CLOUD NUCLEI FROM LAUNCHES AND FIRINGS OF SOLID ROCKET BOOSTERS+

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ABSTRACT

Ground clouds from launches of Titan III rockets were bright, white, and cumulus-like early in their lives and contained up to 3.5 g m^{-3} of liquid in micron to millimeter-size droplets. The clouds traveled up to 76 n m and were visible and detectable from aircraft up to 5 hours after launch. The clouds contained concentrations of cloud condensation nuclei (CCN) significantly above values in nearby air for periods of 3 to 5 hours after launch. The initial production of CCN active at 0.5% supersaturation is equivalent to a 30 minute emission by the city of Denver, Colorado. Concentrations of ice nuclei (IN) in the clouds could not be determined because of inconsistent results between measurement techniques. Concentrations of IN in exhaust clouds from nozzle-up solid rocket booster firings are at least two to three orders greater than background values. In comparison, concentrations of IN one to two orders greater than background are believed sufficient to augment precipitation from winter mountain clouds.

INTRODUCTION

When spacecraft are launched using solid rocket boosters (SRB), residual clouds of effluent material remain suspended in the atmosphere. The clouds consist of two components: the stabilized ground cloud (SGC) which contains material from ignition and lift-off of the vehicle, and the column cloud which contains material exhausted in flight. The SGC consists of approximately 30% of the mass of the SRB, and the remainder of the mass forms the column cloud (Potter, 1978).

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The SGC's resulting from launches of Titan III spacecraft have been investigated (e.g., Strand and Varsi, 1974; Woods, 1977) to determine the physical, chemical and optical properties of the constituent aerosol particles (approximately 1.2 X 10^8 g of Al_2O_3 particles are generated during each launch and flight). The SGC's have been monitored up to one hour after launch (Woods, 1977).

In this paper we report the results of airborne measurements made for periods up to five hours in SGC's from launches of the Voyager I and II spacecraft by Titan III vehicles at Kennedy Space Center (KSC), 5 September and 20 August 1977, respectively. The clouds persisted longer for unknown periods (operational limitations precluded further sampling). The purposes of the measurements were to determine the concentrations of the aerosol particles which can serve as cloud droplet forming nuclei (called cloud condensation nuclei (CCN) and as ice crystal forming nuclei (called ice nuclei (IN)). Also, measurements were made to determine the sizes and concentrations of the liquid droplets in the SGC's. Results of IN measurements in exhaust clouds from nozzle-up static firings of SRB's are given in Appendix A.

AIRBORNE MEASUREMENT FACILITY

The National Oceanic and Atmospheric Administration WC-130 (41C) was used as the airborne platform.[1] The aircraft was fitted with a unique grab-sampling system (Figure 1) because the aircraft cruised at 110 m s^{-1} and was in the SGC for only 10 to 40 s. Outside air continually flowed through a 2 inch diameter tube. The inlet was forward on the aircraft and the exhaust was aft, through the dropsonde chute. Outside air flowing through the tube was first sampled by an integrating nephelometer[2] (Charlson, et al., 1969), and a condensation nucleus (CN) counter[3] (Liu and Pui, 1974). The nephelometer measures the integrated light scattering coefficient (b_{scat}) of aerosol particles. The instrument is most responsive to particles 0.1 to 1 μm diameter and was found to be an excellent SGC detector. The CN counter responds to particles 0.003 - 0.01 diameter (the instrument malfunctioned due to improper hook-up).

After the air passed the nephelometer and CN counter, it reached a two-way valve which caused the air either to be exhausted through the dropsonde chute or to flow into the 0.5 m^3 aluminized, fiberglass reinforced, mylar bag; to fill the bag at 110 m s^{-1} airspeed took 2 to 5 s.

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[1]Details of the platform contained in "Research Facilities Center Five Year Plan," Weather Modification Program Office, NOAA/ERL, Boulder CO 80302.

[2]Model 1550, Meteorology Research Inc., Box 637, Altadena, CA 91001.

[3]Model Rich 100, Environment/One Corp., 2773 Balltown Rd., Schenectady, NY 12309.

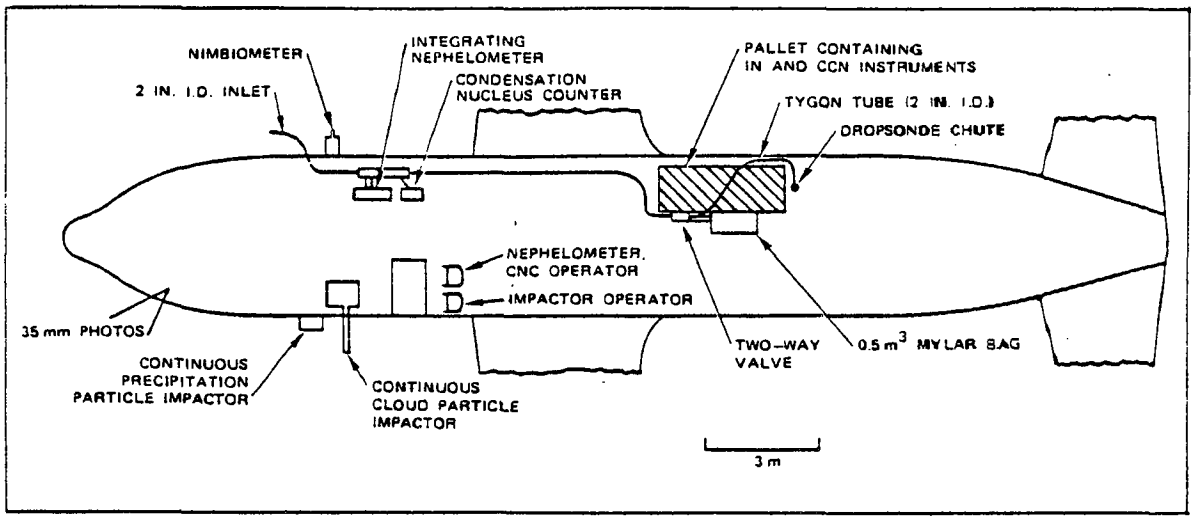

FIGURE 1. Schematic of the Aerosol Particle Sampling Equipment Aboard the NOAA WC-130. The equipment was used to sample SGCs resulting from launches of Titan III vehicles.

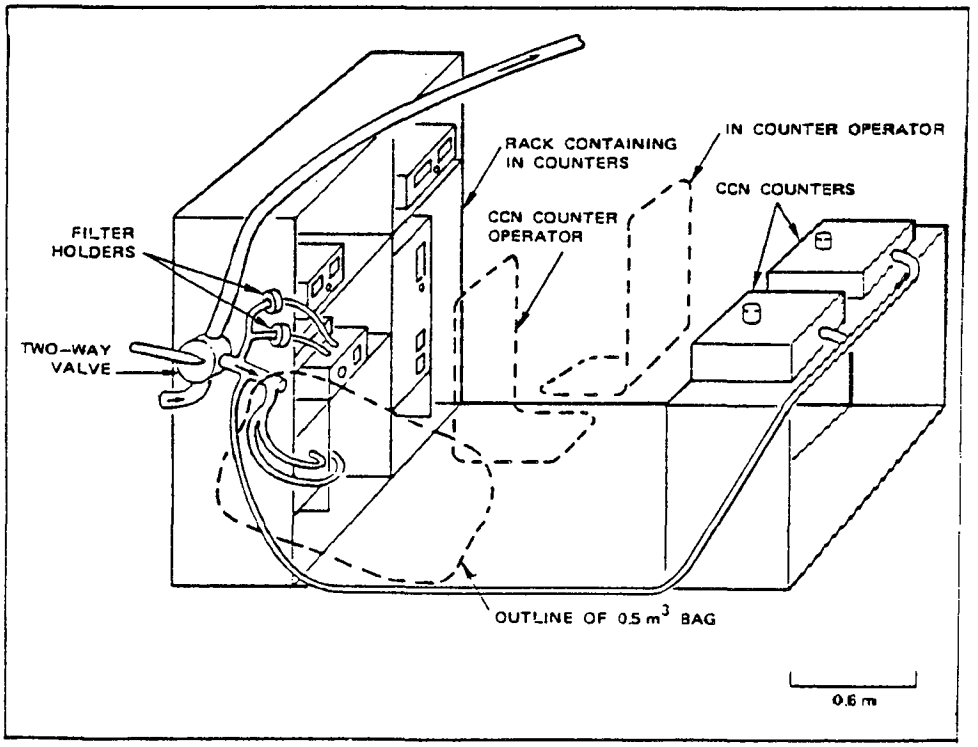

FIGURE 2. Expanded Diagram of the Pallet Identified in Figure 1. The pallet contains the IN counters, CCN counters, and the filter sampling apparatus.

The two-way valve and sampling bag were attached to a pallet which contained the IN and CN instruments (Figure 2). The bag was sampled by two IN counters,[4] two CCN counters[5] and two filters (the IN and CCN instruments are described in the IN and CCN sections, respectively).

The aerosol particles in the bag were collected on Nuclepore and Millipore filters. The particles collected on the Nuclepore filters were analyzed using a scanning electron microscope equipped with an X-ray energy spectrometer to determine the particle sized, concentrations and elemental compositions, and using a transmission electron microscope to determine the particle sizes and concentrations. The details of this procedure and the results are discussed by Parungo and Allee (1978). The particles collected on both filter surfaces were analyzed to determine their activity as IN using a procedure discussed by Zamurs et al. (1977), and a similar procedure discussed by Langer and Rogers (1975). One half of each filter was processed with the first procedure and the other half with the second procedure.

Air from the bag supplied the IN, CCN and filter devices which were operated simultaneously for four-minute periods. Instrument operation began as soon as the bag was full of SGC material. The bag was exposed to the SGC as soon as the reading from the nephelometer began to rise rapidly (the nephelometer was upstream of the bag). After the four-minute period, the partially exhausted bag was sealed off, placed in the rear of the aircraft, and a new bag was mounted.

The effects of the aircraft boundary layer on the inlet to the sampling line and the loss of particles within the sampling lines and bag are shown in Appendix B to cause negligible errors.

The sizes and concentrations of the liquid droplets in the SGC were determined using direct impactor surfaces. The cloud size droplets (5 to 50 μm diameter) were impacted onto a strip of soft plastic and replicated; the continuous cloud particle impactor was developed by Hallet et al. (1975). The precipitation size drops (> 200 μm diameter) impacted onto a strip of soft aluminum foil; the continuous precipitation particle impactor is described by Schecter and Russ (1970). The liquid content of the SGC was measured with the nimbiometer developed by Merceret and Schricker (1975). Locations of instruments which sampled the SGC liquid particles on the WC-130 are shown in Figure 1.

BEHAVIOR OF THE STABILIZED GROUND CLOUDS

The positions of the SGC's from the launches on 20 August 1977 and 5 September 1977 were determined from aircraft penetrations for over three hours on 20 August 1977 and for over five hours on 5 September 1977 (Figures 3 and 4).

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[4]Mee Model 140, Mee Industries, 1629 S. Del Mar, San Gabriel, CA 91776.

[5]Mee Model 130, Mee Industries, 1629 S. Del Mar, San Gabriel, CA 91776.

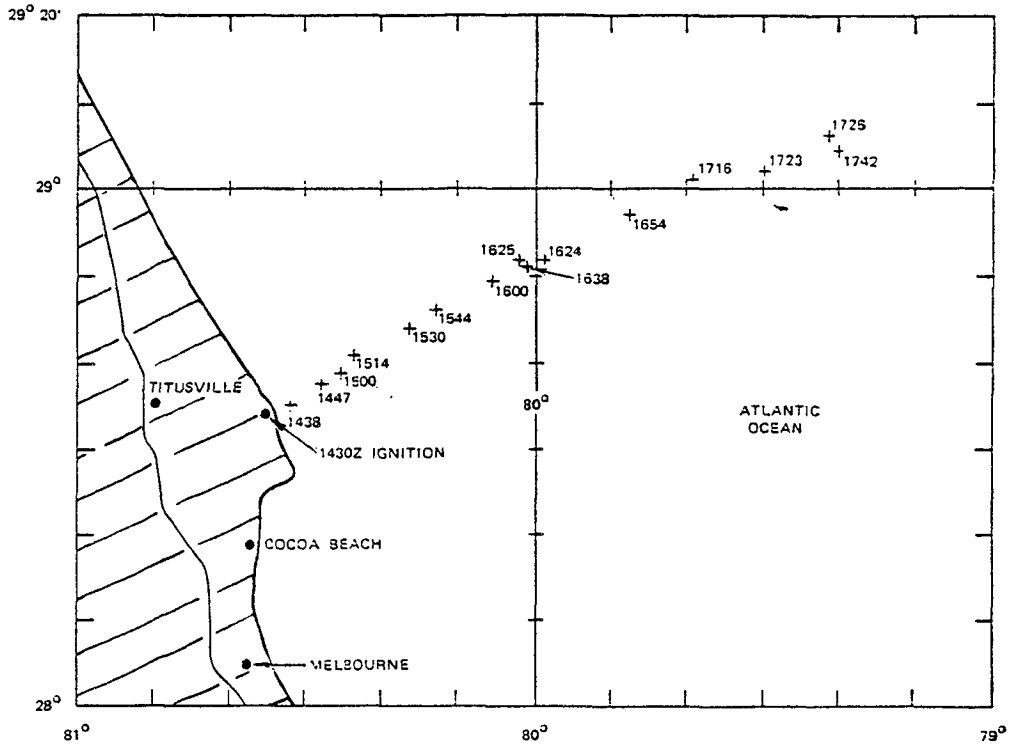


FIGURE 3. Positions of SGC on 20 August 1977. Times are given in Z time. Distances: 1° latitude = 60 nmi.

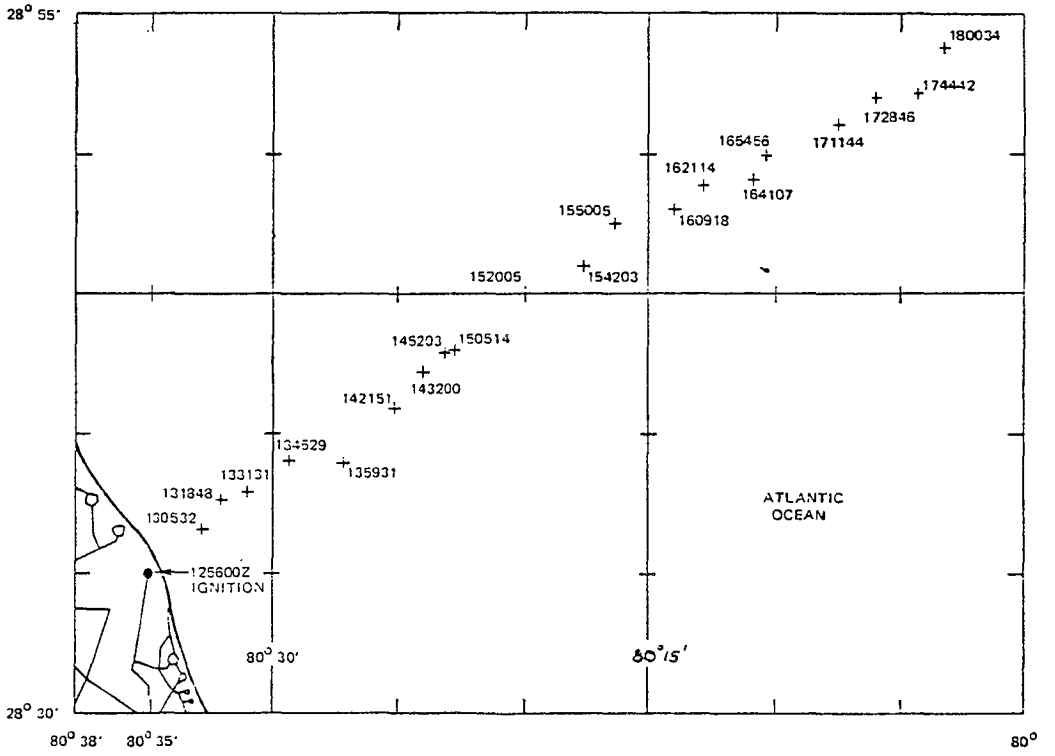


FIGURE 4. Positions of SGC on 5 September 1977. Times are given in Z time (hr, min, sec). Distances: 5' latitude = 5 nmi.

Sampling ended, in both cases, because the supply of 0.5 m^3 bags was depleted; we had planned for the SGC's surviving only three hours! The clouds were still measurable; CCN concentrations were above background concentrations and the SGC's were still clearly visible at the termination of sampling (Figures 9 and 10).

Shortly after both launches, the SGC's were bright, white, cumulus-like clouds, indicating that they contained high concentrations of micron and supermicron size liquid droplets. Thereafter, the SGC's became either brown or grey in color when viewed against white clouds and white in color when viewed against the blue sky; this indicates that extremely large numbers of small particles (probably droplets) persist in SGC's five hours old.

The clouds contained up to 3.5 g m^{-3} of liquid in micron to millimeter size droplets, as indicated from measurements from the nimbiometer and the impactor surfaces (Hindman et al., 1978). The data from the nimbiometer indicated that the SGC on 5 September contained liquid particles for at least the first hour.

Hand held, 35 mm photographs were obtained of both SGC's; evolution of the SGC on 5 September 1977 (Figure 5) was similar to that on 20 August 1977.

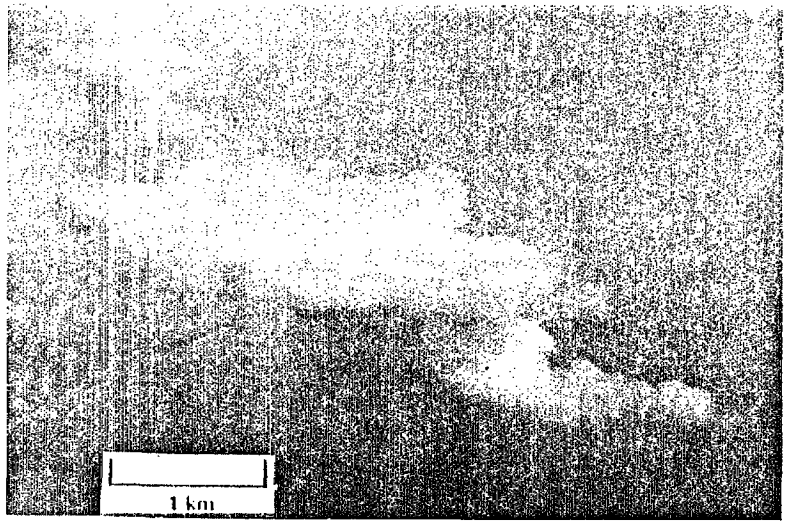
SGC volumes, estimated from photographs and penetration data by methods represented schematically in Figure 6, are listed in Table I. The SGC increased in volume 15 fold in three hours (1447Z to 1742Z) on 20 August 1977, during which CCN concentration (0.2% supersaturation) decreased 22 times (Figure 9). However, on 5 September 1977, the SGC increased in volume only 2.9 times from 1334Z to 1800Z, concurrent with a decrease in b_{scat} of 1.9 times (15×10^{-4} m^{-1} at 1334Z and $7.8 \times 10^{-4} m^{-1}$ at 1800Z).

ICE NUCLEUS MEASUREMENTS

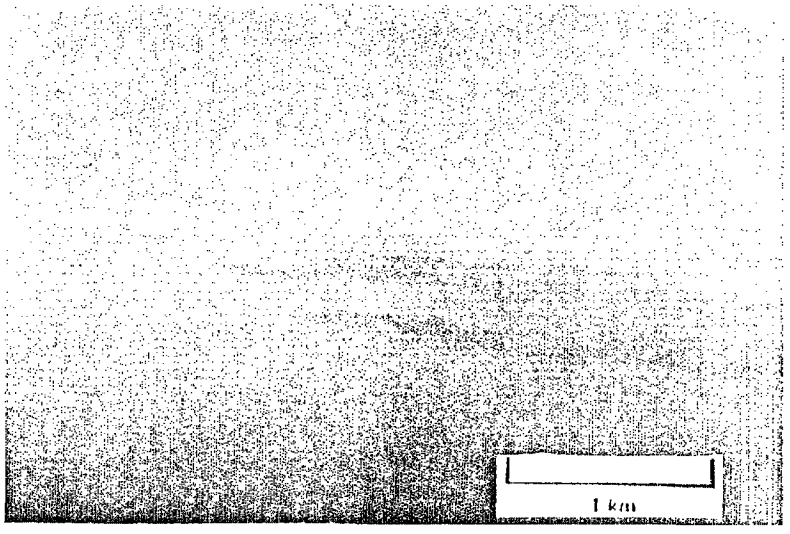
The IN counters are basically portable supercooled cloud chambers into which the SGC particles are injected (the principle of the cloud chamber is after Langer, 1973); schematic of the Mee IN instrument if given in Figure 7. In the cloud chamber, particles which act as IN form ice crystals, which pass through plane-polarized light and depolarize it. The depolarized light triggers a photo detector (similar to the detector described by Sheets and Odencrantz, 1974). A threshold level is set to discriminate between the large pulses caused by crystals and the smaller pulses caused by droplets in the supercooled cloud. The number of light pulses counted per period, divided by the volume of air which passed through the detecting volume during that period, gives the number of IN per liter of air. The cloud chamber is typically operated at -20C, although it can be operated over a temperature range from 0C to -25C. The counter can detect IN over a concentration range from 0 to $2000 \ell^{-1}$.

To calibrate the Naval Weapons Center (NWC) instrument, small, milligram samples of solid rocket motor propellant were burned in a 24 m^3 cloud chamber (described by Odencrantz, 1968) which contained a supercooled cloud at -25C.

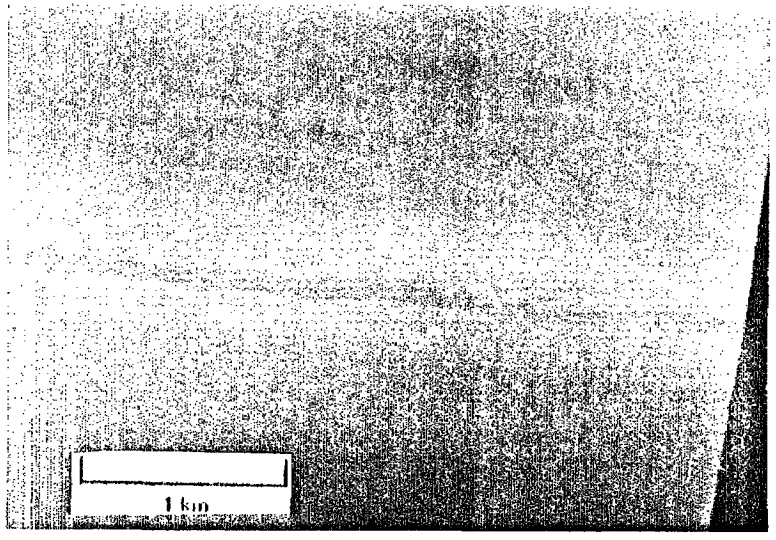
1259Z



1313Z



1402Z



1739Z

FIGURE 5. Evolution of the SGC From Titan III Launch, 1256Z, 5 September 1977. The scale is valid only for the dimensions of the SGC.

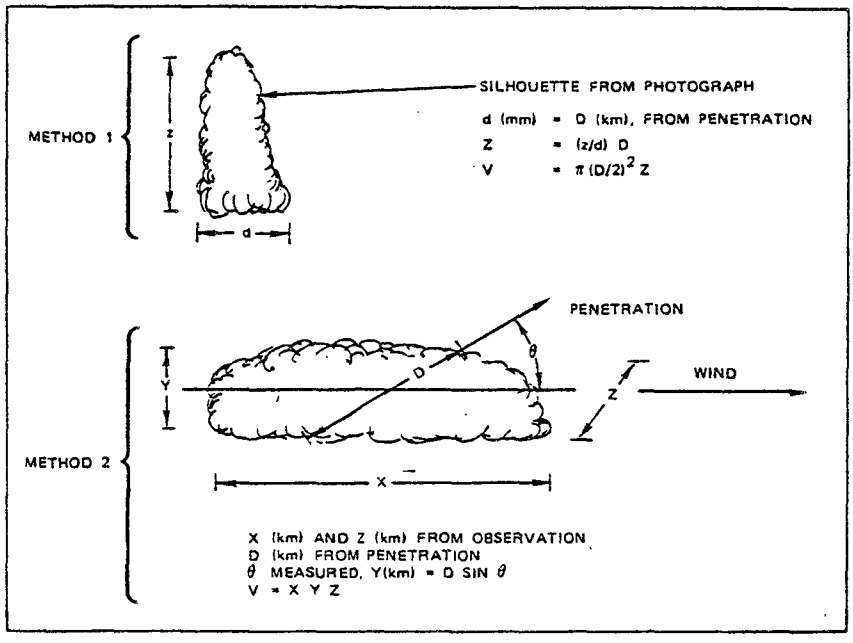


FIGURE 6. Methods Used to Estimate the Volumes of the SGCs Listed in Table 1.

TABLE 1. Characteristics of the Stabilized Ground Clouds and Nearby Environment.

Date, (1977)	Time, (Z)	Age of SGC, hr	Calculation method (From Fig. 6)	SGC Volume, km^3	SGC Distance from pad, km	SGC Penetration alt. MSL, km	Air temp., C	Relative humidity, %
20 Aug	1438	0.13	1	4.1	5.6	1.4	18.5	77
	1447	0.28	1	2.8[a]	14.0	1.4	18.5	73
	1559	1.5	2	2.4	56.0	1.2	19.0	67
	1742	3.2	2	41.0	135.0	1.3	18.6	68
5 Sept	1318	0.33	1	1.9	7.0	1.5	16.5	91
	1344	0.80	1	1.5[a]	12.0	1.5	16.8	95
	1421	1.4	2	1.6	20.0	1.3	18.5	85
	1520	2.4	2	1.2	31.0	1.2	18.4	84
	1621	3.4	2	1.1	44.0	1.2	19.0	83
	1800	5.0	2	4.3	63.0	1.3	18.2	84

[a]SGC broke into segments, monitored largest segment.

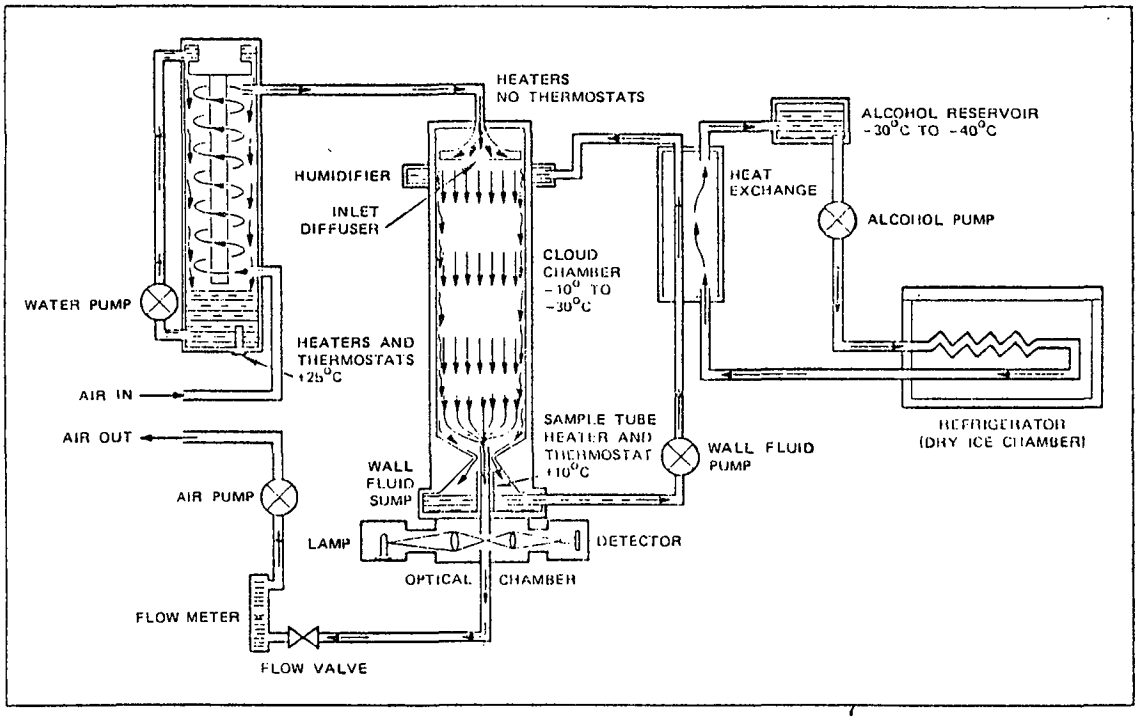


FIGURE 7. Schematic of Mee Industries Model 140 Ice Nucleus Counter.

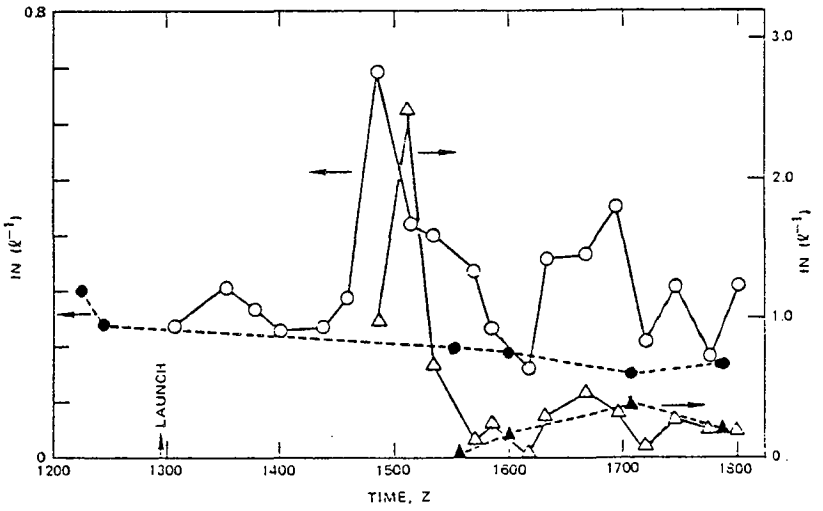


Figure 8. Ice Nucleus (IN) concentrations (ℓ^{-1}) measured in the SGC (open symbols) from the Voyager launch on 5 September 1977 and measured in nearby air (solid symbols). The data were collected with the NWC IN counter (circles) operated at 10 ℓ/min, -25C and 3 mv threshold, and with the NOAA IN counter (triangles) operated at 10 ℓ/min, -20C and 200 mv threshold. The IN concentrations have not been corrected for the presence of HCl. Each data point represents the total number of IN measured during the 4 minute sampling periods divided by 40 ℓ (10 ℓ/min x 4 min).

HCl gas was released during the burns to produce an estimated concentration of 1ppm. The concentrations of ice crystals formed in the chamber were measured ($1000\ell^{-1}$). Then the chamber was cleared of cloud, warmed and the propellant burns were duplicated. The IN counter was hooked to the chamber and operated at -25C, $10\ell\ min^{-1}$ flow, and 3 mv threshold. The concentrations of ice crystals measured in the counter were $\sim 1\ \ell^{-1}$. Thus, the counter undercounts by a factor of 1000 at -25C in the presence of approximately 1 ppm HCl.

The factor of 1000 was found to occur at -20C in comparison tests between the NWC IN counter and a 1 m^3 isothermal cloud chamber (ICC, described by Grant and Steel, 1977). In these tests, milligram samples of Shuttle propellant were burned in a 700 ℓ holding tank. The IN counter was hooked directly to the tank and a 4 ℓsyringe was used to transfer sample from the holding tank to the ICC. Additional details are given by Hindman et al. (1980).

The factor of 1000 difference between IN counts from the portable chamber and the ICC is valid only for an Al_2O_3 aerosol in the presence of HCl ($\sim$1 ppm). Lower concentrations of HCl may cause the difference to be less than 1000 but additional research is needed to determine the values. The difference is a factor of about 10 for AgI ice nuclei.

Both IN counters were operated in the SGC's produced by the Voyager launches. Useful data were obtained on 20 August 1977 from the first background sample, thereafter both instruments malfunctioned. Useful data were obtained from the NWC counter for the entire flight on 5 September 1977 and from the NOAA counter for the last half of the flight. The IN concentrations measured on the 5 September 1977 flight (Figure 8) were above background concentrations for the five-hour duration of the flight, according to the data from the NWC instrument. Furthermore, there is general agreement between the data from both instruments. The concentrations in Figure 8 have not been corrected for the presence of HCl because no calibration data exist for the high peak concentrations measured: 25 ppm at 1300Z, 6 ppm at 1400Z, 3 ppm at 1440Z and 3 ppm between 1600 and 1730 (Bendura, private communication; measured with a Goemet HCl monitor, 0.5 ppm threshold, Gregory and Moyer (1977), on NASA/LaRC Cessna 402B, Wornom et al., 1977).

The data in Figure 8 should be considered suggestive but not absolute because the NWC counter was operating with a poor signal-to-noise ratio and the NOAA counter was operating with an excessive threshold level (200 mv). The NOAA instrument, however, operated normally before and after the flight in the laboratory (19 mv threshold).

The bags and the NOAA counter were removed from the aircraft immediately following the 5 September 1977 flight. The bags were sampled with the counter, which operated normally in the laboratory, The extreme age of the air samples (5 to 10 hours) should have led to considerable particle losses to the walls, particle coagulation and chemical changes of the particles. Nevertheless, an average of $9.1 \pm 0.9\ \ell^{-1}$ IN were measured from 16 bags (the instrument was operated at 10 ℓ/min air flow, -25C chamber temperature and 19 mv threshold level). In contrast, background air concentrations were 1 to $2\ \ell^{-1}$ (measured on 20 August 1978 flight prior to instrument malfunction).

The IN measurements obtained from the portable counters in the SGC and in the laboratory on 5 September 1977 indicate that IN exist in the SGC in concentrations greater than background by an unknown magnitude for 5 and possibly 10 hours. Moreover, the NWC IN counter was flown in an exhaust cloud from a nozzle-up firing of a SRB at Edwards Air Force Base, California, concentrations of IN were measured significantly above background concentrations as shown in Appendix A.

The IN measurements from the filters exposed to the Voyager SGC's have been reported by Parungo and Allee (1978) and Hindman and Lala (1980). The results obtained using the Langer and Rogers (1975) procedure show that IN concentrations existed in the SGC in concentrations significantly higher than background concentrations (Parungo and Allee, 1978). The results obtained using the Zamurs et al. (1977) procedure show no significant increase in IN concentrations in the SGC's above background concentrations (Hindman and Lala, 1980). Curiously, similar filters exposed to effluent from burning Shuttle propellant in the laboratory (Hindman et al., 1980) showed high IN concentrations when analyzed with both procedures. Furthermore, as shown in Appendix A, IN were detected using filters in the exhaust cloud from a nozzle-up firing of a motor burning propellant similar to that used in the Titan III rocket.

Research is underway to resolve the conflicting IN results between the portable counters and filters and between the filters themselves.

CLOUD CONDENSATION NUCLEUS MEASUREMENTS

The CCN counters are thermal gradient diffusion cloud chambers in which a selected supersaturation with respect to water is maintained. The particles sampled from the SGC are injected to this chamber. The particles which act as CCN are grown to cloud droplet sizes ($\sim$2 μm diameter). The concentrations of the CCN are determined from the intensity of light scattered from an intense beam shining through the cloud of droplets. Lala and Jiusto (1977) describe a CCN counter almost identical to the Mee instrument.

The CCN counters can be operated over a supersaturation range from about 0.2 to 2.0%, and can detect CCN concentrations from about 10 cm^{-3} to 2.0×10^4 cm^{-3} although concentrations above about 1000 cm^{-3} at 1% supersaturation are meaningless according to Squires (1966) because of excessive vapor depletion leading to uncertain supersaturations.

Lala and Jiusto calibrated their instrument by comparing concentrations of CCN determined photographically with those obtained automatically over a wide range of supersaturations. They obtained the following relationship between the light scattered (E_{sc}), the photographic count (N) and supersaturation (S):

$$E_{sc}/N = 0.13\ S^{0.55} \qquad 0.25 < S < 1.0\% \qquad (1)$$

The relationship between E_{sc} and the automatically derived CCN concentrations (N_{auto}) for the Mee instrument is

$$E_{sc} = 0.1016\ N_{auto} \qquad (2)$$

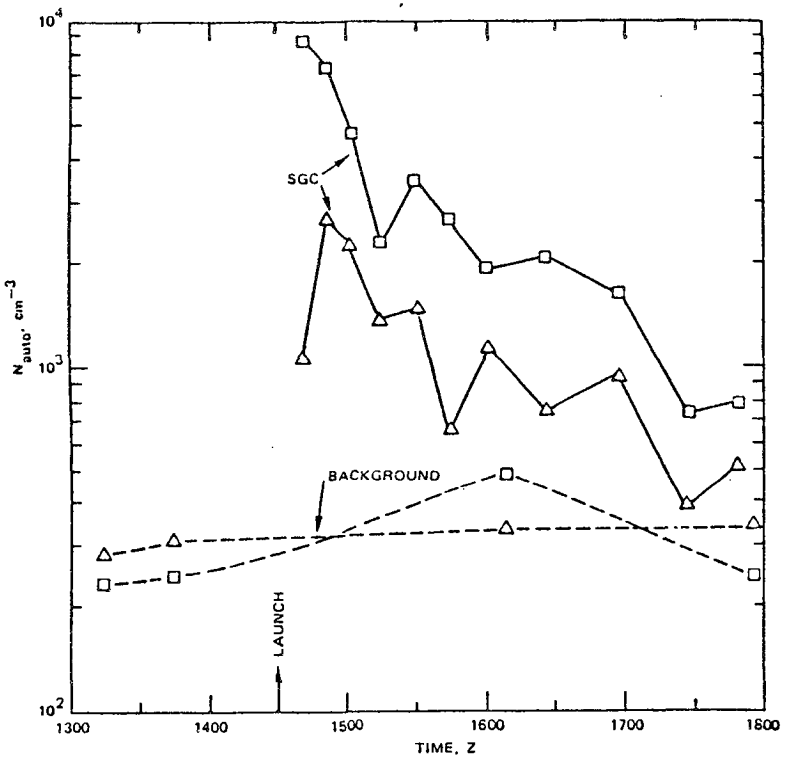


Figure 9. Cloud condensation nucleus concentrations (N_{auto}, cm^{-3}) measured in the stabilized ground cloud (SGC) from the Voyager launch on 20 August 1977 and measured in nearby air (background). The data were collected with the NWC CCN counter (triangles) at 1% supersaturation and with the NOAA CCN counter (squares) at 0.2%. The CCN concentrations have not been corrected using (3). Each data point represents an average of 10 to 11 samples during the 4 min sampling period. The absolute values (not the relative values) of the concentrations from the NWC instrument are suspect due to a malfunctioning instrument.

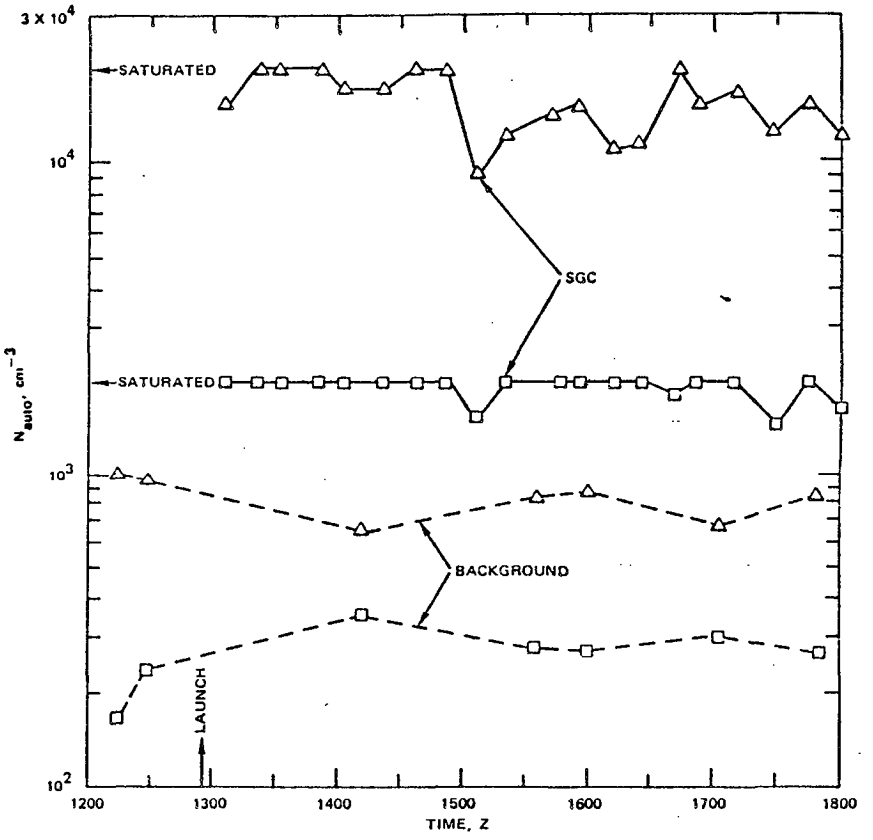


Figure 10. Cloud condensation nucleus concentrations (N_{auto}, cm^{-3}) measured in the stabilized ground cloud (SGC) from the Voyager launch on 5 September 1977 and measured in nearby air (background). The data were collected with the NWC counter (squares) at 0.5% supersaturation and with the NOAA counter (triangles) at 1.0%. The CCN concentrations have not been corrected using (3). Each data point represents an average of 10 to 11 samples during the 4 min sampling period. The "saturated" label defines the maximum measurable concentrations.

Since the Lala-Jiusto and Mee instruments are almost identical, a first approximation to the calibration of Mee's instrument is found by substituting (2) into (1):

$$N_{auto}/N = 1.28\ S^{0.55} \qquad (3)$$

Simultaneous operation of the Mee CCN counter with the Naval Research Laboratory (NRL) CCN counter, considered the standard CCN instrument, (Appendix C) showed that the Mee instrument measures the concentrations of CCN satisfactorily over a range of supersaturations from 0.26 to 1.08%.

Both Mee CCN counters gave useful data from the SGC's produced by the two Voyager launches (Figures 9 and 10); CCN concentrations were above background concentrations for the three- and five-hour durations of the respective flights. In fact, during the 5 September flight, the instrument operating at 0.5% supersaturation was saturated most of the flight! Furthermore, there is general agreement between the SGC data from the instruments on the respective flights.

Although the data (Figures 9 and 10) should not be considered absolute because of the exceedingly high CCN concentrations, they permit the conclusion that CCN active at 0.2, 0.5 and 1.0% supersaturation exist in the SGC in concentrations well above background concentrations for periods of three to five hours. Early in its life the SGC is an intense, white cumulus-like cloud (Figure 5) which is believed filled with exceedingly high concentrations of cloud droplets, which require high concentrations of CCN.

The production of CCN was estimated from the initial CCN and cloud volume measurements. The CCN concentration (N) active at 0.5% S was estimated from Figure 9 using N_{auto} values (S = 0.2 and 1%) and the known behavior of CCN ($N = CS^k$) resulting in $N = 4.5 \times 10^3$ cm^{-3}. The cloud volume was 4.1 km^3 (Table 1). Consequently, the initial CCN production was 1.8×10^{19} (4.5×10^3 cm^{-3} x 4.1×10^5 cm^3). The production is equivalent to a 30 min. emission by the city of Denver, Colorado using the $\sim 10^{16} s^{-1}$ figure from Squires (1966).

CONCLUSIONS

A unique airborne measurement facility was constructed in a C-130 aircraft to measure the ice nuclei, cloud condensation nuclei and liquid particle properties of stabilized ground clouds (SGC) from Titan III rocket launches. The SGC's monitored were bright, white, cumulus-like clouds early in their life, and contained high concentrations of liquid droplets for at least the first hour of their existence and perhaps more.

The two SGC's monitored traveled considerable distances (56 and 76 n mi) and were clearly visible at the end of the sampling periods (5 and 3 hours, respectively). One surprising finding was that after 5 hours of sampling, the SGC had diluted only 2.9 times.

The results of the ice nucleus (IN) measurements from the portable counters indicate that these instruments detected IN in SGC's in concentrations greater than background by an unknown magnitude (due to instrument difficulties) for at least five hours and possibly ten. The results of the IN measurements from the filters are conflicting: one analysis indicated no IN in SGC's in concentrations greater than background concentrations, another that IN were detected. Consequently, the concentrations of IN in the Titan III SGC's could not be determined because of the inconsistent results between the measurement techniques. Concentrations of IN in exhaust clouds from nozzle-up solid rocket booster firings are at least two to three orders greater than background values. In comparison, concentrations of IN one to two orders greater than background are believed sufficient to augment precipitation from winter mountain clouds.

The cloud condensation nuclei measurements indicate that the nuclei active at 0.2, 0.5 and 1.0% supersaturation exist in SGC's in concentrations well above background for three to five hours. The initial production of CCN active at 0.5% supersaturation is equivalent to a 30 min. emmission by the city of Denver, Colorado.

ACKNOWLEDGEMENTS

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APPENDIX A

Ice Nucleus (IN) and Hydrogen Chloride (HCl) Measurements at Edwards Air Force Base (EAFB), California

In December 1976, the NWC IN counter was installed in the U-21 (King-Air) aircraft of the Army Aviation Engineering Flight Activity at EAFB. Also, on board was a Geomet HCl monitor (Gregory and Moyer, 1977) from the Air Force Rooket Propulsion Laboratory (AFRPL) at EAFB. The air which fed these instruments entered the aircraft from a probe mounted forward of the cockpit on the nose. The air entered a 0.32 cm ID tube and traveled 5.5 m in 2 s to the inlet of the IN counter; the loss of 0.1 μm IN in this line was calculated to be negligible (n/n_0= 0.97) following the procedure outlined in Appendix B. The HCl sensor was located in the probe.

On 22 December 1976, a 4 x 10^4 kg (88,000 lb) Super-Hippo solid rocket motor was static-fired, nozzle-up, at the AFRPL at 1400 PDT. The U-21 made eight penetrations of the exhaust cloud at its stabilization altitude of 1000 m AGL (6,000 ft MSL) between 6 and 37 minutes after the firing. The nearby ambient air unaffected by the cloud was sampled between cloud penetrations. Due to the stable air and low wind speeds the cloud remained visible until 1700 PDT when the sun set.

Ice nuclei concentrations measured in the exhaust cloud were above background concentrations on all eight penetrations. The peak IN concentrations measured during each penetration are given in Figure 11. The HCl concentrations measured during the first five penetrations(data unavailable for remaining penetrations) were, respectively, 55, 22, 22, 19 and 19 ppm. The results are consistent with those reported from the 5 September 1978 flight at KSC using the

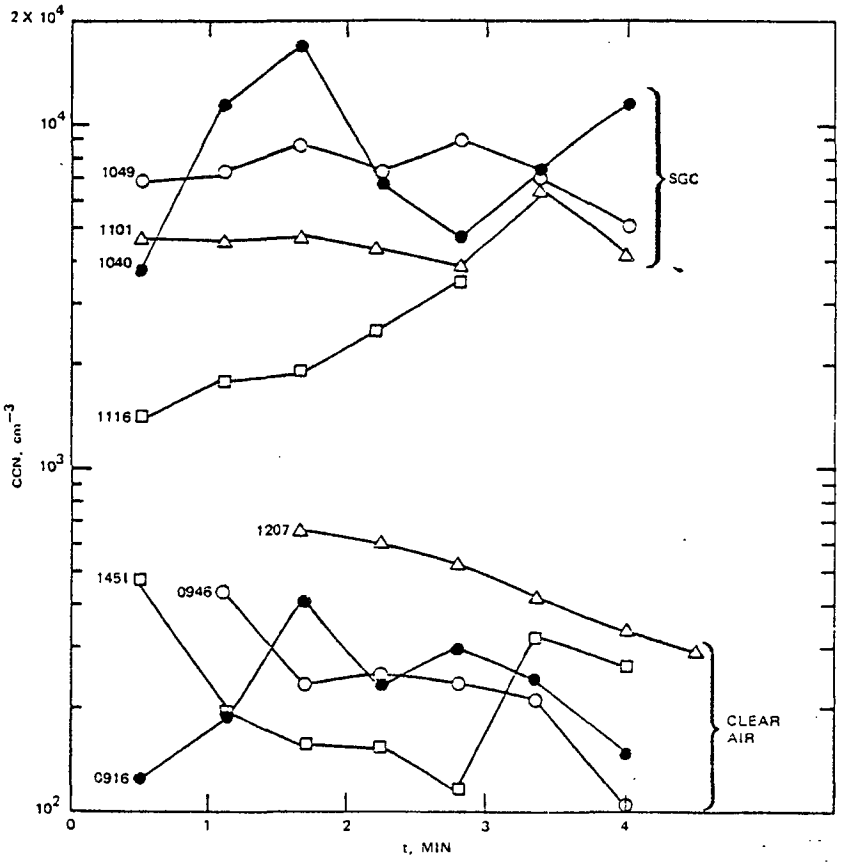

Figure 11. Concentrations of cloud condensation nuclei (CCN) active at 0.2% supersaturation as a function of time (t) after inflation of the 0.5 m^3 bag with either SGC material or nearby clear air. The data were collected on 20 August 1977 at the indicated times (EDT).

TABLE 2. Ice Nucleus Concentrations From First and Second Samples Collected From the Same Bag and for the Same Volume.[a]

Date	Time (Z)	Process[b]	First sample	Second sample	First sample/second sample
20 Aug	1440	SUNYA	15.8	9.5	1.7
		NOAA	60.0	47.0	1.3
	1449	SUNYA	26.0	---	---
		NOAA	48.0	3.2	15.0
	1502	SUNYA	16.0	226.0	0.07
		NOAA	45.0	52.0	0.87
5 Sept	1306	SUNYA	27.0	12.0	2.3
		NOAA	15.0	8.2	1.8
	1319	SUNYA	6.1	15.3	0.40
		NOAA	9.0	9.1	0.99

[a]The time difference between the first and second samples was about 3 minutes. The sample volumes were 1.3 ℓ for the samples reported here.

[b]SUNYA used the process described by Zamurs et al. and NOAA used the process described by Langer and Rogers.

same IN counter: IN concentrations measured greater than background concentrations in the presence of HCl gas.

Nuclepore filters (0.4 μm pore size) replaced the NWC IN counter on the 8 September 1978 static firing of a 3.1×10^4 kg (68,300 lb) Super-Hippo motor. The motor was fired at 1424 PDT and the cloud penetrations occurred between 1426 and 1538 PDT. The cloud stabilized at 2438 m. MSL (8,000 ft) and was invisible and not detectable with the HCl monitor after 1540 PDT. The filters were processed by G. Langer (NCAR) at -20C and 101% RH with respect to water, using the same procedure and apparatus used by Parungo and Allee in their analysis of the Voyager filters (see IN filter section).

The IN concentrations (not corrected for the sample-volume effect) were as follows:

1. $<0.2\ \ell^{-1}$ (background air, 1335 to 1340 PDT, 47 ℓ sample)
2. $76\ \ell^{-1}$ (exhaust cloud, 1426 to 1429 PDT, 37.3 ℓ sample)
3. $203\ \ell^{-1}$ (exhaust cloud, 1437 to 1439 PDT, 22.1 ℓ sample)
4. $113\ \ell^{-1}$ (exhaust cloud, 1454 to 1458 PDT, 17 ℓ sample)
5. $13\ \ell^{-1}$ (exhaust cloud, 1525 to 1538 PDT, 23.8 ℓ sample)

The corresponding HCl concentrations were 0, 17, 6.5, 4, and 0.1 ppm. These results indicate the filter method detected IN in the cloud significantly above background concentrations and in the presence of HCl gas.

The IN measurements obtained with the portable counter and filters in Super-Hippo exhaust clouds are consistent: the concentrations of IN in the exhaust clouds are at least two to three orders of magnitude higher than in background air. This difference in concentrations cannot be considered absolute because the data have not been adjusted for the presence of HCl gas (calibration data not established) and for the sample-volume effect in the case of the filters.

APPENDIX B

Sampling Errors

In the facility depicted in Figure 1, sampling errors are expected at the direct impactor surfaces, at the inlet to the sampling line, along the sampling lines, and within the 0.5 m^3 bag. The potential errors at the direct impactor surfaces and the inlet are caused by the aircraft boundary layer and anisokinetic sampling. Those along the sampling lines are due to inertial impaction and diffusion, and those within the bag are due to diffusion, coagulation and chemical changes.

Particle trajectories in the boundary layer of the C-130 have been modeled numerically by Norment (1976). For particles <40 μm diameter, the boundary

layer does not affect significantly the measurement of particle concentrations at the inlet (40 cm from the fuselage). Since the measured IN and CCN are less than about 0.1 μm, no sampling errors would occur due to the boundary layer. Furthermore, the large diameter of the inlet and small sizes of IN and CCN make anisokinetic sampling errors negligible; as shown in the next paragraph, the flow in the tube was calculated to be ~100 m s^{-1} , which is not far from the airspeed of 110 m s^{-1}. The errors caused by the boundary layer at the inlet to the continuous cloud particle impactor are limited to discrimination of 150 to 200 μm particles; those errors at the inlet to the continuous precipitation particle sampler are negligible because of the large size of the impacted particles exceed 200 μm diameter.

The losses in IN and CCN in the inlet line due to inertial impaction and diffusion were calculated to be negligible. The Stokes Number (Butcher and Charlson, 1972) for 0.1 μm particles at the first bend in the inlet tube (r = 1 m) was calculated to be 5 x 10^{-5}; for impaction to be possible this number had to be <0.5. The diffusion losses to the walls of the circular inlet tube were calculated using the approximations of Fuchs (1969). Knowing the diffusion coefficient of 0.1 μm particles (d = 2 x 10^{-5} cm^2 s^{-1}), the length of the tube (x = 1.2 X 10^3 cm), the radius of the tube (r = 2.5 cm) and the airspeed in the tube (v = 100 m s^{-1}),[6] Fuch's dimensional parameter μ (Dx/r^2v) equaled 3.6 x 10^{-7}. This corresponds to n/n_0 = 1.0 where n_0 is the concentration at the inlet to the tube and n is the concentration at the exhaust.

The diffusion losses to the walls of the sampling tubes connecting the IN and CCN to the 0.5 m^3 bag (Figure 2) were measured using the condensation nucleus counter, connected alternately to and disconnected from the end of the 3.7 m long Tygon CCN sample line 0.636 cm in diameter. It was found that n/n_0= 0.5. Repeating this procedure with the 1.7 m long Tygon IN sample line 0.636 cm in diameter gave n/n_0 = 0.75. Since CN are much smaller than either CCN or IN, these sampling losses are overestimated. Losses of less than a factor of two are within the experimental uncertainties.

The CCN sampling losses within the bag were estimated using one of the CCN instruments operating at 0.2% supersaturation. The bag, when filled with either SGC material or clear air unaffected by the SGC, was sampled with the CCN instrument for 4 minutes. The variations of the CCN concentrations in the bag for eight samples are shown in Figure 12. Four samples had final concentrations $\geq$ initial concentrations and vice versa for the other four samples. These results indicate no systematic decay of the CCN concentrations within the bag for the sample interval.

The IN sampling losses within the bag were estimated using the IN concentrations determined from the filter samples. Each sample consisted of a pair of filters exposed to air volumes differing by a factor of 10. Two pairs of filters were taken per bag (early in the flights), the first pair immediately after bag inflation and the second pair 2 to 3 minutes later. The two pairs were

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[6]Determined by dividing the flow rate in the tube (0.5 m^3 bag filled in 2.5 s) by the cross-sectional area of the tube.

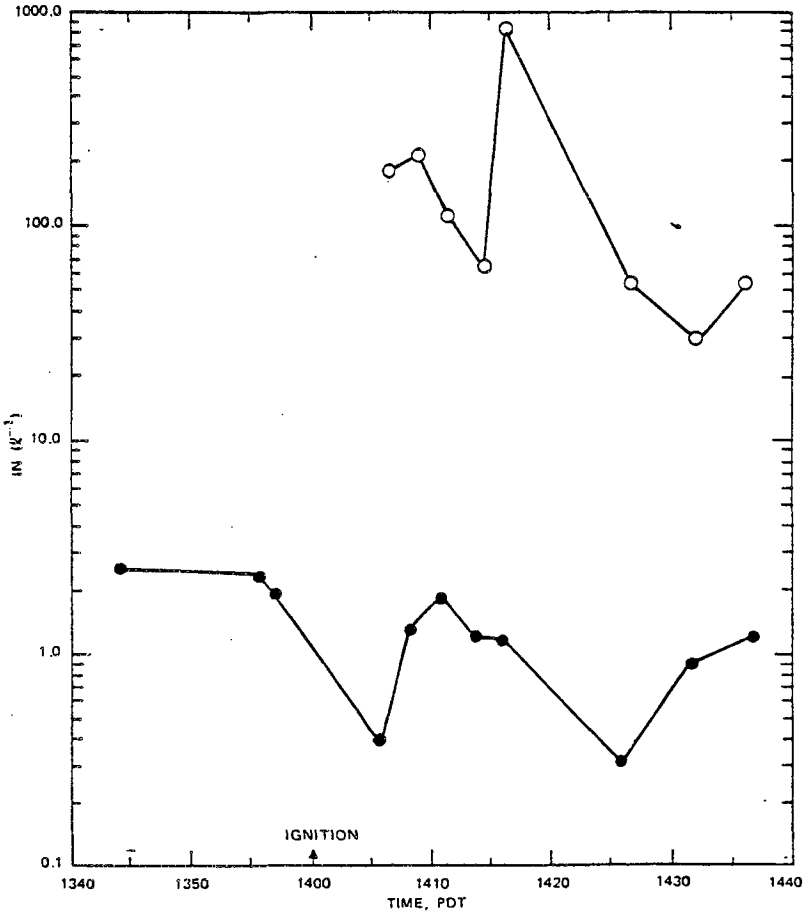

Figure 12. Maximum ice nucleus (IN) concentrations (ℓ^{-1}) measured in the exhaust cloud (open symbols) of the Super-Hippo firing on 22 December 1976 and measured in nearby air (solid symbols). The data were collected with the NWC IN counter operated at 10 ℓ/min sample flow, -25C cloud chamber temperature and 18C inlet air temperature (the threshold level was unknown). The IN concentrations have not been corrected for the presence of HCl.

taken at volumes which differed by a factor of 10. Consequently, one filter from each pair was exposed to the same volume. Nine such cases (with similar volumes) are reported in Table 2. For five cases, the concentration of IN was greater from the first samples and for four cases, the concentration of IN was greater from the second samples. This result indicates that no systematic or significant IN loss occurred due to the 2- to 3-minute intervals between samples.

In summary, the sampling errors were negligible. Sampling losses for CCN and IN were negligible within the bag for the first 4 minutes of the life of the contained air. The bag-sampling system aboard the WC-130 was a true grab-sampling system.

APPENDIX C

Comparison of CCN Counters

The Mee CCN counter was operated simultaneously with the NRL CCN counter in the field at Trinidad, California in July 1976 (Hindman, 1977). The NRL instrument can be considered the standard CCN instrument because of its well-known characteristics. The results of the comparison (Figure 13) are grouped about the one-to-one correspondence line. No systematic differences between the data from the two instruments are observed; similar behavior of the NRL and Desert Research Institute (U. of Nevada) CCN instruments was reported as a satisfactory comparison, (Hudson et al., 1977). Consequently, it is concluded that the Mee instrument measures the concentrations of CCN satisfactorily over a range of supersaturations from 0.26 to 1.08%.

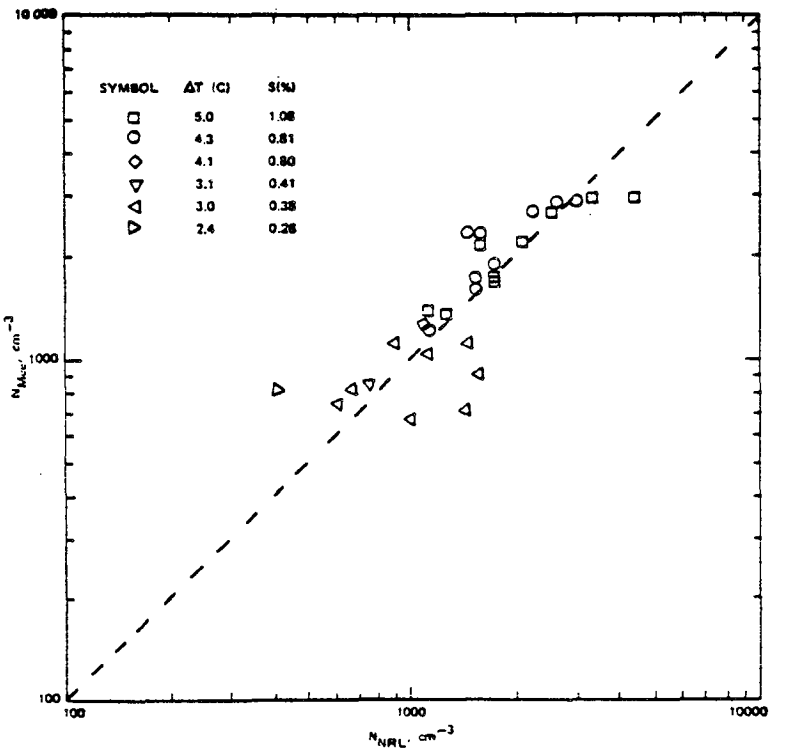

Figure 13. Cloud condensation nucleus (CCN) concentrations measured simultaneously with the Mee CCN counter (N_{Mee}) and with the Naval Research Laboratory CCN counter (N_{NRL}) over a range of supersaturations (S). The ΔT values indicate the temperature difference between the top and bottom plate of the CCN chamber. The dashed line is the one-to-one correspondence line. Equation (3) was used to reduce data from the Mee instrument.