

A LABORATORY STUDY OF CONTRAILS

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ABSTRACT

Contrails were produced for laboratory study by burning aircraft fuels under controlled conditions of ambient temperature and humidity at pressure altitudes between 1000 and 300 mb. Observed critical formation temperatures differ from Appleman's theoretical data in a manner similar to that obtained on project CLOUD TRAIL flights. Laboratory experiments with these trails proved that the initial phase of the condensed moisture is liquid and produced strong evidence that, contrary to general belief, the final phase is sometimes liquid. Additional evidence was obtained indicating that Appleman's criterion for a barely visible trail (0.004 g per m³ of condensed moisture) is very nearly correct for ideal conditions of observation such as used in the laboratory, but is probably small by an order of magnitude or more for adverse conditions. By modifying Appleman's theory to allow for the production of a visible quantity of liquid water under adverse viewing conditions, agreement is reached with project CLOUD TRAIL data. Also presented is a simple interpretation of the theory which substantially reduces the labor required to compute critical temperatures for contrail formation.

1. Introduction

The criteria on which exhaust contrail forecasting is based are shown in fig. 1, the solid lines being derived by Appleman [1] and the dashed lines being obtained experimentally during project CLOUD TRAIL [2]. By Appleman's reasoning, contrails always occur in the region labeled ALWAYS, never in the area labeled NEVER, and their formation depends on relative humidity in the POSSIBLE region. The dashed lines denote the percentage of CLOUD TRAIL flights which actually produced contrails at the indicated atmospheric conditions. Thus, visible trails

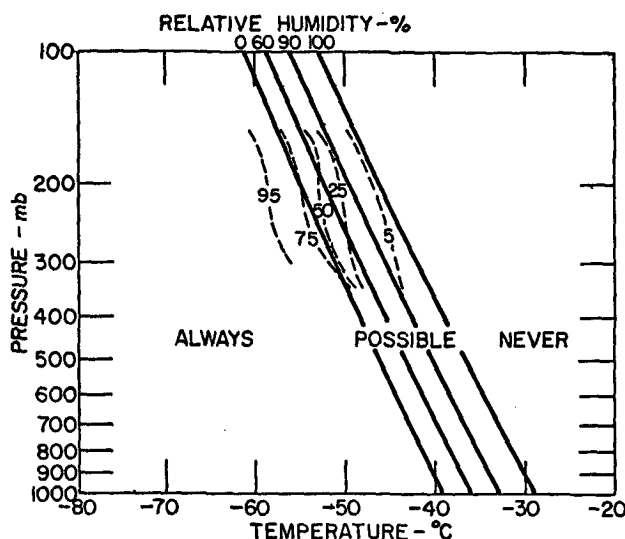


FIG. 1. Contrail formation as a function of pressure, temperature and relative humidity of the environment. Solid lines were theoretically derived by Appleman. Dashed lines are empirically derived curves of contrail probability in per cent as obtained by project CLOUD TRAIL.

were not produced during approximately 25 per cent of the flights at maximum temperatures where theory predicts their formation, even in perfectly dry air. Further, contrails did not always occur at temperatures four to five degrees colder than these maximum theoretical temperatures. The experimentally determined POSSIBLE region is, therefore, roughly 50 per cent wider than the theoretically derived region.

The consistency of the direction of this discrepancy suggests that improved understanding of the fundamental processes occurring in contrail formation might lead to improved contrail forecasting. As part of the contrail investigation at Cornell Aeronautical Laboratory, we have attempted to examine experimentally the assumptions made by Appleman in developing the contrail theory. This paper summarizes some of the pertinent information thus far obtained and presents a simplified form of the theory which significantly reduces the labor required for computing critical temperatures for contrail formation.

2. A simplified expression of the contrail theory

The analysis in reference 1 was based on the following four assumptions:

1. All heat and water produced by the combustion of fuel are discharged in the exhaust with their subsequent dilution being due entirely to mixing with ambient air.
2. The initial phase of condensed moisture is always liquid.
3. The final phase of condensed moisture is always ice.
4. The minimum water content of a barely visible trail is 0.004 g per m³.

From assumption 1 Appleman showed that the change in mixing ratio, $\Delta\omega$, in the aircraft wake was directly proportional to the change in wake tempera-

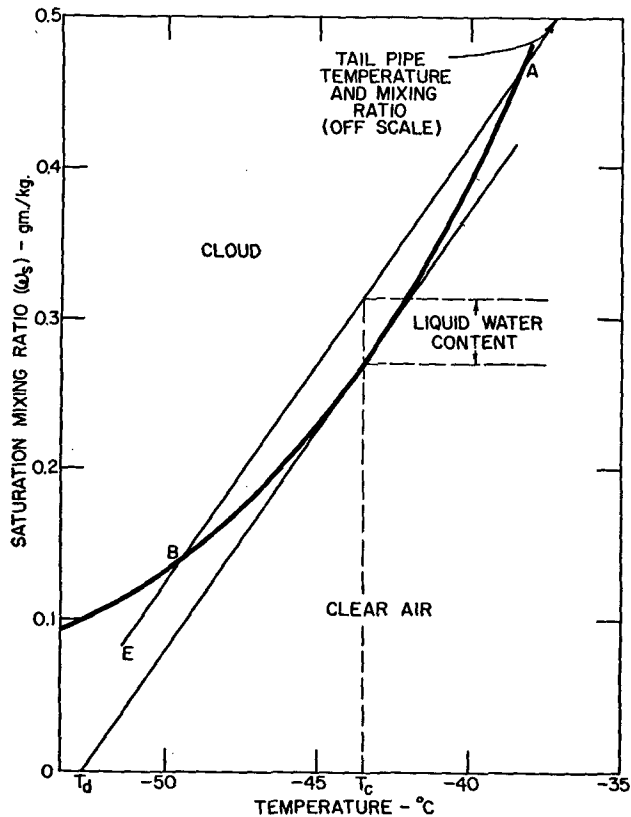


FIG. 2. 300-mb contrail predictor diagram. The curved line represents saturation mixing ratio *versus* temperature while the straight lines indicate aircraft wake conditions.

ture, ΔT . The proportionality constant is a property of the fuel alone and is given by

$$\frac{\Delta\omega}{\Delta T} = 1000 \frac{Wc}{H} \text{ gm per kg C,} \quad (1)$$

where W is the mass of water produced by the combustion of one gram of fuel, c the specific heat of air, and H the heat of combustion of the fuel. Appleman obtained 0.0336 for the value of this ratio. According to recent aircraft fuel specifications, [3] we find 0.0295 a more representative figure and hence have used that value in our computations.

This constant being known, the conditions for contrail formation may be obtained directly from a phase diagram of mixing ratio *versus* temperature, as shown in fig. 2. The solid curved line represents the saturation mixing ratio, ω_s , relative to water (assumption 2). Clear air is indicated by the region beneath the saturation curve while clouds are represented by points in the region above the saturation curve. Consider an aircraft flying through ambient air described by point E. As exhaust leaves the aircraft it is characterized by tailpipe temperature and mixing ratio which are off-scale in the figure. As air-exhaust mixing progresses, the temperature and mixing ratio of the wake return from tailpipe to ambient conditions via a straight line having a slope equal to the characteristic

$\Delta\omega/\Delta T$ of the fuel used (0.0295 in this example). Condensation commences at the critical air exhaust mixture which produces saturation (point A) and, barring freezing, evaporation is complete when wake conditions reach point B.

Now, consider the line having the characteristic slope $\Delta\omega/\Delta T$ and tangent to the saturation mixing ratio curve at temperature T_c . An aircraft flying in air described by any point on this line which is colder than T_c will produce in its wake all conditions along this line. At T_c , the maximum ambient temperature for contrail formation at 300 mb, vapor will condense into liquid water and, by assumption 3, freeze into ice. Because of the difference between saturation mixing ratio over water and ice, additional moisture will sublime onto the frozen droplets, thereby fulfilling the visibility criterion (assumption 4). Hence, contrails will always form in the region of fig. 2 above the tangent line and colder than T_c .

In a saturated atmosphere, therefore, contrails would be produced at all ambient temperatures colder than T_c while, for a perfectly dry atmosphere, their occurrence would require temperatures colder than T_a , the temperature at which the tangent line crosses the zero-humidity axis. At intermediate temperatures contrail formation is dependent on relative humidity. If T_c and T_a are plotted as a function of pressure, the ALWAYS, NEVER, and POSSIBLE regions of fig. 1 are defined. Exact correspondence, of course, is not realized since a different value of $\Delta\omega/\Delta T$ (0.0295 rather than 0.0336) was employed. More detailed utilization of this method of computation is covered in reference 4.

3. The initial phase of condensed moisture

Because of the inaccessibility of aircraft-produced contrails, we have performed all of our experiments in the laboratory. Contrails were generated by burning several hydrocarbon fuels, including 80, 91, and 100 octane aviation gasoline and JP-4 (a modified kerosene) [3]. Observations were made in a Revco model SFH-653 cold chamber at sea-level pressures and in the C.A.L. altitude chamber at pressures between 1000 and 300 mb. The altitude chamber is a 30-ft long cylinder, 10 ft in diameter, in which pressure between station and 70 mb and temperatures between ambient and -65°C can be produced. The fuel burners consisted of wick lamps and occasionally a blow torch for selected experiments with 100 octane gasoline. Combustion of fuel under suitable ALWAYS or POSSIBLE conditions automatically produced the contrails. Although the burners used were not perfect simulators of jet engines, we have argued that the chemical processes and exhaust products are essentially the same as those which occur in flight.

The complete lack of scintillations in all laboratory contrails in the region nearest the flame was our first experimental evidence that the initial phase of condensed moisture was liquid rather than ice. These results were confirmed by microscopic examination of samples of the condensate collected on a rotating rod. Fig. 3 shows, respectively, samples collected from (a) a known water cloud at -20°C , (b) a contrail produced at 1000 mb and -21°C using methyl alcohol as fuel, (c) a contrail produced at 400 mb and -51°C using 100 octane gasoline as fuel, and (d) ice crystals collected from an old contrail at 1000 mb and -53°C . The similarity of figs. 3b and 3c to collected supercooled water and the photographic impression of flow after collection leave no doubt that the initial phase of the condensate is liquid. Observations of this type were made at the maximum temperatures at which contrails could be produced in a saturated atmosphere. Since the dew point of the critical exhaust air mixture at which condensation first occurs in any contrail increases as ambient temperature decreases (evident from fig. 2), condensate phase data obtained at maximum ambient temperature may be extrapolated safely to all temperatures.

4. The final phase of the condensed moisture

The lack of scintillations in some laboratory contrails from time of formation to dissipation led us to suspect that nonpersistent trails often do not glaciate.

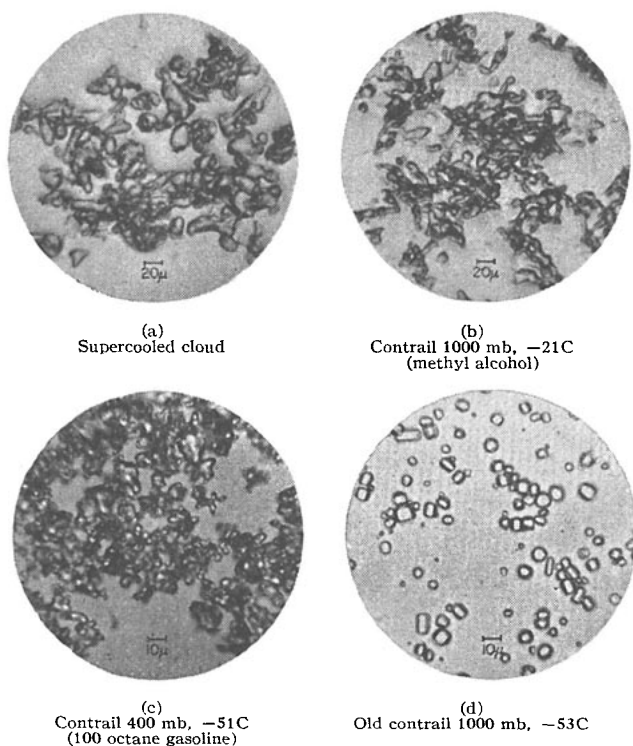


FIG. 3. Comparison of contrail condensate with rime ice collected from a supercooled cloud. All samples collected on rotating rod.

The fact that completely liquid trails do exist was demonstrated in a series of experiments designed to measure the maximum temperature of contrail formation in a water-saturated atmosphere as a function of pressure.

For these experiments wick-type burners were used to produce contrails from 100 octane aviation gasoline in the altitude chamber. Measurements were made at pressure intervals of 100 mb between 1000 and 300 mb. The chamber was maintained at water saturation by boiling water continuously from a household deep-fat-fryer. Temperature was measured with alcohol thermometers and thermocouples at four heights in the chamber. The alcohol thermometers were standardized at -30°C against a mercury thermometer which itself had been standardized at 0°C in an equilibrium mixture of ice and distilled water. The thermocouples, which gave reproducible readings within 0.5°C , were used to assure equilibrium conditions and to permit remote reading by members of the team not exposed to the harsh experimental conditions. Throughout the experiment vertical temperature variations did not exceed 0.5°C per ft.

In each experimental run the temperature of the chamber was reduced several degrees below the point at which the contrail was first observed. Dampers to the refrigerator coils were then closed to allow the chamber to warm gradually until the contrail disappeared and this temperature was recorded. The contrail was illuminated by an intense beam of parallel light in an otherwise darkened chamber and observed against a black velvet background. To assure detection of minimum possible concentrations of condensed moisture, light scattered into the near-forward direction (20 to 30 deg) was observed. In this way the trail could be detected at temperatures between 1 and 2°C warmer than when viewed at right angles to the incident beam. Trails observed in the T_c region were about one inch in diameter and ranged from one to four inches long.

Critical temperatures for initial contrail formation are represented by the circles in fig. 4. The solid lines on this figure were taken from Appleman. From the experimental data it appears, at first, that the chamber was approximately 90 per cent saturated relative to water. Even under these conditions it would have been supersaturated by 30 to 40 per cent relative to ice, and a trail composed of ice crystals could not have sublimed. Since evaporation was observed, the condensed moisture must have remained in the liquid phase.

This information prompted us to compute the maximum ambient temperature of a saturated atmosphere at which a barely visible quantity, 0.004 gm per m^3 , of condensed liquid water would be produced. Dashed line (a) in fig. 4 is the result of this computa-

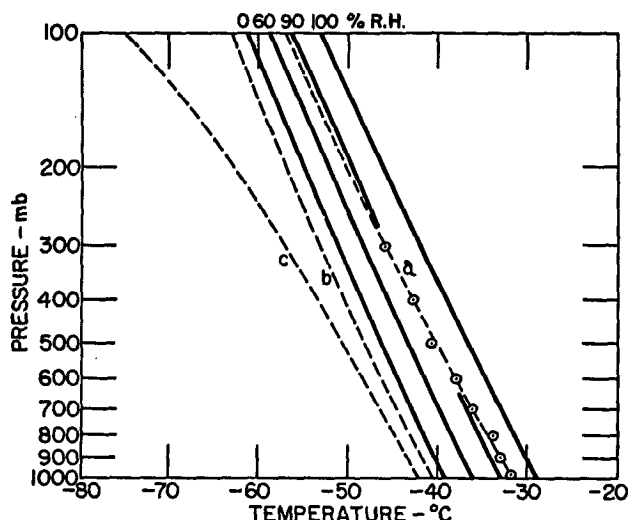


FIG. 4. Contrail detection as a function of ambient pressure, temperature and relative humidity, and of trail liquid water content. Solid lines were taken from Appleman. Dashed lines a and b allow for production of 0.004 gm per m^3 of liquid water in a water saturated and perfectly dry environment respectively, and curve c for the production of 0.055 gm per m^3 in a dry atmosphere. Circles represent observed points in altitude chamber experiments.

tion. Maximum deviation between our experimentally determined temperatures and computed temperatures is 0.7°C. Such excellent agreement indicates that the chamber was very nearly saturated relative to water during the experiments and leaves little doubt that the final phase of the condensed moisture was liquid in the T_c region.

The existence of supercooled water at temperatures significantly colder than -40°C is not a generally accepted fact, but has been suspected by theorists [5] for some time. Fig. 5 demonstrates that such supercooling of contrail condensate, whatever its purity, is possible. The two photographs show the same sample of condensate collected from a dense contrail produced at 400 mb by burning 100 octane gasoline in a blow torch at an ambient temperature of -52°C .

The sample was collected on a $\frac{1}{4}$ -in wide glass slide rotated at 1700 RPM at the end of a four-inch rod mounted perpendicular to the axis of a hand drill. The system was operated in the contrail for approximately 10 sec to allow impaction of a suitable sample of condensate, and the slide then removed immediately to the stage of a prefocused microscope. Visual observation and minor adjustments were made through the focusing telescope of an American Optical Company Model No. 682B camera, attached to the microscope. Total magnification of the system was 520. Kodak Super Pancro-Press Type B, 4×5 sheet film was used with two-sec exposures. The film was stored in an oven maintained at 0°C during the experiments to preserve speed. Photograph 5A was taken about 30 sec after collection, and photograph 5B was taken about 30 sec later without moving the sample from the microscope-camera. The seven arrows in fig. 5A

point to particles which had evaporated before 5B was taken. From the preceding paragraphs we must conclude that the atmosphere was supersaturated by at least 30 per cent relative to ice. The fact that some growth (up to 0.5μ), occurred on almost all other particles shows without doubt that the ice crystals were exposed to supersaturated conditions and could not have sublimed away. We must conclude, therefore, that the particles designated by arrows remained in the liquid phase until evaporation.

Although the temperature of the trail ranged from -34 to -52°C in this experiment, the slide was at ambient temperature, -52°C . Within the first thirty seconds after collection the liquid drops must also have achieved ambient temperature.

All droplets that evaporated measured no larger than 1.5μ diameter and these must have been flattened previously upon impact with the slide. All larger circular particles appear to have frozen. The fact that such small droplets may not be substantially larger than the nuclei on which they were formed suggests that we may not have been dealing with pure water but fairly strong solutions which would not obey the same laws. Even if the drops consisted of pure water, their inability to freeze at such low temperatures seems reasonable in view of the probable dependency of freezing point on droplet size and exposure time. According to the freezing equation derived by Bigg [5], for example, the time required for 90 per cent probability of freezing of a 1μ diameter droplet at -50°C is 163 sec. Since our exposure time for similar conditions was less than one minute, the presence of liquid drops is not surprising. Further research is under way to determine the nature and size of nuclei which participate in contrail formation.

5. The true visibility criterion

From the experiments discussed above it appears that a water concentration of $0.004 \text{ gm per } m^3$ is sufficient to produce a visible trail under the idealized conditions of observation used. It was noted that the liquid water content had to be increased by 50 to 100

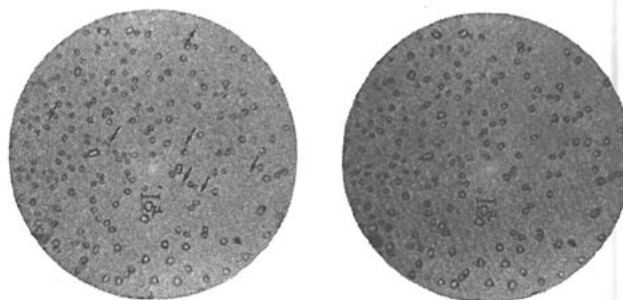


FIG. 5. Condensate collected 2 ft above torch with whirling slide. Arrows point to droplets which evaporated in an ice supersaturated atmosphere before photograph b was taken. (-52°C , 400 mb.)

per cent to allow the trail to be detectable with the same illumination and background but with more nearly right angle scattering, although this is still a somewhat favorable condition.

The visibility criteria can be improved by applying the conventional mathematics for atmospheric visibility and luminance contrast to the contrail problem, provided the average differential scattering cross section of condensate is known. Determination of this function, although not yet complete, has advanced sufficiently at C.A.L. to allow tentative comparisons of project CLOUD TRAIL data and Appleman's theory, the latter corrected for a barely visible quantity of liquid water when observed under more adverse conditions than used in our experiments.

Volumetric differential scattering functions have been measured for supercooled water clouds and for ice crystal clouds in the Revco cold chamber. The scattering photometer, which is described in detail in reference 4, consists of a light source and detector, each fitted with a suitable collimator and mounted on a student spectrometer frame. The source illuminates a fixed cylindrical volume of the cloud. The detector accepts parallel light from a limited field in any desired direction. Thus, it accepts light scattered from particles in a second known but movable cylinder of cloud. The instrument is operated in an otherwise dark chamber so that detected radiation must have been scattered by particles which occupy the volume common to both cylinders. To obtain volumetric differential scattering cross section it is simply necessary to divide the measured light by the volume common to both cylinders at each angle of observation. Fig. 6 shows normalized scattering functions for (a) the water cloud and (b) the ice cloud obtained in this manner. Curves (c) and (d) show calculated values [6] of volumetric differential scattering cross section of monodispersed clouds of diameter equal to 1.4 and 1.75 μ , respectively. They are shown for comparison with the experimental curves. It is readily apparent that the volume scattering function for the ice and water clouds varies over two orders of magnitude depending on scattering angle, thus indicating that the detection of contrails is highly dependent on the angle of observation.

6. Probable correction to Appleman's theory

From the foregoing paragraphs, it is evident that the final condensate phase (sometimes liquid) and the variability with viewing angle of the critical amount of liquid water are two factors that must be considered in contrail detection. It is suggested that the discrepancies between observed and theoretical contrail formation temperatures can be resolved by modifying the theory to include these variables.

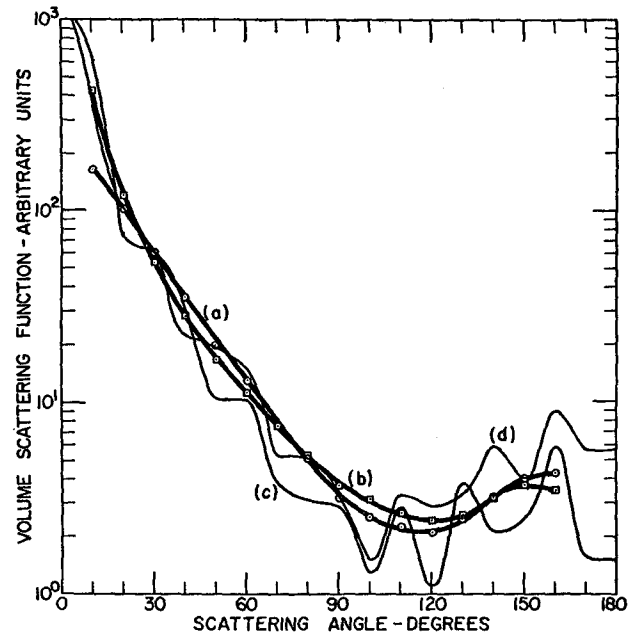


FIG. 6. Normalized volumetric differential scattering cross section. (a) measured in water cloud, (b) measured in ice cloud, (c) and (d) calculated for monodispersed clouds of 1.4 and 1.7 μ diameter droplets respectively. (c) and (d) taken from reference 6.

Since project CLOUD TRAIL data contain no humidity information, comparison of experiment and theory can be made only in the ALWAYS region of fig. 1. By altering Appleman's theory to allow for the production of 0.004 gm per m^3 of liquid water, which would be visible under ideal conditions, dashed line b of fig. 4 is obtained. $\Delta\omega/\Delta T$ was assumed to be 0.0295 for these and all subsequent computations. Assuming that more adverse viewing conditions and a final liquid condensate phase were involved on project CLOUD TRAIL flights where contrails were expected but not observed, we arbitrarily increased the liquid water content required for contrail detection at 300 mb until all nonobservation cases were covered. This resulted in a critical visibility value of 0.055 gm per m^3 from which dashed line c of fig. 4 was computed. This number, although large, does not appear unreasonable in light of the variation of volumetric scattering cross section for water clouds shown in fig. 6. For example, to be consistent with the altitude chamber results, we assigned 0.004 g per m^3 as the visibility criterion for a scattering angle of observation equal to 25 deg. Curve (a) of fig. 6 then indicates that the minimum visible liquid water concentration exceeds 0.055 gm per m^3 for all scattering angles of observation greater than 80 deg.

Extrapolation on this simple basis is probably over-optimistic. Such matters as the increase in total scattering cross section per drop with the increase in RMS drop size that must accompany greater liquid water contents, and the decrease of background brightness at greater angular distances from the sun

must moderate this optimism. Our contrail visibility studies have not yet progressed sufficiently to permit evaluation of the extent of this moderation. Without further study of the basic visibility problem and additional information concerning the method and angle of observation used on project CLOUD TRAIL, no conclusions can be drawn as to the number of non-observations of contrails which can be explained on the basis of the foregoing discussion. A combination of this source of error and possible temperature measurement errors during project CLOUD TRAIL (1C standard deviation for radiosondes) is of sufficient magnitude to explain the deviation between theory and experiment.

7. Conclusions

We have shown that the initial phase of condensed moisture in a contrail is liquid, at least for pressures greater than 300 mb, and have presented very strong evidence that the final phase of the condensate is sometimes liquid. A liquid water content of 0.004 gm per m³ appears to be correct for a barely visible contrail under ideal conditions of observation but is probably small by an order of magnitude for adverse conditions of observation (for example, at large scattering angles). Corrections which could be applied to Appleman's theory to account for pure liquid trails and for the non-uniformity of the visibility

criterion are large enough to account for most of the deviation between theory and project CLOUD TRAIL observations.

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