AWS/TR-81/001

FORECASTING AIRCRAFT CONDENSATION TRAILS

September 1981

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AIR WEATHER SERVICE (MAC)
Scott AFB, Illinois 62225

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Kirk E. Lehneis

KIRK E. LEHNEIS, Capt, USAF
Reviewing Officer

FOR THE COMMANDER

THOMAS A. STUDER, Col, USAF
DCS/Aerospace Sciences

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Aircraft condensation trails (contrails) are caused by aircraft aerodynamics or engine exhaust in the proper atmospheric conditions. Engine-exhaust trails are the most common and are discussed in this report. Jet aircraft contrail-formation graphs facilitate yes-or-no forecasts for any season with forecasts of pressure, temperature, and relative humidity. Contrail probability curves give condensation trail probabilities with forecast pressure and temperature. Engine power setting does not affect contrail formation, but does affect intensity. The contrail-formation graph for propeller aircraft is similar to the jet graph.

PREFACE

This technical report presents a method of diagnosing and forecasting aircraft condensation trails (contrails). This method has been extensively tried and found generally useful. The original research was done in the early 1950s; little new work has been done since that time.

This report is a republication of AWSM 105-100, 11 March 1960 with change 1. A few additional changes and corrections have been incorporated. New material is included in Section 2.6 and Chapter 5.

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Chapter 1

INTRODUCTION

1.1 Definition

Condensation trails (contrails) are elongated tubular-shaped clouds composed of water droplets or ice crystals which form behind aircraft when the wake becomes supersaturated with respect to water. Depending upon their origin, they are called either "aerodynamic" or "engine-exhaust" trails.

1.2 Aerodynamic Trails

Aerodynamic trails are caused by the momentary reduction in pressure of air flowing at high speed past an airfoil. This pressure fall can cause sufficient adiabatic cooling of the air to raise the relative humidity of the affected environment to saturation. In such cases condensation will occur, and if enough liquid water is produced, a visible trail will form. (This is comparable to the formation of "conventional" clouds from air parcels by upward vertical motion which reduces pressure and increases relative humidity, e.g., over mountains or frontal surfaces and in incipient cumulus clouds.) The trails are generally associated with the areas of maximum pressure decrease, i.e., the tips of the wings and propellers.

Aerodynamic trails are rare in occurrence and short in duration. They occur in layers where the atmosphere is near saturation, especially during times of extreme flight maneuvers such as sharp "pull-outs" and high-speed diving turns. If trails do form, a small change of altitude or a reduction in airspeed may stop their formation.

1.3 Engine-Exhaust Trails

The second and most important type of condensation trail arises when the water vapor in the exhaust gas mixes with and saturates the air in the wake of the aircraft (Appleman, 1953). Combustion of the hydrocarbon fuels used in aircraft--both propeller and jet--injects both water vapor and heat into the aircraft wake. The added moisture raises the relative humidity in the wake, while the added heat lowers it. Whether or not the wake will reach saturation depends on the ratio of water vapor to heat in the exhaust gas and on the initial pressure, temperature, and relative humidity of the environment. The remainder of this report deals with engine-exhaust trails.

1.4 Operational Importance of Condensation Trails

During an aerial invasion, contrails are of vital importance. They generally aid the defender and hinder the attacker. Sections 1.4.1 through 1.4.4 list the most important ways in which the defenders are helped directly and the attackers are hindered indirectly. Section 1.4.4 summarizes some of the ways in which the attackers are hindered directly. In some cases both the attackers and defenders are hindered.

1.4.1 Detection by Defenders. Radar defense networks are never perfect. Aircraft can penetrate holes in the radar coverage or use electronic countermeasures. This is of little use, however, if long white trails give away their position and direction of flight.

1.4.2 Interception by Defenders. Intercepting aircraft are vectored to the position of the invading aircraft by means of radar. The presence of contrails enhances visual contact, thus tremendously increasing the efficiency of the radar control.

1.4.3 Identification by Defenders. By showing the number and spacing of the engines, contrails can reveal aircraft type.

1.4.4 Direct Obstacles to Invaders. Contrails produced by a flight of aircraft may spread out to form a cirrus cloud layer which can hinder the rendezvous of aircraft and refueling operations. Also, contrails may interfere with some of the radar-controlled apparatus on an aircraft.

Chapter 2

CONTRAIL-FORMATION GRAPH FOR JET AIRCRAFT

2.1. Introduction

The parameters which determine whether or not the wake of an aircraft will become saturated and contrails will form fall into two classes. Three of the parameters are associated with the environment and one with the aircraft. The environmental parameters are pressure (p), temperature (T), and relative humidity (RH). The aircraft parameter is the ratio of water vapor to heat (W/H) injected into the wake. For jet aircraft (unlike propeller aircraft), almost the entire amount of heat and all the water vapor liberated by the combustion process go into the wake. Consequently, the ratio W/H does not change with the type of jet aircraft nor with the rate of burning of the fuel. Thus, only the environmental parameters--p, T, and RH--determine whether or not a trail will form.

2.2 Construction of the Contrail-Formation Graph

The critical values of p, T, and RH for contrail formation were derived for pressure ranging from 1000 to 40 mb and for relative humidities of 0, 60, 90, and 100 percent with respect to water (Table 1 and Figure 1). The complete theoretical treatment is given in AWS TR 105-145 (Appleman, 1957).

Figure 1 shows the minimum relative humidity of the environment which will give rise to jet exhaust trail formation at given values of pressure and temperature. Since the atmospheric humidity must always be between 0 and 100 percent, the graph can be divided into three main areas. If a pressure-temperature value lies to the left of the 0 percent line, contrails should always form--even in absolutely dry air. This is the "Yes" area. If the value falls to the right of the 100 percent line, contrails should never form--even in initially saturated air. This is the "No" area. If the point falls between the 0 and 100 percent lines, contrails will form if (and only if) the actual relative humidity is equal to or greater than the value indicated at that point on the graph. This is the uncertain or "Possible" area.

2.3 Reliability of Data Used with the Contrail-Formation Graph

In actual practice, forecasting contrails is not so objective. To begin with, the forecaster must enter the graph with a forecast value of temperature for the particular pressure level. If the resulting point falls in the "Possible" area, a forecast relative humidity is also required. Chance for error occurs in forecasting both of these parameters. In addition to the uncertainties in forecasts of upper-air temperatures, very large horizontal temperature gradients occasionally exist in the atmosphere. Measurements have

Table 1. Critical Temperatures (°C) for Jet Aircraft Contrail Formation as a Function of Pressure and Relative Humidity.

Pressure (mb)	Relative Humidity (percent) 0	60	90	100
40	-69.1	-66.9	-63.9	-61.3
50	-67.4	-65.0	-62.0	-59.2
60	-65.9	-63.4	-60.3	-57.7
70	-64.6	-62.0	-59.0	-56.2
80	-63.3	-60.9	-58.0	-55.0
90	-62.4	-59.8	-56.9	-53.9
100	-61.5	-58.9	-56.0	-53.0
150	-58.0	-55.1	-52.3	-49.0
200	-55.4	-52.6	-49.6	-46.2
250	-53.2	-50.3	-47.4	-44.0
300	-51.5	-48.6	-45.6	-42.0
400	-48.6	-45.6	-42.7	-39.0
500	-46.5	-43.3	-40.3	-36.7
600	-44.7	-41.4	-38.4	-34.6
700	-43.0	-39.9	-36.8	-32.9
800	-41.7	-38.3	-35.2	-31.3
900	-40.3	-37.0	-34.0	-30.0
1000	-39.2	-36.0	-32.9	-28.9

shown gradients of up to 11°C per 60 nautical miles with a possible gradient of 13°C per 30 nautical miles (Kochanski, 1956). This temperature uncertainty must be kept in mind while using Figure 1. For all practical purposes it amounts to widening the "Possible" area. A glance at the spacing of the relative humidity curves on Figure 1 shows that the left side of the "Possible" area is extremely sensitive to temperature errors while the right side is relatively insensitive. For example, a temperature error of 1°C is equivalent to a humidity error of 22 percent on the left edge of the area but only 1.5 percent on the right edge--a sensitivity ratio about 15 to 1. Thus, the left side of the graph is primarily affected by temperature uncertainty.

The other parameter, relative humidity, also is subject to special difficulties. Figure 1 shows that the entire region of contrail formation lies at temperatures below -29°C, and most of it below -40°C. Because of the small water vapor content of cold air, low-temperature humidities cannot be measured accurately with present instruments. In fact, as a rule, no humidities at all are reported at temperatures below -40°C. This means that the humidity used in

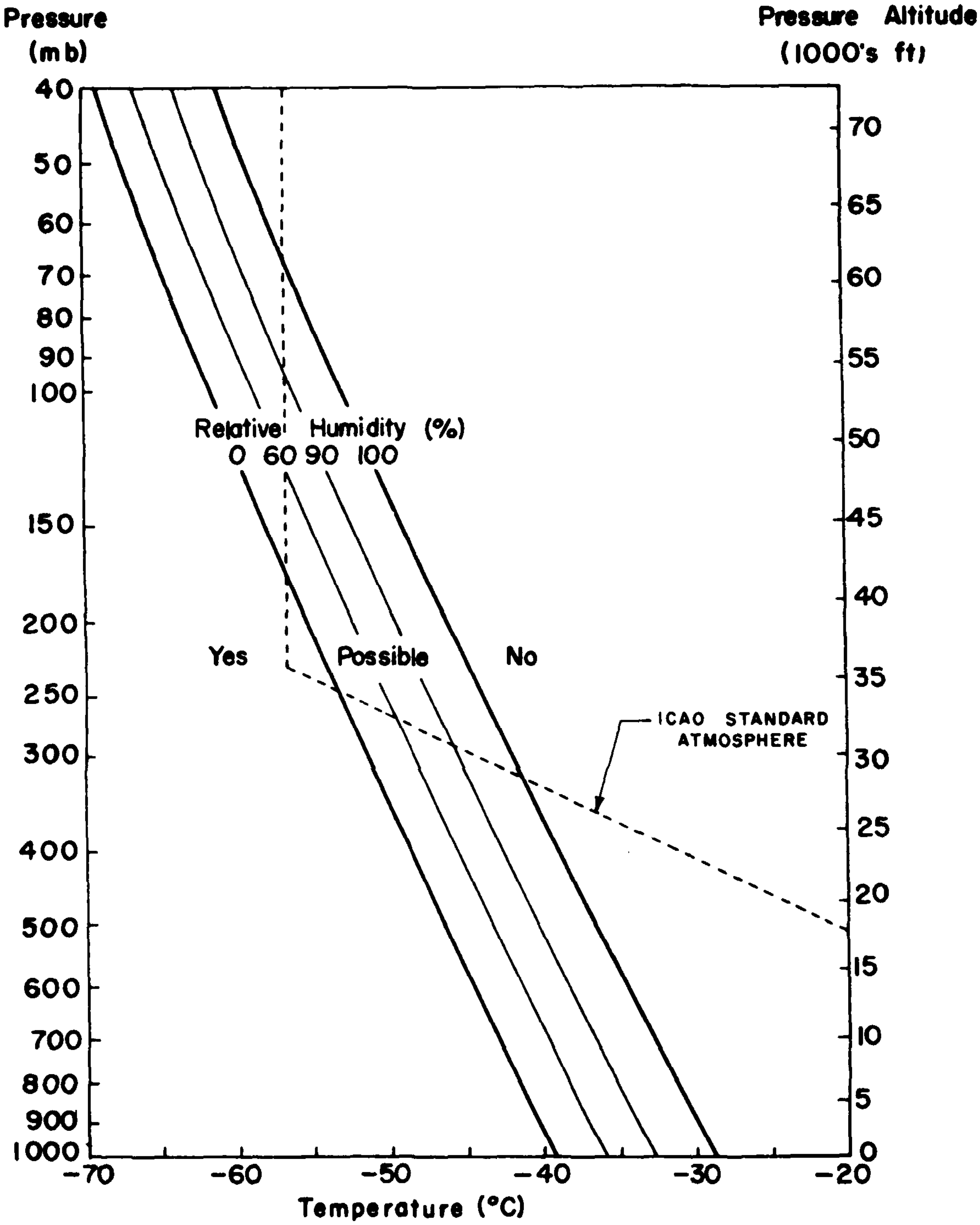

Figure 1. Graph of the Relative Humidity Required for Jet Aircraft Contrail Formation as a Function of the Pressure and Temperature of the Environment.

accurately with present instruments. In fact, as a rule, no humidities at all are reported at temperatures below -40°C. This means that the humidity used in Figure 1 must be "forecast" almost entirely from general knowledge of upper-air humidity. However, low-temperature humidity measurements have been made so seldom that our knowledge of them is scant. Empirical studies indicate that best results will generally be obtained by assuming a relative humidity of 40 percent. In the immediate vicinity of a high-cloud deck or near the tropopause, it is recommended that a humidity of 70 percent be assumed.

The final difficulty with contrail forecasting is that trails are frequently not observed under adverse viewing conditions, such as against a dense cirrostratus background or looking into the sun. Thus, there will always be a sizable number of "no-trail" reports in the "Yes" region of the graph.

2.4 Forecasting with the Contrail-Formation Graph

If a flight is planned for a specific altitude, the temperatures along the path at that altitude are forecast using radiosondes, upper-air charts, reconnaissance reports, etc. The humidity is assumed to be 40 percent everywhere along the route, except near the tropopause or where clouds are present at flight level where it is assumed to be 70 percent. The pressure-temperature values along the path are entered in Figure 1 (or Figure 2, which presents the curves of Figure 1 on a Skew T, Log P Diagram). If the required relative humidity shown on the graph is greater than the assumed value, no contrails are forecast; if the required value is less than the assumed value, contrails are forecast. The farther apart the required and assumed values, the more confidence can be placed in the forecast.

In addition to the flight level forecast, the forecaster should determine the proper direction (up or down) that the aircraft should take to leave a contrail-producing layer quickly.

2.5 Accuracy of Contrail-Graph Forecasts

An extensive evaluation of the contrail-formation graph, based on over 3000 jet aircraft observations, was carried out in 1952 and 1953 (AWS, 1953, Table 28). The "Yes" area (to the left of the 0 percent line) showed 857 positive reports and 125 negative reports for an accuracy of 87 percent. The "No" area (to the right of the 100 percent line) showed 70 positive reports and 546 negative reports for an accuracy of 89 percent. Since no humidity data were available, no determination could be made of forecast accuracy inside the "Possible" area. However, this area was divided into subregions P1, P2, and P3 as delineated on the 0-60, 60-90, and 90-100 percent lines, and the contrail frequencies determined; these were 69, 54, and 30 percent, respectively. Most of the temperatures were measured by the aircraft and corrected for dynamic heating. Such measurements are generally not as accurate as desired for research purposes.

A second test, carried out in Europe, was based on radiosonde temperatures. It was reported in AWS TR 105-126 (AWS, 1954). The "Yes" area showed 297 positive reports and 49 negative reports for an accuracy of 86 percent.

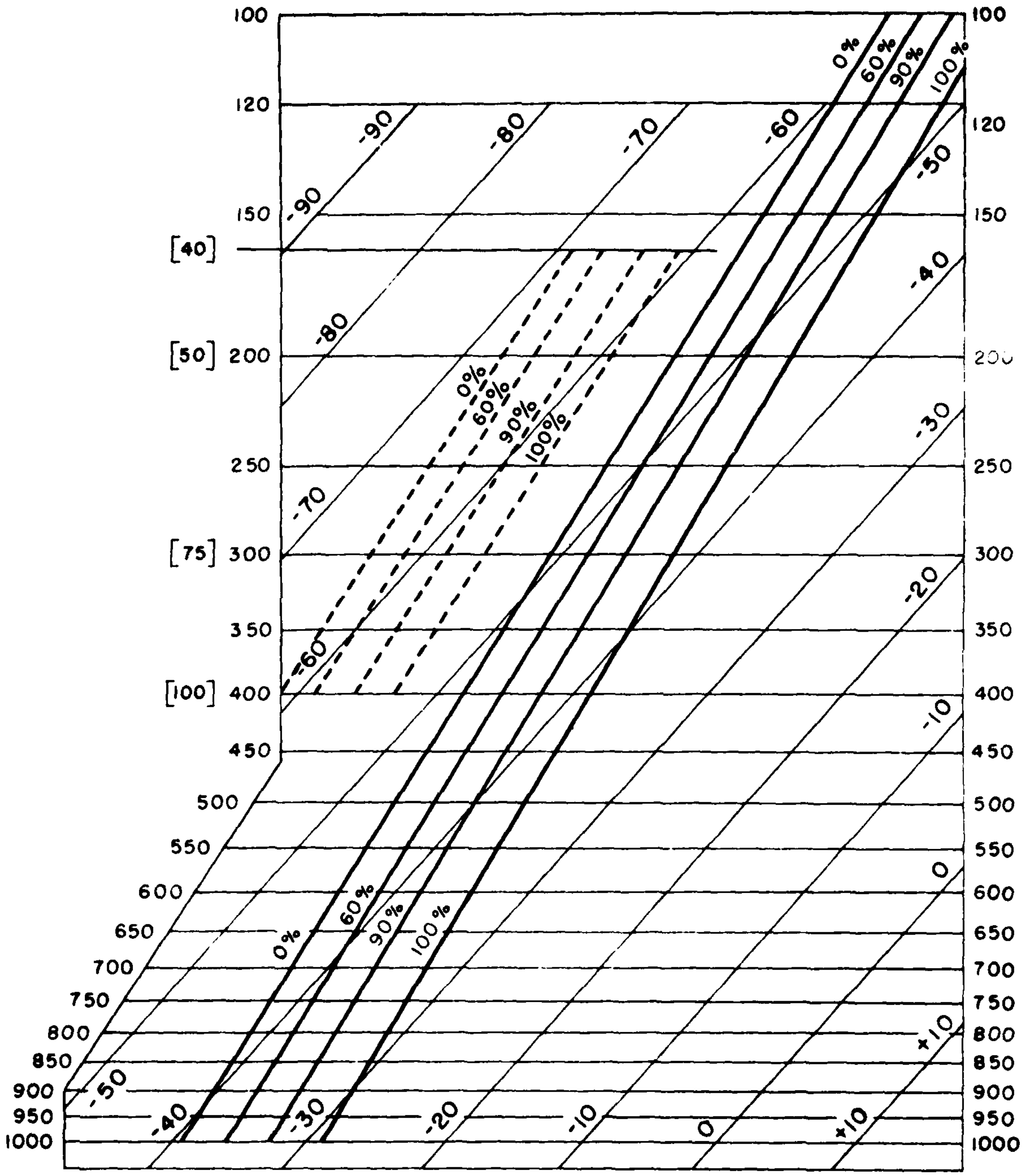

Figure 2. The Jet Aircraft Contrail-Formation Curves Plotted on a Portion of a Skew T, Log P Diagram. Dashed lines and brackets indicate curves in the 100- to 40-mb region. One version of the Skew T, Log P Diagram, DOD-WPC 9-16 has the curves overprinted on it.

The "No" area showed 33 positive reports and 698 negative reports for an accuracy of 95 percent. Region P1, P2, and P3 showed contrail frequencies of 55, 41, and 34 percent respectively.

In general, therefore, the accuracy of the contrail graph using radiosonde temperature data can be considered to be about 85 percent in the "Yes" region and close to 95 percent in the "No" region. Both accuracies would, of course, increase with distance of the points from the 0 and 100 percent relative humidity curves. With a decrease in reliability of the temperature data and/or the need to forecast relative humidities for points falling in the "Possible" region of the graph, forecast accuracies would decrease. In these cases, it may frequently prove more useful not to attempt a yes-or-no forecast, but rather to give the probability of contrail formation as a function of the pressure and temperature. Such contrail probability curves are presented in Chapter 3.

2.6 AFGWC Forecasting of Contrail Formation

AFGWC has a contrail computer program for determining tops and bottoms of layers within which contrails are expected to occur. Because of operational considerations, only two contrail layers are retained for each grid point concerned. The program assumes relative humidity values of 40 percent from 500 mb to approximately 300 meters below the tropopause level, 70 percent in the vicinity of the tropopause, and 10 percent in the stratosphere. Predictions are made for the Northern Hemisphere and the tropics.

2.7 Effect of Power Setting on Contrail Formation by Jet Aircraft

It has been suggested that the formation of condensation trails might be prevented by varying the power setting of the aircraft engines. Because of the importance of this point, a test was set up to gather data which would show the relationship between contrail frequency and power setting (AWS, 1954). Using a total of 1878 F-84 observations, it was found that a variation in power setting from 85 to 98 percent of full power had no effect on contrail frequency. However, increased power settings did seem to result in increased trail intensity. These empirical results are in accordance with theoretical expectations (see Section 2.1 above).

Godson (1954), a Canadian meteorologist, reached the same conclusion. In an independent derivation of the critical conditions for contrail formation by jet aircraft, he states, "This relation is independent of fuel consumption rate and is therefore valid for any type of jet aircraft which uses a fuel comparable to kerosene."

Chapter 3

EMPIRICAL CONTRAIL-PROBABILITY CURVES FOR JET AIRCRAFT

3.1 Introduction

The theoretically derived curves presented in Chapter 2 show the pressure-temperature-relative humidity relationship necessary for contrail formation by the exhaust from jet aircraft. These curves permit a specific yes-or-no contrail forecast provided the temperature and relative humidity are known for the level of interest. As pointed out in Section 2.3, however, there is an uncertainty in the temperature measurement, and generally only a guess can be made regarding the true relative humidity.

To bypass these difficulties, AWS decided to obtain sufficient data to make an empirical study of contrail frequency as a function of pressure and temperature alone. In this way, both the temperature uncertainty and the actual mean relative humidity at each pressure-level point are absorbed into the frequency curves. This method does not generally allow a yes-or-no forecast; it does, however, permit a statement as to the relative frequency (i.e., empirical probability) of contrail formation for any given value of pressure and temperature.

3.2 Procedure

Project Cloud Trail was set up for one year (1 December 1954 to 1 December 1955) to obtain the necessary data. Data from twenty-three rawinsonde stations were utilized in conjunction with data collected by Air Defense Command F-86 aircraft. These fighter-interceptors climbed above the stations within one hour before to two hours after 1530Z. A wingman observed and recorded the bases and tops of any contrail layers on a special card.

Data on the occurrence and nonoccurrence of contrails at six pressure levels--350, 300, 250, 200, 175, and 150 mb--were extracted from the cards. The associated temperatures were obtained from the raob. The contrail frequency was determined for each pressure-temperature point, and curves of contrail frequency drawn as functions of pressure and temperature. A more detailed account of this procedure is given by Appleman (1957) in AWS TR 105-145. Separate studies were made for each season, for the northern and southern halves of the United States, and for the troposphere and stratosphere. Finally, a mean study was made combining the data from all seasons and stations (Table 2 and Figure 3). There was little difference between this mean graph and the individual graphs. Consequently, the mean graph can be used for all regions and seasons.

3.3 Use of the Contrail-Probability Graph

The solid lines of Figure 3 show the probability of a jet aircraft producing visible trails at the indicated pressures and temperatures. Unfortunately, the vertical range of the empirical curves is limited to the region between 350 and 150 mb. Below 350 mb, temperatures tend to be too warm for contrail formation; above 150 mb, observations were too few to derive reliable probabilities.

The dashed lines on Figure 3 are the theoretically derived critical relative humidity curves for contrail formation from figure 1. Assuming that the theoretical curves are exact, perfect data would result in the 0 percent contrail-probability curve coinciding with the 100 percent humidity line, and the 100 percent probability curve coinciding with the 0 percent humidity line. As expected from the discussion in Section 2.3, on the right side of the graph the theoretical and empirical curves are in good agreement; on the left side, there is a temperature deviation of from 2.5 to 5°C between the theoretical curves and the 95 percent probability line. The deviation is largest near 250 mb, and is 4°C or more between 210 and 300 mb; this is the region between the polar and tropical tropopauses. Below 300 mb, the deviation reduces markedly and would be only 1 or 2°C at 350 mb.

Although the theoretical curves may actually be more representative of contrail formation with perfect data, the probability curves are more representative of the data available to the operational forecaster. To use the probability curves, the forecaster refers to the most recent radiosonde temperatures and upper-air charts available for the altitudes under consideration. Time and space extrapolation is then applied to bring the temperature to its most likely value at the time and place of interest. Using this temperature and altitude, the contrail-probability graph gives the actual percentage probability of contrail formation.

Table 2. Probability of Jet Aircraft Contrail Formation as a Function of Pressure and Temperature

Pressure (mb)	Contrail Probability (percent)						
	95	90	75	50	25	10	5
150	-60.5°C	-59.3°C	-57.1°C	-55.5°C	-53.6°C	-51.5°C	-50.7°C
175	-58.8	-57.4	-55.3	-53.6	-51.4	-49.6	-48.5
200	-58.5	-56.6	-54.8	-53.1	-51.0	-48.5	-47.0
250	-58.1	-56.3	-53.8	-52.2	-50.1	-47.1	-45.3
300	-55.5	-54.0	-52.0	-50.7	-49.1	-46.3	-44.3
350	-----	-49.9	-49.4	-49.0	-48.0	-45.9	-43.6

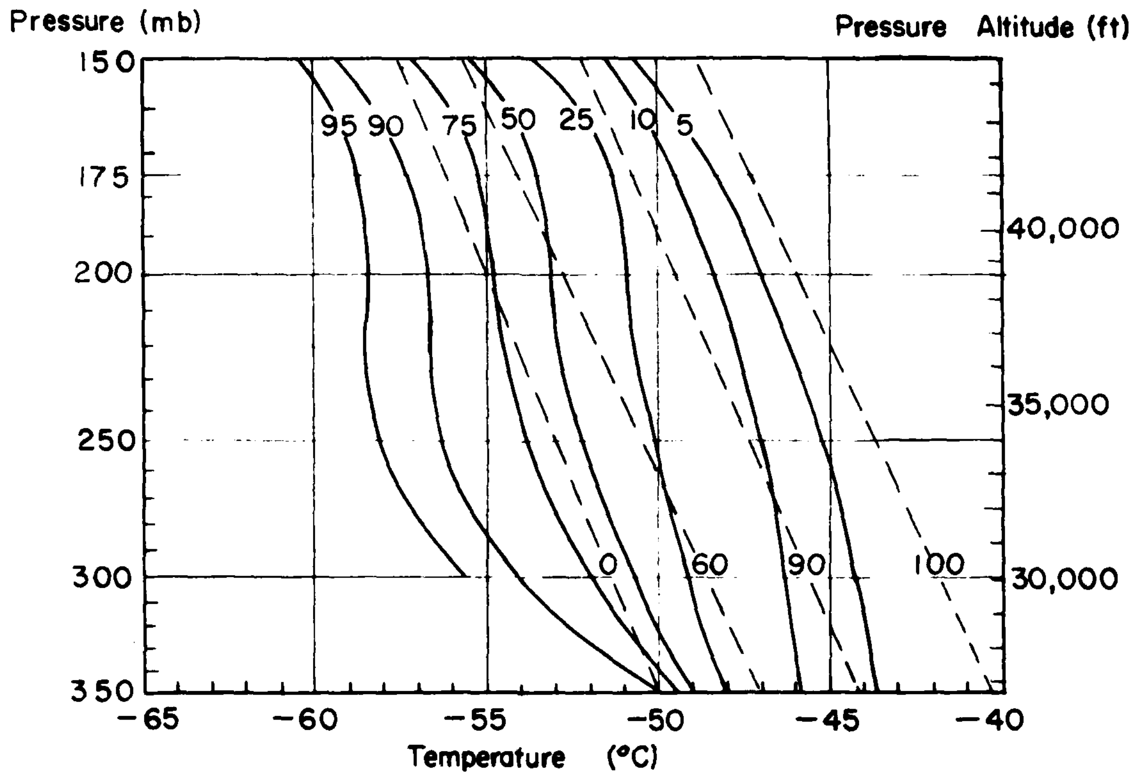

Figure 3. Probability of Jet Aircraft Contrail Formation as a Function of Pressure and Temperature. Solid lines are empirically derived curves of contrail probability (percent). Dashed lines are theoretically derived curves of minimum relative humidity (percent) required for contrail formation.

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Chapter 4

CONTRAIL-FORMATION GRAPH FOR PROPELLER AIRCRAFT

4.1 Introduction

In the case of jet exhaust trails, the parameters which determine the formation of a saturated wake (p, T, RH, W/H) are independent of the aircraft type and fuel consumption rate. With conventional propeller aircraft, however, although all the water vapor is injected into the wake, a significant portion of the heat is dissipated outside the wake in the form of heat losses from the radiator and mechanical losses from the propeller. The exact amount lost in this manner varies with the type of aircraft and the conditions under which it is operating. It is generally assumed to run 20 to 40 percent. With turboprop aircraft the loss would be less. Such external heat losses result in higher relative humidities inside the wake and increase the probability of trail formation.

Since the value of W/H injected into the wake of propeller aircraft is not a constant, it is not feasible to construct theoretical curves showing the conditions under which contrails form. Instead, actual data were gathered from B-29 and B-36 aircraft, and empirical curves constructed. These curves apply primarily to multiengine aircraft flying under normal cruise conditions. Under conditions of excessive fuel consumption, such as climbing or operating near maximum altitude, there is an increased tendency for trail formation.

4.2 Propeller Aircraft Contrail-Formation Graph

The best graph for propeller aircraft proved to be similar to the graph for jet aircraft but displaced a few degrees to the right (Table 3 and Figure 4). The line of demarcation separating the new "Yes" and "Possible" regions is the jet aircraft 90 percent relative humidity line. The line of demarcation separating the new "Possible" and "No" regions is a line parallel to and 3°C to the right of the jet aircraft 100 percent relative humidity line--the R-line in AWS TR 105-112 (AWS, 1953).

As mentioned previously, the operation of a propeller aircraft near its maximum altitude results in increased contrail probability. To compensate for this effect, it is recommended that the two bounding curves be broken at a point 5000 feet below the operating ceiling of the aircraft, and drawn through temperature values at the operating ceiling 5°C warmer than their former positions. An example of this adjustment for a propeller aircraft with an operating ceiling of 45,000 feet is shown in Figure 5.

4.3 Evaluation of the Formation-Graph Accuracy

An evaluation of the graph in Figure 4 was carried out using a large quantity of B-36 data (AWS, 1953, Table 14). Only the propeller engines were tested. In the "Yes" area, there were 1459 positive contrail reports and 54 negative reports for an accuracy of 96 percent. In the "No" area, there were 3069 negative reports but only 92 positive reports for an accuracy of 97 percent. The contrail frequency in the area between the new "Yes" boundary line in Figure 4 (the jet aircraft 90 percent relative humidity line) and the jet aircraft 100 percent relative humidity line was 81 percent and between the 100 percent line and the boundary of the new "No" area was 44 percent.

Table 3. Critical Temperatures for Contrail Formation by Propeller Aircraft

Pressure (mb)	Temperature (°C) Left Boundary	Right Boundary
100	-56.0	-50.0
150	-52.3	-46.0
200	-49.6	-43.2
250	-47.4	-41.0
300	-45.6	-39.0
400	-42.7	-36.0
500	-40.3	-33.7
600	-38.4	-31.6
700	-36.8	-29.9
800	-35.2	-28.3
900	-34.0	-27.0
1000	-32.9	-25.9

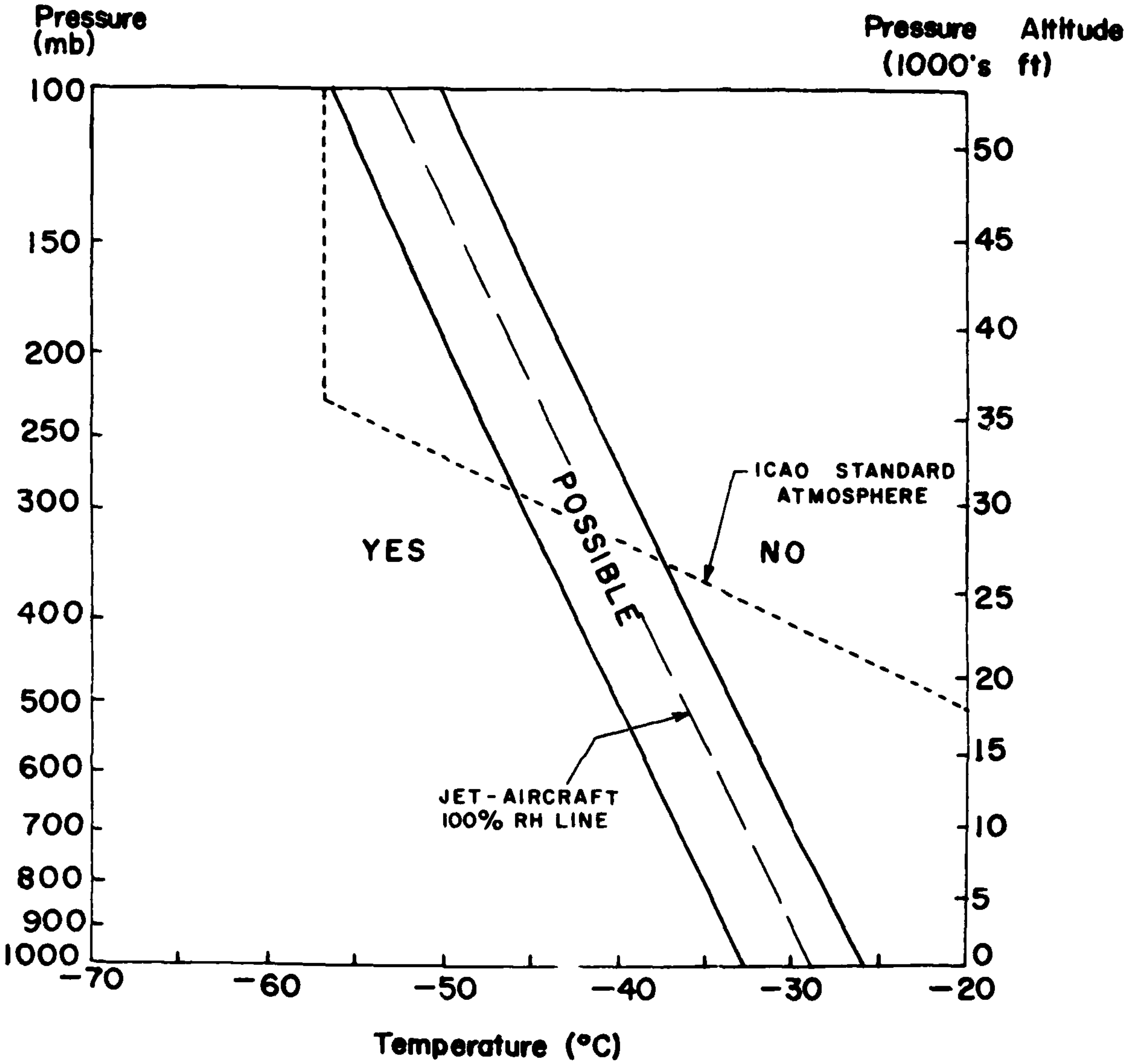

Figure 4. Propeller Aircraft Contrail-Formation Graph.

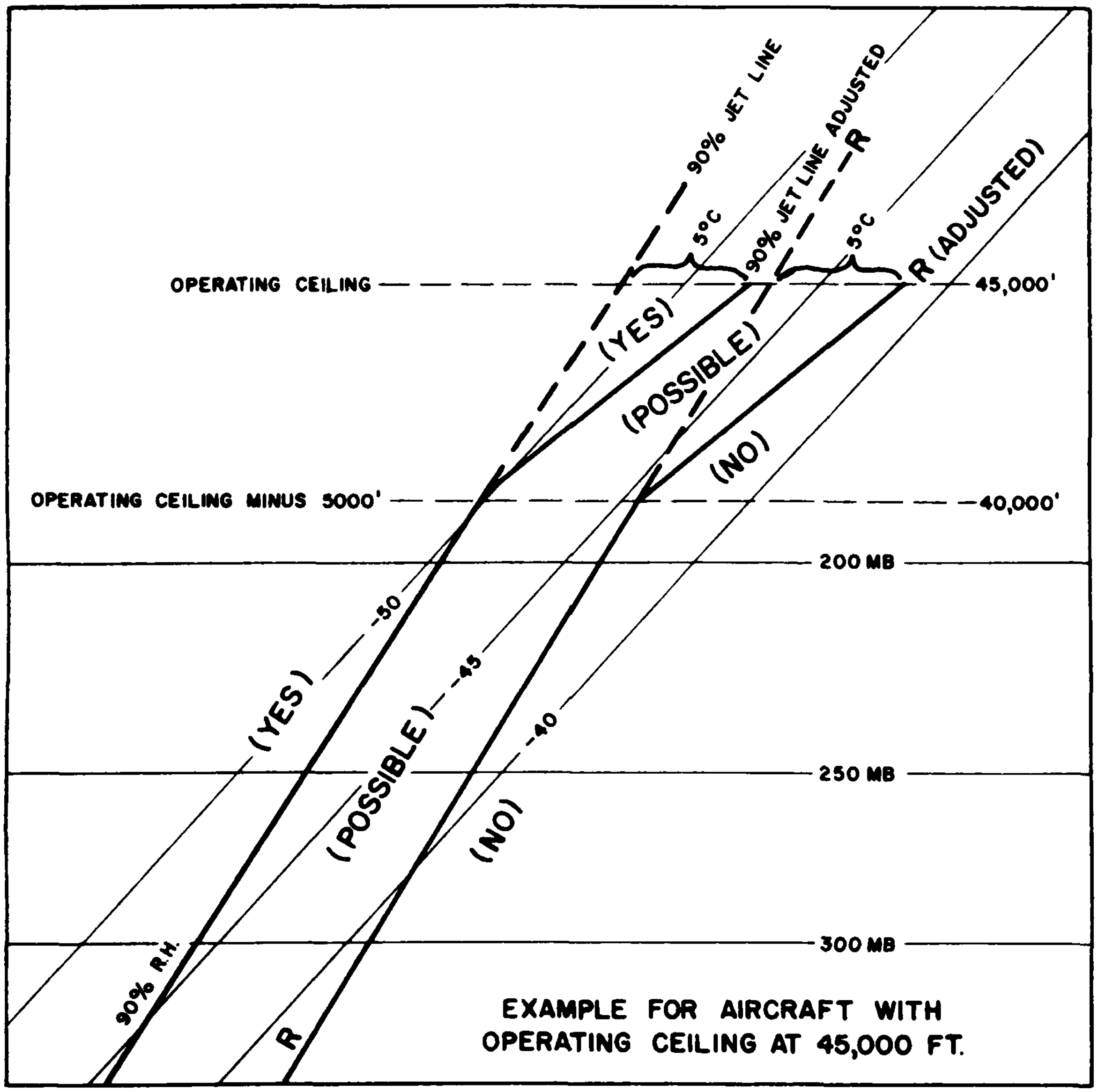

Figure 5. Modification of Propeller Aircraft Contrail Curves Near Operating Ceiling.

Chapter 5

POSSIBLE IMPROVEMENTS IN CONTRAIL FORECASTING

When humidity elements sufficiently responsive at low temperatures are developed for rawinsondes, the forecasting of contrails by these methods should improve. Meanwhile, several empirical methods of estimating the humidity parameter have been suggested, such as correlating the wind direction aloft with humidity or with contrail occurrences (Kern, 1956).

Pilie and Jiusto (1956) suggest that the assumed critical water content for visibility of a contrail is valid only for ideal illumination conditions and viewing angles. This effect may also greatly depend on the contrail particle size and type. For including these effects, theoretical or empirical corrections to the present curves might be feasible. One study (Wilson, 1978) discussed a computer program to calculate the contrasts of a smoky rocket exhaust trail in various prevailing weather conditions and estimated the threshold contrast necessary for the plume to be visible to an average observer. Two kinds of observations were considered: side-on, in which the rocket that produced the smoke trail is assumed to be flying horizontal and at right angles to the observer, and head-on, in which the rocket is assumed to be flying directly at the observer.

Another study suggested that not all the energy from fuel combustion immediately appears as heat. Thus, condensation (and the almost immediate ice nucleation) may occur before all the heat from combustion has been manifested. If the ambient condition is saturated with respect to ice, the contrail will persist (Knollenberg, 1972). This could allow contrails to appear in the "No" region of Figure 1 as is sometimes observed (Knollenberg, 1972; Konrad and Howard, 1974).

Chapter 6

SUMMARY

6.1 Forecasting Jet Aircraft Condensation Trails

Figures 1 and 2 can be used to issue a yes-or-no contrail forecast in any area and any season from the surface of the earth to the 40-mb surface. The major weakness is the difficulty in accurately forecasting the temperature and relative humidity, the former because of the large horizontal temperature gradients that occasionally occur in the upper atmosphere, the latter because relative humidity is rarely measured at the low temperatures where contrails occur. Past studies indicate best results are obtained by assuming a relative humidity near 40 percent, except when near the tropopause or clouds where the value should be 70 percent.

To avoid the above temperature and relative humidity uncertainties, empirically determined contrail probability curves (Figure 3) enable the forecaster to state the probability of contrail formation for a given value of pressure and temperature. These curves do not permit a yes-or-no type of forecast. Also, they are presently available only between the 350- and 150-mb pressure surfaces.

Both the theory and the results of a detailed and extensive test program indicate that a change in engine power setting has no affect on whether or not contrails form. There is some indication that an increase in power setting results in a somewhat more intense trail. The same conclusions can be drawn with regard to other factors affecting the rate of fuel consumption such as the type of jet aircraft, and flight altitude (climbing, level flight, or descending). Only contrail intensity is affected, not contrail probability.

6.2 Forecasting Propeller Aircraft Condensation Trails

Although all the combustion water vapor is injected into the wake of propeller-driven aircraft, from 20 to 40 percent of the heat is dissipated outside the wake in the form of heat losses from the radiator and mechanical losses from the propeller. This results in a higher relative humidity in the wake and a greater probability of contrails. The percentage of heat loss is not constant; it varies somewhat with aircraft type, altitude, operating efficiency, etc.

Because of the variation in the ratio of water vapor to heat in the exhaust gas, empirical contrail-forecasting curves were determined for the most important case--multiengine aircraft in normal flight. The curves are shown in Figure 4. They were found to be parallel to the jet curves but displaced a few degrees to the right. Although most of the data were obtained from between 25,000 and 40,000 feet, the curves were arbitrarily continued parallel to the jet curves from 1000 to 100 mb.

When flying near the operational ceiling, the water vapor to heat ratio in aircraft exhaust increases, thus increasing contrail probability. A correction for this effect is given in Section 4.2 and is illustrated in Figure 5. Climbing also results in a greater tendency for contrail formation by propeller aircraft.

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