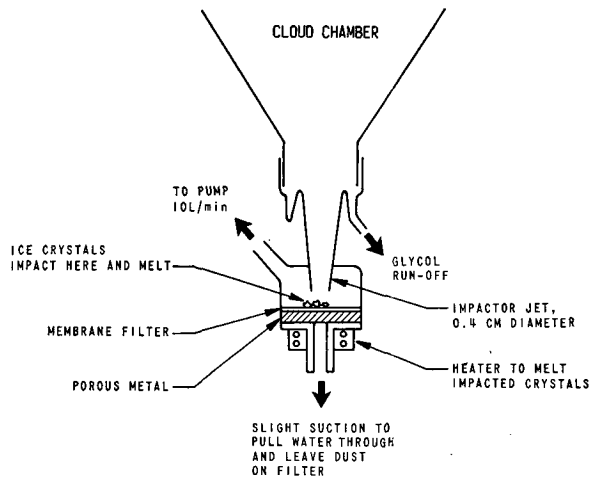


FIG. 15. Ice crystal impactor.

generates nuclei active below  $-24^{\circ}\text{C}$ .<sup>6</sup> The next flight on 3 June (Fig. 14) failed to show this source but gave a general increase over Denver and a higher count at 15,000 than at 7000 ft. Also, a low count was noted when flying over the mountains. On this day the inversion was over 15,000 ft and the weather was clear. The previous flight had a strong inversion below 10,000 ft and it was very hazy over the city. Obviously, a large city can be a substantial source of ice nuclei.

Another interesting aspect of the 3 June flight was the counts obtained on the ground that same afternoon. First the counter was operated on the roof of our laboratory on the east side of Boulder. The count was three times that found in the plane. The wind was from the northeast quadrant at 5–10 mph. The counter was then moved into the laboratory and the count went below that of the aircraft measurements. This indicates that the nuclei at the laboratory were mainly blown off the ground and were large enough so they would not pass through the ventilating system of the building.

### 5. Collection of ice crystals for analysis of nucleating substance

As an adjunct to the continuous ice nucleus counter, a device was developed to collect the ice crystals for examination of the nucleus composition. Such collections are necessary to establish the origin of the natural nuclei. The low velocity impactor (Fig. 15) is attached, in place of the acoustic sensor, to the cloud chamber shown in Fig. 3. The crystals, but not the drops, impact because of their large size and melt on the heated membrane filter. The liquid water is pulled through the filter and any solid residue is retained by the filter for subsequent examination. So far, the device has only been applied in the laboratory to identify silver iodide released in the room.

<sup>6</sup> Private communication, G. Morgan, E. Bollay Associates, Inc., Boulder, Colo., 1966.

### 6. Summary

The ice nucleus counter meets the goal of automatically detecting and counting natural or artificial ice nuclei from an airplane, ground vehicle, or fixed site. Electronics to record and display the counts were developed and tested in the field. The success of the instrument has justified its commercial production.

Initial survey flights and ground sampling of natural ice nuclei show that human activity can give local high counts approaching that of a silver iodide burner at  $-21^{\circ}\text{C}$ . Large cities are a source of nuclei and particular operations, such as a steel mill, can create large numbers of nuclei. Wind will entrain nuclei off the ground but their size is such that they do not appear to rise more than a few hundred feet into the air.

Tracking of silver iodide plumes under conditions approximating those conducive to cloud seeding gave results of general interest. Plumes were tracked as far as 20 mi. Particles were trapped in mountain valleys even though the smoke is released from a peak. Their presence was verified down to ground levels by sampling from a truck. The plume pattern is erratic in the mountains in agreement with Henderson.<sup>7</sup> Turbulent conditions appear to be more effective in carrying the smoke up and over mountain ranges as previously shown by dePena (1964). Under turbulent conditions, 10 nuclei liter<sup>-1</sup> were found 15 mi away in a several mile wide plume. However, no indication was found in these tests that the ground generators formed plumes with a reasonable number of nuclei that rose more than a few thousand feet above the ground. This result agrees also with Henderson's data,<sup>7</sup> although his coldbox detector has 1/1000 the sensitivity of our counter.

A comparison was run between tracking a plume with a zinc sulfide tracer and by the nuclei themselves using the counter. The nucleus counter showed a 1-min delay in response to the hold up of the cloud chamber. The zinc sulfide detector showed more detailed structure of the plume, but the nucleus counter showed all major features.

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### REFERENCES

Bigg, E. K., 1957: January anomalies in cirriform cloud coverage over Australia. *J. Meteor.*, **14**, 524–526.

<sup>7</sup> Henderson, T. J., 1965: Tracking silver iodide under orographic influence. 24th National Meeting of the American Meteorological Society on Cloud Physics and Severe Local Storms, Reno, Nev.

- , 1959: Continuous automatic recording of ice nuclei. *Bull. Obs. Puy de Dome*, No. 4, 125–138.
- , 1963a: Stratospheric ice nucleus measurements from balloons. *Tellus*, **15**, 162–166.
- , 1963b: The measurement of ice nucleus concentration by means of Millipore filters. *J. Appl. Meteor.*, **2**, 266–269.
- , 1964: The results of large scale measurements of natural ice nuclei. *J. Atmos. Sci.*, **21**, 396–403.
- , 1965: Problems in the distribution of ice nuclei. *Proc. Inter. Conf. Cloud Physics*, Tokyo, Japan, 137–140.
- Danielsen, E. F., 1964: Radioactivity and potential vorticity. *Proc. Sec. Conf. Radioactive Fallout from Nuclear Weapons Tests*, U. S. Atomic Energy Commission, Germantown, Md., 436–449.
- dePena, R. G., 1964: Mesures de la diffusion de noyaux glacogenes d'iodure d'argent. *J. Rech. Atmos.*, No., 1, 19–27.
- Dingle, A. N., 1965: Stratospheric tapping by intense convective storms, implications for public health in U. S. *Science*, **148**, 227–229.
- Droessler, E. G., 1965: A note on ice nucleus storms. *J. Atmos. Sci.*, **21**, 701–702.
- E. Bollay Associates, Inc., 1965: Park range atmospheric water resources program, phase I. E. Bollay Associates, Inc., Boulder, Colo., 192 pp.
- Georgii, H. W., 1959: Bemerkungen zu den "Januar-singulari-taeten" der Konzentration atmosphaerischer gefrierkerne. *Geofis. Pura Appl.*, **44**, 249–256.
- Kellner, L., 1963: Alignment of cirrus clouds along the magnetic meridian. *Nature*, **199**, 900.
- Kroenig, J. L., 1965: Stratosphere and troposphere: transport of material between them. *Science*, **147**, 8624.
- Langer, G., 1965: An acoustic particle counter—preliminary results. *J. Colloid Sci.*, **20**, 602–609.
- MacCready, P. B., 1955: Investigations of silver iodide decay and transport and natural nuclei. Meteorology Research, Inc., for Advisory Common Weather Control, Altadena, Calif.
- Reiter, E. R., 1965: Heavy radioactive fallout over the southern U. S., November 1962. *J. Geophys. Res.*, **70**, 4501–4520.
- Reiter, R., 1964: *Felder, Stroeme und Aerosole in der Unteren Troposphaere*. Darmstadt, Germany, Dr. Dietrich Steinkopff Verlag, 500–502.
- Soulage, G., 1958: Contribution des fumes industrielles a l'enrichissement de l'atmosphere en noyaux glacogenes, I. Fumes d'acieries electriques. *Bull. Obs. Puy de Dome*, No. 4, 121–124.
- , 1963: Preliminary recherches on the diffusion of ice nuclei over great distances. Sci. Rep. DA ERO 91 591 3G 001, Puy de Dome, France.
- Telford, J. W., 1960: Freezing nuclei from industrial processes. *Bull. Amer. Meteor. Soc.*, **7**, 676–679.
- Warner, J., 1957: An instrument for the measurement of freezing nucleus concentration. *Bull. Obs. Puy de Dome*, No. 2, 33–46.