Measurements of Cloud Nuclei in the Effluents from Launches of Liquid- and Solid-Fueled Rockets[1]

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ABSTRACT

Airborne measurements of cloud nuclei [cloud condensation nuclei (CCN) and ice nuclei (IN)] were made in the stabilized ground clouds resulting from the launches of a liquid-fueled ATLAS/Centaur rocket and a solid-fueled TITAN III rocket. Concentrations of CCN in both types of clouds were greater than ambient values for the ~2 h duration of the measurements. The initial production of CCN active at 0.5% supersaturation in the ATLAS and TITAN clouds was equivalent to a 20 and 700 s emission, respectively, by the city of Denver, Colorado. Thereafter, the clouds continued to generate CCN at a rate of ~1 cm^{-3} s^{-1}. Concentrations of IN in the ATLAS cloud were greater than ambient values for only a short period after launch; the nuclei were probably from entrained launch pad and ground debris. The concentrations of IN in the TITAN cloud were mainly at or below ambient values (possibly due to the presence of high concentrations of HCl) until ~2 h after launch when they increased substantially above ambient values. Estimates of the IN activity of the ground cloud material have large uncertainties due to unresolved discrepancies with previous laboratory measurements.

1. Introduction

Liquid- and solid-fueled rocket engines consuming large quantities of fuel will be used frequently in the near future to launch space vehicles. For example, each launch of the Space Shuttle will consume 7.2 $\times 10^8$ g of liquid fuel (liquid hydrogen, liquid oxygen) and 10^9 g of solid fuel (aluminum, ammonium perchlorate, PBAN binder).[4] The fuel consumption of such rocket engines can be roughly compared to a large industrial complex such as a western coal-fired power plant which consumes about 10^9 g h^{-1} of subbituminous coal for a rated output of 2000 MW. Consequently, these rocket motors will emit large quantities of combustion gases and aerosols into the atmosphere. Because of the low initial velocity of the launch vehicle, 15–25% of the total effluent is concentrated within the boundary layer (Potter, 1978). Meteorological conditions at the Kennedy Space Center, Florida are often such that most of this effluent rises and forms a shallow "stabilized ground cloud" at the top of the marine boundary layer.

Early field and laboratory tests indicated that the combustion aerosol from the solid fuel used in TITAN III and Shuttle booster motors produced large numbers of cloud nuclei: cloud condensation nuclei (CCN) and ice nuclei (IN). However, estimates of the absolute numbers of nuclei, and hence the size of the potential weather modification effects, have proven difficult (Parungo and Allee, 1978). The lack of absolute numbers in the TITAN booster field tests appears to have been largely due to the complex multiphase combustion aerosols. These aerosols produced different results in the various instrument systems used to monitor IN, and also exhibited a complex time-dependent behavior (Hindman *et al.*, 1980a; Hindman and Lala, 1980; Parungo and Allee, 1980). Furthermore, CCN measurements were underestimated by a lack of instrument dynamic range. However, it was established that the ground cloud CCN concentrations were >3000 cm^{-3} (instrument upper bound) for long periods after launch (Hindman *et al.*, 1980b).

In the absence of cloud nucleus measurements in

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[4] Department of the Air Force Space and Missile Systems Organization, 1976: Candidate Environmental Statement-Space Shuttle Program, Vandenberg AFB, California, Vol. 1, 1088 pp. (Assuming all of the Al is converted to Al_2O_3 and all the Cl to HCl, 100 g of solid fuel will yield, upon combustion, 30.2 g Al_2O_3 and 21.6 g of HCl.)

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ground cloud from liquid-fueled rockets and definitive IN measurements in TITAN III ground clouds, CCN and IN measurements were obtained in ground clouds from an ATLAS/Centaur rocket (liquid, hydrocarbon-fueled) and a TITAN III rocket (solid-fueled). Furthermore, aerosol particle and trace gas measurements were obtained and pertinent results are included here. The complete results of the particle and gas measurements are reported in a companion paper (Radke *et al.*, 1982).

This paper shows that the ATLAS ground cloud contained CCN but few IN, and that the TITAN ground cloud contained appreciable quantities of both CCN and IN. The purpose of these measurements is to provide information for assessing the inadvertent weather modification potential of the ground clouds.

2. Instruments

The University of Washington B-23 research aircraft was used as the platform to monitor both rocket launches. A description of the instruments onboard has been given by Hobbs *et al.* (1979) and Radke *et al.* (1982). Specific cloud nucleus instruments were used for this study. The CCN measurements were made using a thermal gradient diffusion cloud chamber developed by Radke and Turner (1972). Air samples for the chamber were drawn from a 55 L automated bag sampler that could be rapidly filled, on demand, with outside air. The IN measurements were obtained using three devices: 1) A portable IN counter developed by Langer (1973) which continuously sampled outside air through a pressure-reducing plenum. This instrument was onboard only for the TITAN III launch; it replaced the trace gas instruments used during the ATLAS/Centaur launch. 2) Particles were collected on Nuclepore filters (0.4 μm pore size) from a 500 L bag that could be rapidly filled with outside air. 3) Particles were continuously collected on a rotating membrane filter (0.45 μm pore size) using a device (Dye *et al.*, 1976) connected directly to outside air. The volumes drawn through both filters were determined by gas meters downstream of the filters. The volumes were corrected for the reduced pressure experienced by the meters. The Nuclepore and membrane filters were processed for IN using the system developed by Langer and Rogers (1975). This same system was used by Parungo and Allee (1978) to process their filters exposed to TITAN III ground clouds.

In addition, as described by Radke *et al.* (1982), a battery of automated instruments were employed to size, count and weigh the aerosol and to continuously measure its bulk light-scattering coefficient. Elemental composition of micron and submicron particles collected on Nuclepore filters were identified by energy-dispersive x-ray analysis, in concert with a scanning electron microscope (SEM). Supermicron particles were collected for analysis on silicone-coated optical microscope slides exposed to the airstream. "Universal" pH paper was also exposed to the airstream to determine the pH of liquid droplets in the launch clouds.

The light-scattering coefficient of the submicron particles was continuously measured and displayed in the aircraft using an integrating nephelometer. Further, the concentrations of trace gases (NO_x, O_3, SO_2) were continuously measured and displayed during the ATLAS/Centaur launch cloud investigation.

3. Procedures

Both rocket launches occurred at Kennedy Space Center (KSC), Florida. The ATLAS/Centaur launch was at 0024 EST on 13 November 1978 and the TITAN III launch at 1940 EST on 13 December 1978. Since both launches were at night, it was not possible to visually track the clouds after they had drifted away from the illumination of the launch pad lights. Therefore, the NO_x and O_3 measurements were used to track the ATLAS ground cloud and the light-scattering measurements were used to track the TITAN ground cloud. The clouds broke into a number of pieces due to wind shear; the largest piece of each cloud was investigated. The ATLAS ground cloud was penetrated 51 times between 3 and 150 min following launch; the TITAN ground cloud was penetrated 51 times between 4 and 255 min following launch. The penetrations consisted of orthogonal pairs to define the x and y dimensions; the z dimension was determined by a combination of measurements and visual estimates as discussed by Radke *et al.* (1982).

The ATLAS ground cloud was lost at 46 km to the WSW of KSC because of an interfering industrial plume. The TITAN ground cloud was abandoned when it either merged with or formed stratus clouds 58 km NW of KSC. The ground clouds stabilized at altitudes of ~600 and 1200 m, respectively, shortly after the launches.

During the 3 min period prior to both launches, discrete and continuous air samples were obtained in the vicinity of the launch pads at the expected stabilization altitude of the ground clouds. Within 3–4 min following lift-off, the ground clouds were penetrated by the B-23 aircraft. During these and subsequent penetrations, discrete air samples were obtained at the same time as the maximum values were displayed from the trace gas instruments (ATLAS) and the nephelometer (TITAN).

The concentrations of CCN in the discrete air samples were measured at 0.2, 0.5 and 1% supersaturations. When the concentrations exceeded 5000 cm^{-3}, a continuous-flow dilution system was used to dilute the sample by a factor of ten.

Air was drawn through the Nuclepore filters im-

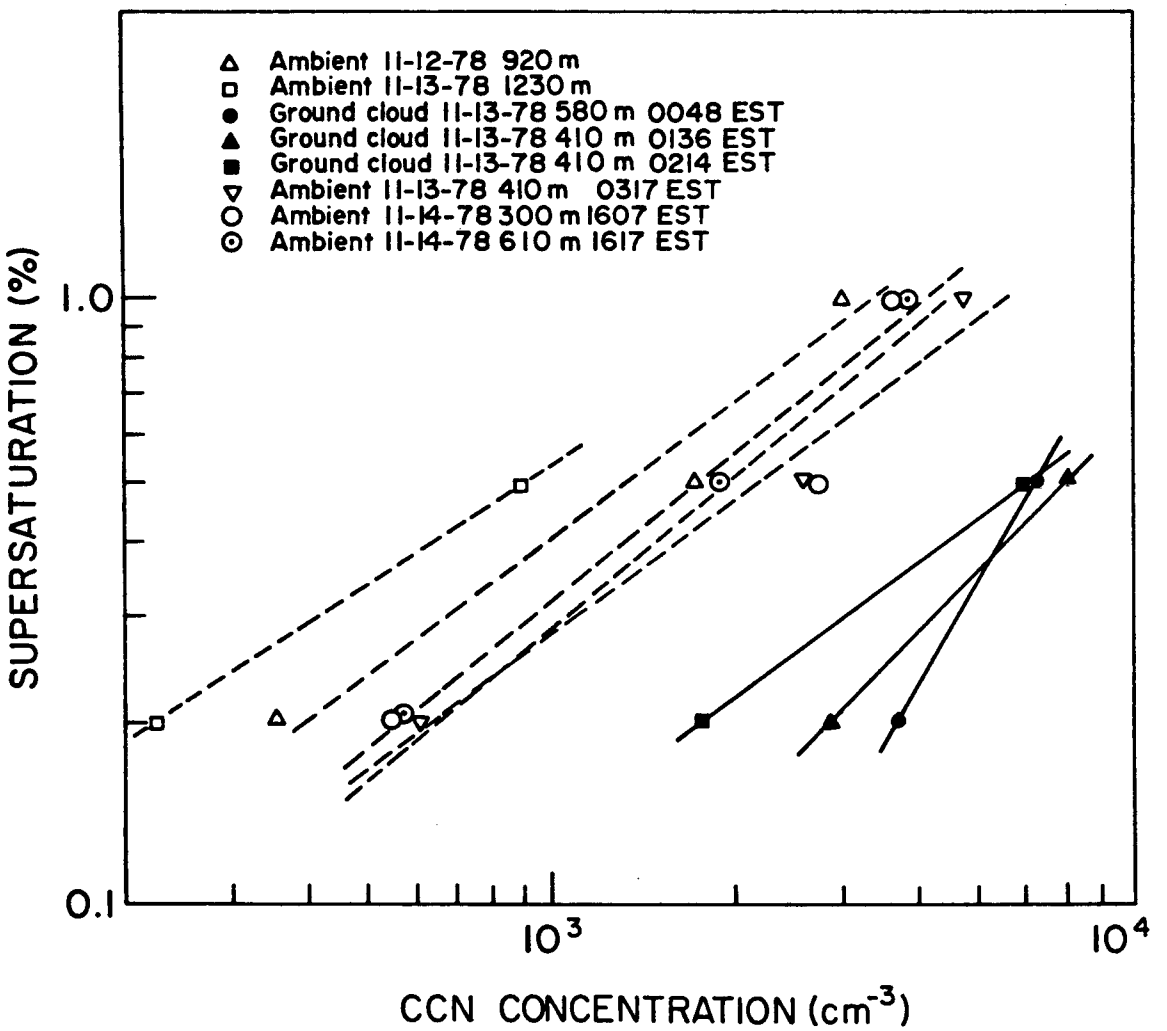

FIG. 1. Concentrations of cloud condensation nuclei (CCN) as a function of water vapor supersaturation in the ATLAS ground cloud. The ambient measurements (open symbols) were made up to 9 h before launch and 16 h after launch and include samples made in air adjacent to the ground cloud.

mediately after the 500 L bag was filled. First, 3 L was drawn through a filter, then 30 L was drawn through an adjacent filter. Thereafter, the bag was completely exhausted and two new filters were mounted and readied for the next air sample. The 3 and 30 L samples were obtained throughout the flight to avoid the variable sample–volume problem discussed by Parungo and Allee (1978). Two volumes were drawn from each air sample to determine if a sample-volume effect was present: large sample volumes correspond to small IN concentrations and *vice versa*.

After the flight, the Nuclepore filters were cut into quarters; one quarter was examined under a scanning electron microscope (SEM), two quarters were processed for IN (one at −16°C and one at −20°C and both at 101% relative humidity with respect to water), and one quarter was retained for future analysis. Because two volumes were drawn from each air sample, two IN concentrations were obtained active at −16°C and two were obtained active at −20°C. Unexposed filters were processed identically to determine the amount of contamination. The number of crystals grown on a quarter-filter surface was multiplied by four and divided by the true volume of air sampled to obtain the IN concentration.

The rotating membrane filter device was activated shortly after takeoff and sampled continuously through the entire flight (filters were changed hourly). The total volume of air drawn through each filter was measured. Each filter was processed at −20°C and 101% relative humidity with respect to water. The number of crystals in an area corresponding to 5 min of filter rotation was counted and divided by the vol-

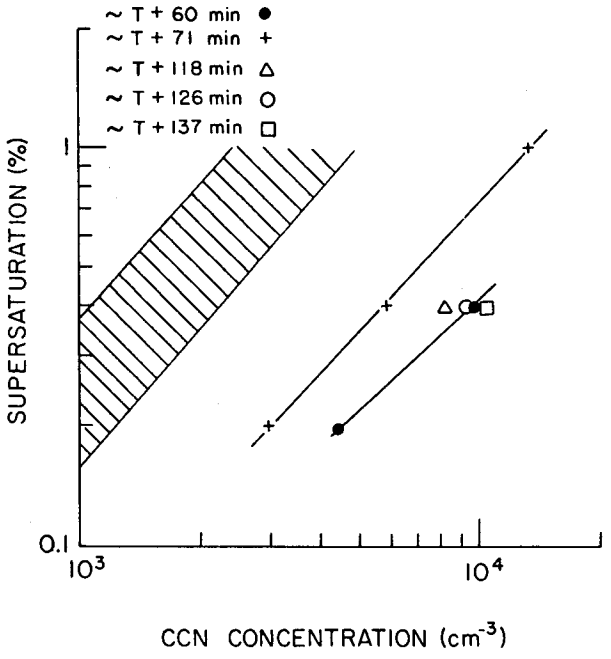

FIG. 2. Concentrations of cloud condensation nuclei (CCN) as a function of water vapor supersaturation in the TITAN ground cloud contrasted with ambient measurements made in the same altitude ranges (shaded region) during the 70-hour period surrounding the launch. T is the time of launch. The measurements at $T + 71$ min may not have been made at the center of the cloud.

ume of air sampled in 5 min (~60 L). This procedure produced average IN concentrations for 5 min intervals.

The portable IN counter was operated at −20°C. At the beginning and end of the flight, organic test IN were introduced. The rapid production and detection of ice crystals visible in the chamber demonstrated that the counter was operating properly. The IN counts were recorded continuously. To obtain the IN concentrations, the counts were summed for 5 min intervals, multiplied by 10 (correction factor according to Langer, 1973) and divided by the sample volume (10 L $min^{-1} \times 5$ min). Further, the resulting concentrations were divided by the fraction of the 5 min interval that the aircraft was in the stabilized ground cloud. This procedure accounted for dilution of the cloud sample by nearby ambient air. The analysis is based on the assumption that the concentrations of IN in the ambient air are negligible compared to those in the cloud. Pre-launch measurements support this assumption.

A wand was deployed from the aircraft to expose slides and pH paper to the air stream for short intervals. After the wand was recovered, the pH paper was inspected and read visually. The exposed slides were stored (along with a slide identically handled but not exposed to the airstream) for subsequent laboratory analysis under an optical microscope.

4. Results

The results of the CCN measurements from the ATLAS and TITAN stabilized ground clouds and nearby ambient air are shown in Figs. 1 and 2, respectively. It can be seen in the figures that the ambient CCN concentrations and supersaturation dependences were homogeneous in the hours before and after the launches. According to the CCN values, the airmasses for both launches were well-aged, polluted and continental in origin. These characteristics were confirmed by both trajectory analysis and other air quality measurements. The measured concentrations of CCN in the ambient air were 10–50 times greater than are typically found in unpolluted marine air masses (Twomey and Wojciechowski, 1969).

The CCN concentrations measured at 0.5% supersaturation were virtually identical in both the ATLAS and TITAN ground clouds and were about four times greater than the local ambient values. Further, the concentrations of CCN at 0.5% do not significantly decrease as the age of the clouds increase, although the ATLAS measurements at 0.2% monotonically decrease with time.

The results from the Nuclepore filter measurements of IN in the ATLAS cloud are shown in Fig. 3. These data have been corrected for the sample-volume effect (Hindman and Lala, 1980). These measurements indicate that shortly after launch, IN concentrations in the cloud were four times greater than concentrations in nearby air, but that they returned to ambient concentrations 25 min after launch.

For the remainder of the flight the IN concentrations in the cloud remained at or below ambient concentrations. The IN detected with the membrane filter (Fig. 4) also indicate a factor of four increase in concentrations following launch with a rapid return to ambient values. The absolute IN values from the two-filter analyses should not be compared because the Nuclepore filters were corrected for the sample-volume effect and the membrane filters could not be so corrected. The relative values, however, should be comparable.

The results from the IN measurements in the TITAN stabilized ground cloud using the Nuclepore filters are given in Fig. 5. These data have been corrected for the sample-volume effect which was known because all filters exposed to the larger volumes (30 L) produced the lowest concentration of IN, and all filters exposed to the smaller volumes (3 L) produced the highest concentrations of IN. Increasing the sample volume led to higher concentrations of particles on the filters. (This is based on the SEM analysis of the filters. It was found to be true for particles larger than 0.01 μm diameter; particles smaller than 0.01 μm were not resolved with the SEM.) The higher particle concentrations, including many CCN, increased the competition for the available vapor, re-

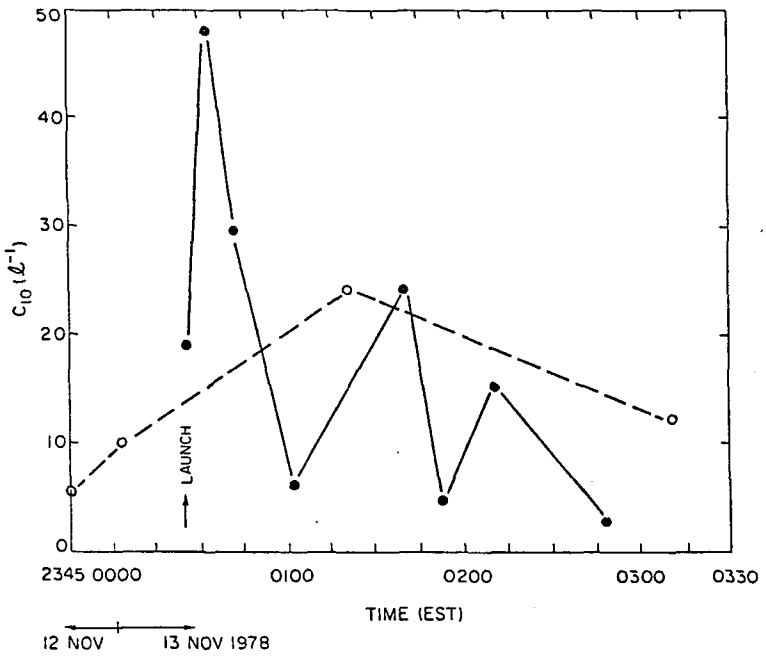

FIG. 3. Ice nucleus concentrations C_{10} (L^{-1}) in the ATLAS ground cloud as detected with the Nuclepore filters. The data have been normalized to a volume of 10 L to correct for the sample-volume effect. The data from the ground cloud and from nearby air unaffected by the cloud are represented by solid and open symbols, respectively. Error bars cannot be assigned because each datum point represents one filter sample.

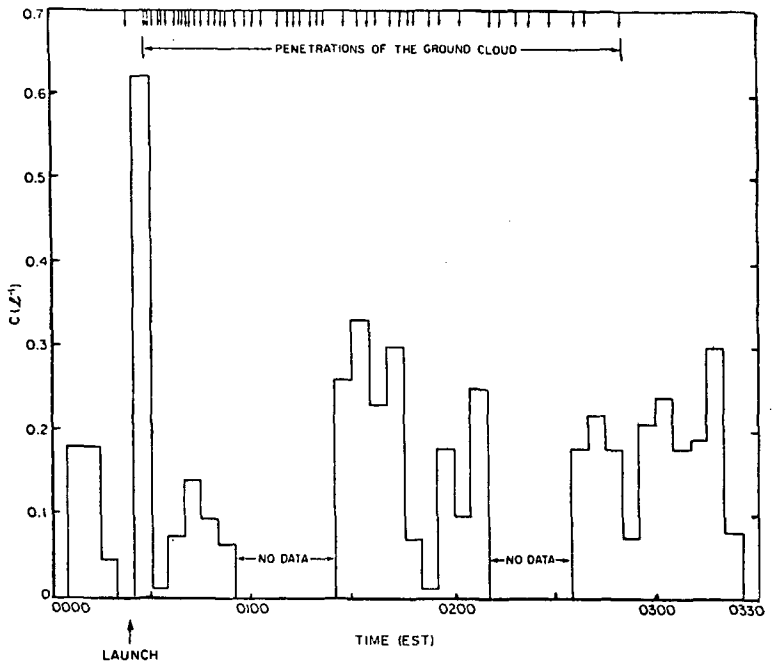

FIG. 4. Ice nucleus concentrations C (L^{-1}) in the ATLAS ground clouds as determined from the membrane filters. The filters were processed at -16°C, t = 3°C. The missing data occurred in regions of the rotating filters that passed the sampling slit twice. The time of the rocket launch and the times of the aircraft penetrations of the ground cloud are given by the arrows.

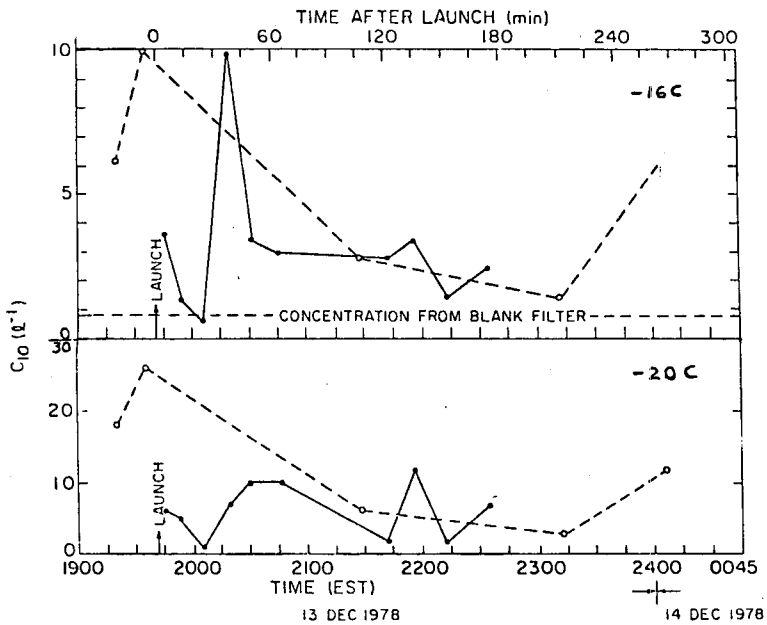

FIG. 5. Ice nucleus concentrations C_{10} (L^{-1}) normalized to 10 L in the TITAN ground cloud as detected with the Nuclepore filters. The filters were processed at −16 and −20°C, ΔT = 3°C. The data from the ground cloud and from nearby ambient air are represented by solid and open symbols, respectively.

sulting in a significantly lower humidity and consequently fewer crystals grew to detectable sizes (Lala and Jiusto, 1972). It can be seen in Fig. 5 that the concentrations of IN in the TITAN ground cloud are less than in ambient air except at ~132 min after launch (the peak at 36 min after launch is probably a processing artifact since it only occurred in the −16°C analysis). The measurements from the membrane filters, shown in Fig. 6, support the measurements from the Nuclepore filters; the IN concentra-

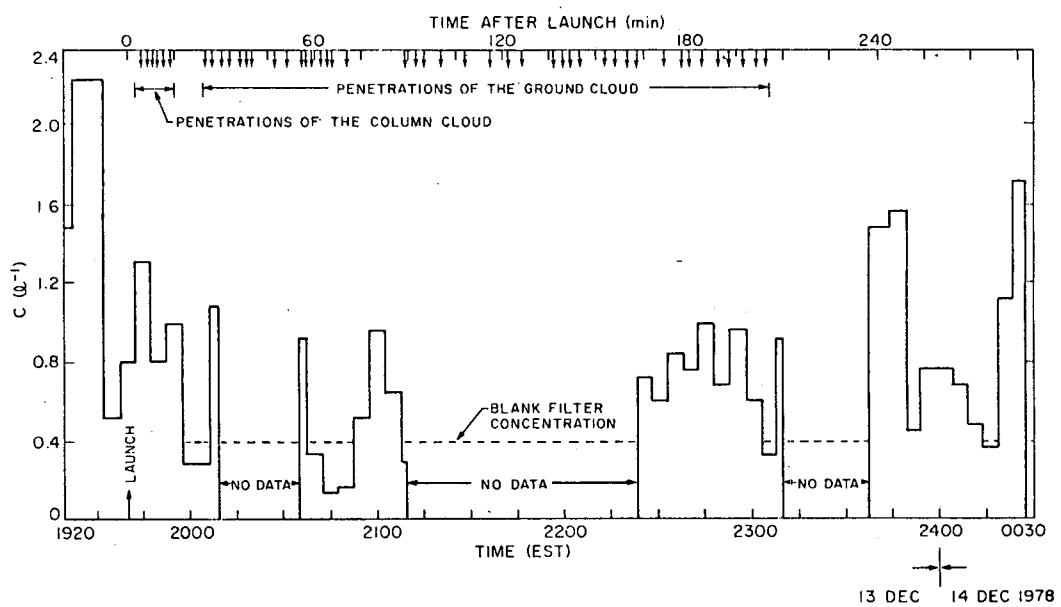

FIG. 6. Ice nucleus concentrations C (L^{-1}) in the TITAN ground cloud as determined from the membrane filters. The filters were processed at −20°C, ΔT = 3°C. The missing data occurred in regions of rotating filters that passed the sampling slit twice and in periods when no filter was mounted. The time of the rocket launch, and the times of the aircraft penetrations of the ground clouds, are shown by the arrows. The column cloud is the rocket exhaust that does not contain ground debris and the ground cloud is the exhaust that does contain ground debris.

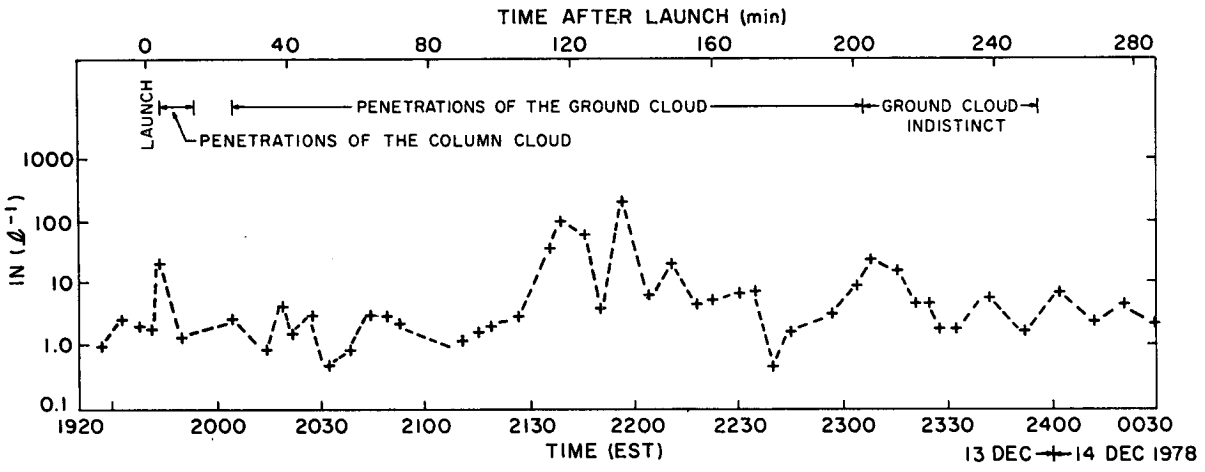

FIG. 7. Ice nucleus concentrations, IN (L^{-1}), active at −20°C, measured in the TITAN ground cloud with the portable IN counter. The measurements represent 5 min integrated concentrations divided by the fraction of time the aircraft was in the clouds (the column cloud is the rocket exhaust that does not contain cloud debris, the ground cloud is the exhaust that does contain ground debris). For specific cloud penetration times consult FIG. 6.

tions in the plume are generally less than pre- and post-launch ambient samples.

The results of the IN concentrations measured in the TITAN ground cloud with Nuclepore filters at −16 and −20°C are mutually consistent. The concentrations at −20°C are, on average, about two times greater than the concentrations at −16°C. This result is consistent with the behavior of IN; the concentrations of IN are inversely related to temperature. Furthermore, the variations in the concentrations between −16 and −20°C samples are correlated: linear correlation coefficient = 0.84.

The IN concentrations measured in the TITAN ground cloud using the portable IN counter are shown in Fig. 7. The measured IN concentrations were above background in the first cloud penetrations (pre-launch background ~3 L^{-1}, cloud ~20 L^{-1}). Thereafter, the concentrations of IN in the ground cloud remained between 1 and 10 L^{-1} until ~100 min after launch (T + 100 min). Between T + 100 minutes and loss of contact with the ground cloud at T + 206 min, the IN concentrations in the cloud were above 10 L^{-1}, with maximum concentrations of 100 and 200 L^{-1} at T + 118 and T + 135 min Background IN concentrations (active at −20°C), measured with the same portable counter at KSC in March, 1978 (Wisniewski and Langer, 1980), ranged between 1 and 5 L^{-1}, a result consistent with the measurements shown in Fig. 7.

The volumes of the ATLAS and TITAN stabilized ground clouds were estimated from the continuous trace gas (ATLAS) and nephelometer (TITAN) measurements. The volume of the ATLAS cloud was 3×10^7 m^3 at T + 24 min and increased linearly to 2×10^8 m^3 at T + 190 min. The volume of the TITAN cloud was 8×10^8 m^3 at T + 60 min and increased linearly to 1.8×10^9 m^3 at T + 137 min.

5. Discussion

Using the first measurements of CCN concentrations N from the ground clouds (Figs. 1 and 2) and the cloud volumes V measured at the same time, the initial production (P) of CCN active at 0.5% supersaturation was calculated: $P = NV$. The values were $\sim 2 \times 10^{17}$ for the ATLAS ground cloud and $\sim 7 \times 10^{18}$ for the TITAN ground cloud. These values may be compared with the estimate of the emissions of CCN from the city of Denver of $\sim 10^{16}$ s^{-1} (Squires, 1966). The initial production of CCN in the ATLAS and TITAN clouds is equivalent to, respectively, 20 and 700 s emissions from Denver.

Additional CCN active at 0.5% supersaturation formed within both the ATLAS and TITAN ground clouds during the period of the CCN measurements; the concentrations of CCN in both clouds remained approximately constant through this period, while the volumes of both clouds increased substantially. The formation rate was calculated by dividing the concentration of CCN, which was nearly constant, by the measurement period. The rates in both clouds were found to be ~0.5 to 1 cm^{-3} s^{-1}.

As discussed by Radke *et al.* (1982), it appears that the production of CCN in the TITAN ground cloud by gas-to-particle conversion is a potentially long-lived process that may produce orders of magnitude more CCN over the lifetime of the cloud than are originally produced at launch. In this event, the larger ground clouds produced by a Shuttle launch may influence warm-rain processes over a modest area as the cloud disperses downwind; a conclusion consis-

tent with Lala (1980). This impact would be increased if the launch were to take place in a relatively unpolluted airmass.

The IN detected in the ATLAS ground cloud in concentrations above background values (Figs. 3 and 4) were probably ground debris and not particles generated by the rocket. First, the SEM analysis of the particles collected from the cloud on the filters and slides revealed that none of the particles ≥ 0.1 μm diameter could be traced to the rocket or its fuel. The particles were primarily calcium-containing, indicating that they originated from the launch pad, the brakish deluge water and the entrained sandy soil. Secondly, high concentrations of particles < 0.1 μm diameter resulted from combustion of the liquid, hydrocarbon fuel. These particles were probably carbonaceous. To our knowledge, carbonaceous particles have not been found to be active IN.

The IN concentrations measured in the TITAN ground cloud with the portable counter (Fig. 7) tend to support the following picture. The measured IN concentrations in the cloud, early in its life, were equal to or less than the IN concentrations in the pre-launch atmosphere. After $\sim T + 100$ min, the measured concentrations in the cloud increased to above pre-launch values and remained at about this level until loss of contact with the cloud. The maximum concentration of 200 L^{-1} was detected at $T + 134$ min.

A similar IN pattern was measured in another TITAN III ground cloud (Hindman *et al.*, 1980b). We believe that the delayed detection could be due to the high concentrations of HCl present early in the life of the cloud (pH of cloud liquid was near zero) which inhibits either the nucleation or growth (or both) of ice crystals. Later in the life of the cloud the HCl concentrations are reduced (pH of cloud liquid increased) and IN were detected. Parungo and Allee (1978) provide evidence of the inverse relationship between HCl concentrations and activity of IN in the aerosol from laboratory burns of solid rocket propellant using the same portable IN counter as employed here. However, we were unable to duplicate this effect in the laboratory. Using a vapor diffusion neutralizer to substantially eliminate the HCl, no significant increase in IN were observed when the HCl was removed during laboratory burns of propellant.

Our uncertainty with the IN measurements must be emphasized. The measurement of IN employing both filter techniques is generally considered a standard method. While we have offered reasons for the results in Figs. 5 and 6, it is emphasized that the filter measurements indicate that the TITAN effluent contains no significant quantity of IN. This result is not surprising because the filters detected 10–100 times fewer IN than did the portable counter in the laboratory test reported by Hindman *et al.* (1980a).

Using the IN data from the portable counter (Fig. 7), together with data from the companion paper (Radke *et al.*, 1982), it is possible to estimate an upper-bound to the apparent IN activity. Using the peak IN measurement at $T + 134$ min (200 L^{-1} at -20°C), a cloud volume of 3.5×10^{12} L and a cloud aerosol mass of 60 kg, the IN activity is $\sim 10^{10}$ g^{-1}. In comparison, the IN activity of the combustion aerosol in the laboratory measured with the same portable counter was $\sim 10^6$ g^{-1} active at -15°C (Parungo and Allee, 1978) and $\sim 10^6$ g^{-1} active at -20°C (Radke *et al.*, 1979). Lala (1978) reports a value of $\sim 10^7$ g^{-1} active at -20°C from laboratory tests using a similar portable counter. Further, the IN activity of the combustion aerosol in the laboratory, measured with a large, permanent cloud chamber, was $\sim 10^{10}$ g^{-1} active at -20°C (Hindman *et al.*, 1980a).

It is apparent that the field and laboratory measurements are not mutually consistent. The discrepancy between the IN activities measured with the portable counter in the field and laboratory could be due to different IN properties between the ground cloud and laboratory combustion aerosol, and uncertainties in the measured ground-cloud volumes and mass concentrations. Consequently, we do not consider the 10^{10} g^{-1} value to be a reliable estimate for the IN activity in the TITAN ground cloud. Additional careful and coordinated laboratory and field measurements are required to produce a reliable IN estimate.

Our IN results for a TITAN ground cloud differ from those of Parungo and Allee (1978). They reported concentrations of IN to be at a maximum in the clouds shortly after launch and to reduce to background values within three hours following launch. Hindman and Lala (1980) argue that Parungo and Allee's results were primarily a reflection of a significant sample-volume effect: small sample volumes were obtained early in the flight which produced high IN concentrations; large sample volumes were obtained later in the flight which produced low IN concentrations. Here we report IN concentrations determined from filter samples with the same volumes throughout the flight. Further, the filters and processing procedures used here were the same as employed by Parungo and Allee. In contrast to their results, we found IN concentrations less than background values from launch until about $T + 132$ min (Fig. 5), a pattern consistent with that from the simultaneously operating portable IN counter. [The linear correlation coefficient between filter and portable counter IN concentrations (ambient concentrations divided by cloud concentrations) is 0.34.]

IN concentrations lower than background values were also measured in the ATLAS cloud (Fig. 3). The lower IN concentrations in the cloud relative to background concentrations may be due to some mechanism in the cloud that "poisons" ambient IN, similar to the role of HCl in the TITAN ground cloud. Con-

sequently, the concentrations of IN in the ground clouds from liquid-fueled rockets may be larger than those reported here, if the "poisoning" effect diminishes with time.

6. Conclusions

The initial production rates of CCN active at 0.5% supersaturation, in the ATLAS (liquid fuel) and TITAN III (solid-fuel) ground clouds have been shown to be equivalent to 20 and 700 s emissions, respectively, estimated from the city of Denver, Colorado. Thereafter, the ground clouds continued to generate CCN for many hours. These results indicate a potential for the ground clouds from rocket launches to interfere with the production of rain in warm clouds.

The ATLAS ground cloud contained few IN. The measured concentrations, however, may have been underestimated due to an apparent "poisoning" phenomenon.

The IN concentrations measured in the TITAN stabilized ground cloud with a portable counter were at or below background values until ~100 min after launch (except for an initial IN impulse in the column cloud ~4 min after launch). After 100 min the IN concentrations peaked at 200 L^{-1} active at −20°C. The initially low IN concentrations early in the life of the ground cloud may be due to high HCl concentrations. As the HCl concentration diminished, the IN concentrations increased. Estimates of the IN activity of the ground cloud material have large uncertainties due to unresolved discrepancies with previous laboratory measurements.

It is premature to forecast the meteorological impact of large rocket motor effluent. Nevertheless, it appears likely that systems such as the Shuttle may exhaust meteorologically significant concentrations of ice nuclei and cloud condensation nuclei, a conclusion consistent with Hindman and Finnegan (1982). A more confident assessment will require both resolution of the measuring uncertainties discussed and an extension of our research to the actual interactions between the effluent clouds and natural cloud systems.

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