AIR LIQUEFACTION BOUNDARIES EXPERIMENTALLY DETERMINED FOR THE BALLISTIC RESEARCH LABORATORIES' SUPERSONIC AND HYPERSONIC WIND TUNNELS

ARMY BALLISTIC RESEARCH LAB ABERDEEN PROVING GROUND MD

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by

Maurice A. Sylvester

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BALLISTIC RESEARCH LABORATORIES
ABERDEEN PROVING GROUND, MARYLAND

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RDT&E Project No. 1P222901A201

A B E R D E E N P R O V I N G G R O U N D, M A R Y L A N D

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MASylvester/sjw
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ABSTRACT

The boundaries for the onset of air liquefaction have been experimentally determined for the Ballistic Research Laboratories' (BRL) Wind Tunnels. These boundaries indicate the regions where the liquefaction of air constituents has an effect on the flow properties in the test section. The boundaries were determined by making static and total head pressure measurements (with varying temperature) throughout the appropriate Mach and Reynolds number ranges of both the supersonic and hypersonic wind tunnels. The results show that air liquefaction occurs near the theoretical boundary (Clausius-Clapeyron) for Mach numbers 4.75 and 5.00 with little, if any, supersaturation. However, as the Mach number increases to 6.0, 7.5 and 9.2, there is an increase in the amount of supersaturation before liquefaction occurs, and at a given Mach number, the difference between the experimental and theoretical temperature at the onset of liquefaction is about the same at all pressure levels tested. These results may allow a relaxation of our stagnation temperature requirements by an amount which would be of considerable operational significance at M = 9.2.

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LIST OF SYMBOLS

M	Mach number
P	Pressure
P_o	Stagnation pressure
P_s	Free stream static pressure
P_T	Free stream total pressure behind normal shock
Re	Reynolds number
T	Free stream temperature
T_{cc}	Clausius-Clapeyron prediction (extrapolated) for air saturation temperature
X,Y,Z	Coordinates for probe location in hypersonic tunnel

1. INTRODUCTION

The liquefaction of air in wind tunnels and its effects on flow properties and model test results has attracted a considerable amount of attention since high Mach number tunnels first received serious consideration. During the early 1950's, several investigators studied the problem both theoretically and experimentally,[1-7*] and the equilibrium-saturated expansion theory as used by Buhler and others has proved to be quite useful in indicating trends after the onset of liquefaction, but not in predicting the degree of supersaturation before liquefaction commences.

Because the effects of air liquefaction on test results of practical model configurations is a very complex subject and unlikely to be readily resolved, the emphasis in later experimental studies has been put on defining the regions where tests could possibly be conducted in liquefaction free flow. An obvious way to accomplish this is to increase the stagnation temperature sufficiently, but this is not always possible because of material or facility limitations. If, however, appreciable supersaturation can be shown to exist, a given facility may be able to operate at a higher Mach number or at lower stagnation temperature, with resulting time saving and possible simplification of model designs. Thus, it becomes of considerable practical significance to determine the degree of supersaturation which exists in a particular wind tunnel facility.

During the late 1950's and early 1960's, as more high Mach number wind tunnels became available, a number of experimental investigations were made to determine the amount of supersaturation which could be expected in hypersonic wind tunnels. The results of some of these tests (as well as earlier tests) were summarized by Daum[8] and, on the basis of this summary, an "onset of condensation" boundary was proposed to indicate the amount of supersaturation which could be expected before the onset of

Superscript numbers denote references which may be found on page 44.

liquefaction at various pressure levels. This boundary indicated that no supersaturation would occur at the higher test section static pressure levels and that increasing amounts would occur, before the onset of liquefaction, as the pressure was decreased.

The present investigation was made to determine the air liquefaction boundaries for the Ballistic Research Laboratories' (BRL) supersonic and hypersonic wind tunnels, with emphasis on the hypersonic tunnel. The boundaries were obtained by making static or total head pressure measurements with varying temperature and/or Mach number. "Characteristic" total head pressure variations at the onset of liquefaction are shown for several axial and vertical probe locations in the hypersonic tunnel test section. The boundaries are compared with those of Daum, and an operational chart for liquefaction free flow in the test section at M = 7.5 and 9.2 is presented for the BRL hypersonic wind tunnel.

2. TEST EQUIPMENT AND INSTRUMENTATION

The tests were conducted in the BRL Supersonic No. 1 and Hypersonic No. 4 tunnels. Photographs of these tunnels are shown in Figures 1 and 2, and they are described in detail in Reference 9.

The supersonic tunnel is of the continuous flow, closed circuit, variable density type and has a flexible nozzle for obtaining a normal range of Mach numbers from approximately 1.50 to 5.00. However, for these tests only Mach numbers above 4.5 were used, and the range was extended to M = 5.50. The test section size is 13 inches wide by 15 inches high, and the approximate length from the centerline of the viewing window to the nozzle throat is about 78 inches.

The hypersonic tunnel is also of the continuous operating type and has three interchangeable axisymmetric nozzles with nominal Mach numbers of 6.0, 7.5 and 9.2. Although the Mach number varies somewhat with pressure and temperature, the nominal values only will be referred to in this report. The diameter of the usable portion of the jet in the free-jet-type test section is approximately 12 to 13 inches, and the lengths

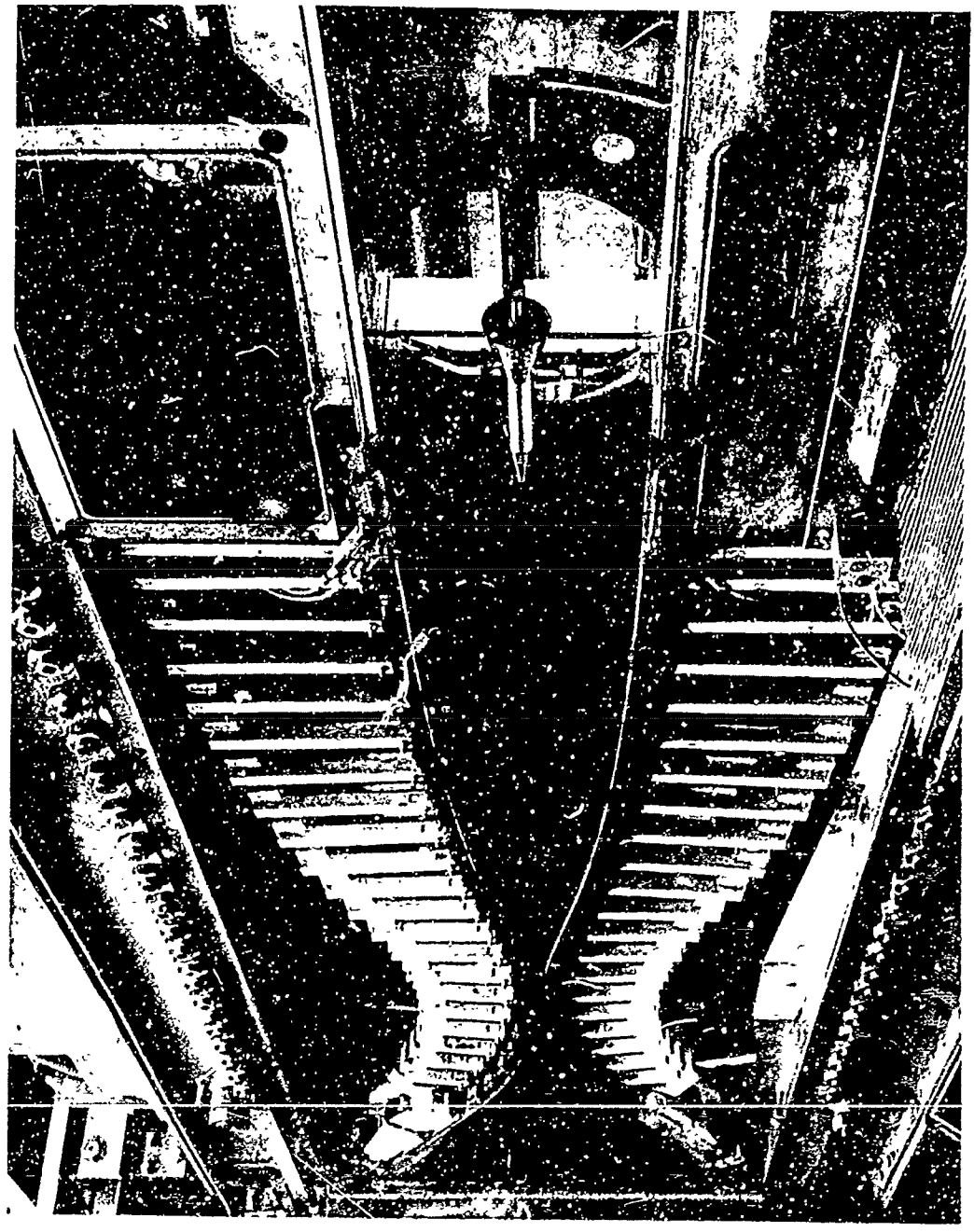

Figure 1. BRL supersonic tunnel No. 1 with sidewall removed

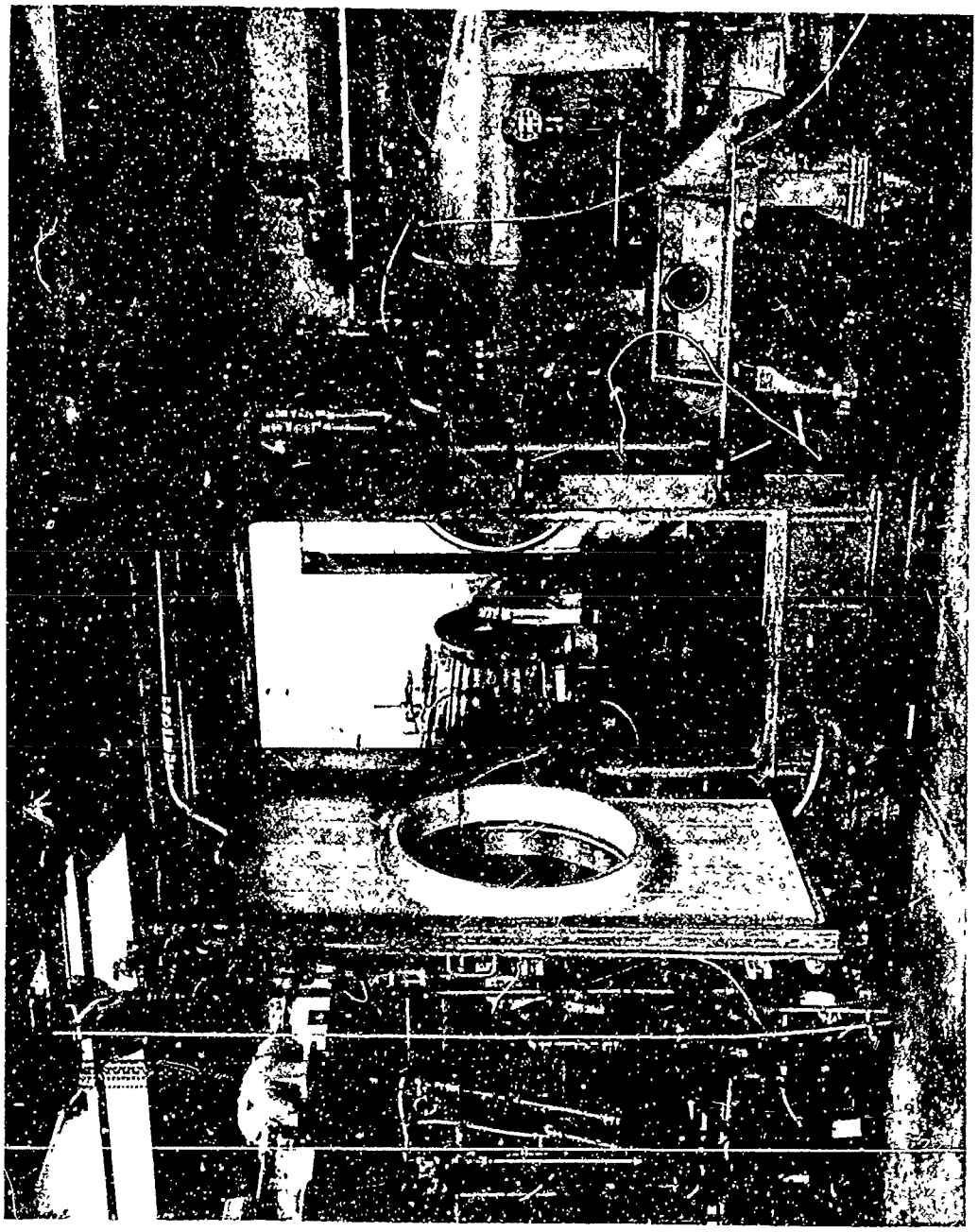

Figure 2. BRL hypersonic tunnel No. 4

from the centerline of the viewing window to the nozzle throats are about 91, 101 and 120 inches, respectively, for the M = 6.0, 7.5 and 9.2 nozzles.

The unit Reynolds numbers for the tests ranged from 0.08 to 1.00×10^6 per inch. No analysis was made of the wind tunnel air, but it is assumed to contain normal concentrations of the impurities typically found in the processed air of this type of facility. The specific humidity was maintained at a value of less than 0.0003 pound of water vapor per pound of air for all tests.

A static pressure orifice (0.052-inch diameter) was located on the centerline of the test section sidewall of the supersonic tunnel approximately 61 inches downstream of the nozzle throat. Static pressure orifices of 0.060-inch diameter were located near the exit at the top and bottom of each hypersonic nozzle 77, 86 and 105 inches from the throat for M = 6.0, 7.5 and 9.2, respectively. In addition, a flat-face total head tube with 0.125-inch outside diameter and 0.085-inch inside diameter was mounted on a movable support and could be moved to various positions in the test-section area of the hypersonic tunnel. The sign convention and coordinate system for the probe locations are shown in Figure 3.

The pressures were measured with absolute-type Statham pressure transducers with a full scale range of 0.5 psi for the static pressures and 5.0 or 25 psi full scale for the total head pressures. The absolute accuracy of the pressure measurements was 0.25 percent of full scale reading. However, during a given test run the relative accuracy from point to point was considerably better and of the order of 0.05 percent full scale. The stagnation temperature was measured in the supersonic tunnel with an iron-constantan thermocouple with an accuracy of $\pm$ 3 $^{\circ}$F and in the hypersonic tunnel with a chromel-alumel thermocouple with an accuracy of $\pm$ 5 $^{\circ}$F or 1 percent of reading, whichever is greater.

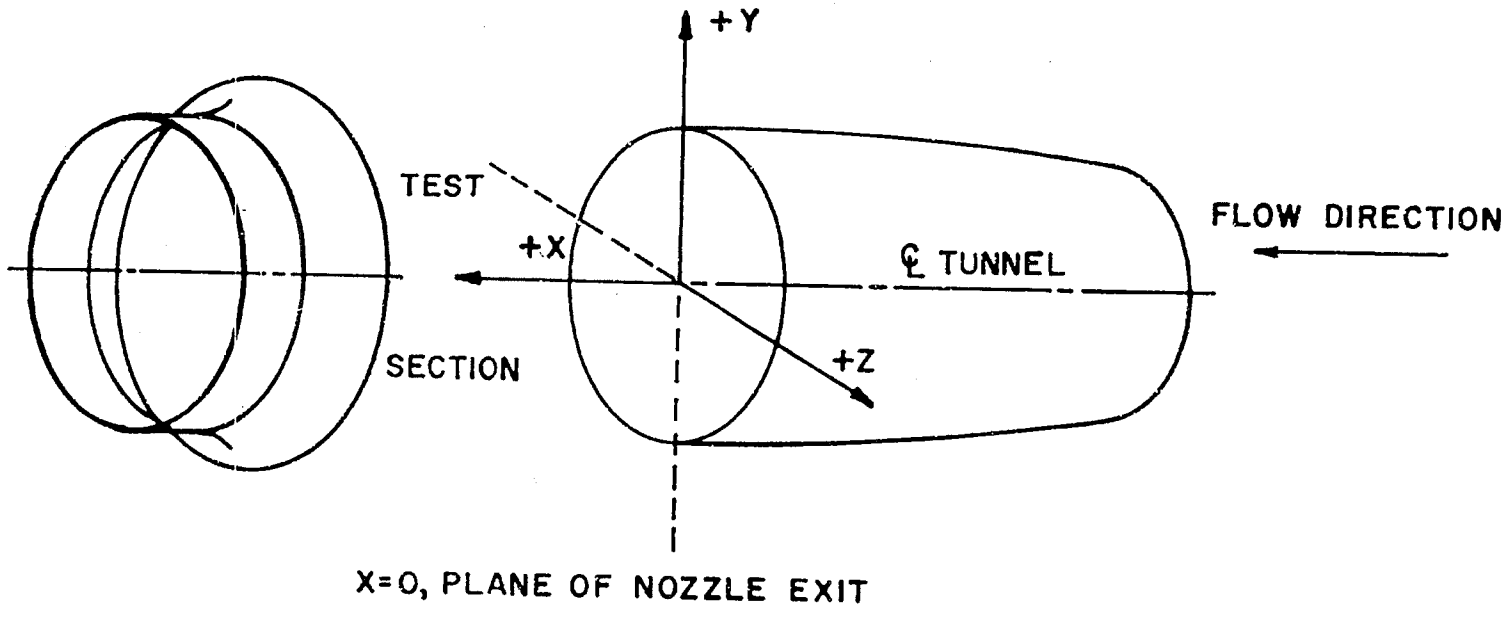

Figure 3. Sign convention for hypersonic tunnel

3. TEST PROCEDURE

Previous experimental studies have established the theoretical air saturation curve as a useful reference for comparison of results, and this curve influenced the test procedure for the present tests. Data on this saturation curve for air are indicated in Figure 4, which shows the Clausius-Clapeyron prediction, the Wagner calculation, and experimental data by Furukawa and McCoskey. Unfortunately, the region of major interest to wind tunnel groups is in the lower range of pressure and temperature where there is no experimental verification and the two available theories diverge. It should also be pointed out that the numerical values provided by the theories depend on experimentally determined constants. Unless otherwise indicated, references in this report to the saturation curve of air refer to the Clausius-Clapeyron data. The test procedure for both tunnels was designed basically to provide static or total head pressure measurements as a function of temperature so that the experimental data would intersect and extend into the regions on either side of the theoretical air saturation curve.

Typical static pressure variations at constant pressure and constant Reynolds number, calculated on the basis of isentropic flow relations (with no liquefaction), are shown in Figure 5a along with the pertinent operating limits of the supersonic tunnel and the theoretical air saturation line. The test procedure in this tunnel consisted of obtaining experimental static pressure data along calculated constant pressure or approximately constant Reynolds number lines similar to those shown. Since the stagnation temperature control for this tunnel was relatively small (70 - 110 $^{\circ}$F), it was necessary to change Mach number as well as stagnation temperature during the tests at constant pressure in order to obtain the data for any appreciable range of pressure and temperature.

The practical operating limits of interest in the hypersonic tunnel are shown in Figure 5b. In this tunnel the stagnation temperature could be varied sufficiently to provide pressure measurements to either side of the theoretical air saturation curve at a given Mach number. (Note, however, that this capability is marginal at M = 9.2. Actually, somewhat

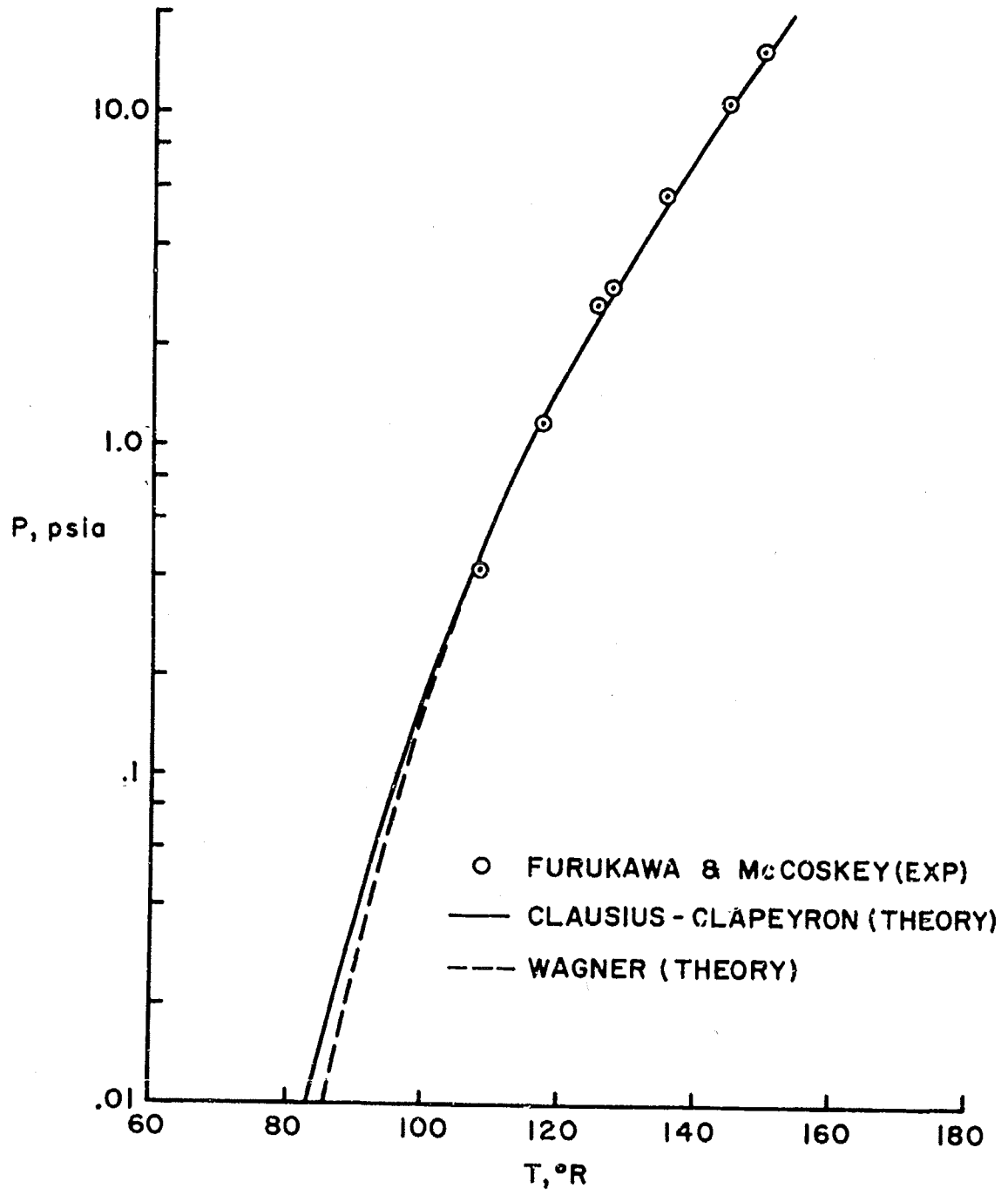

Figure 4. Coexistence line for air

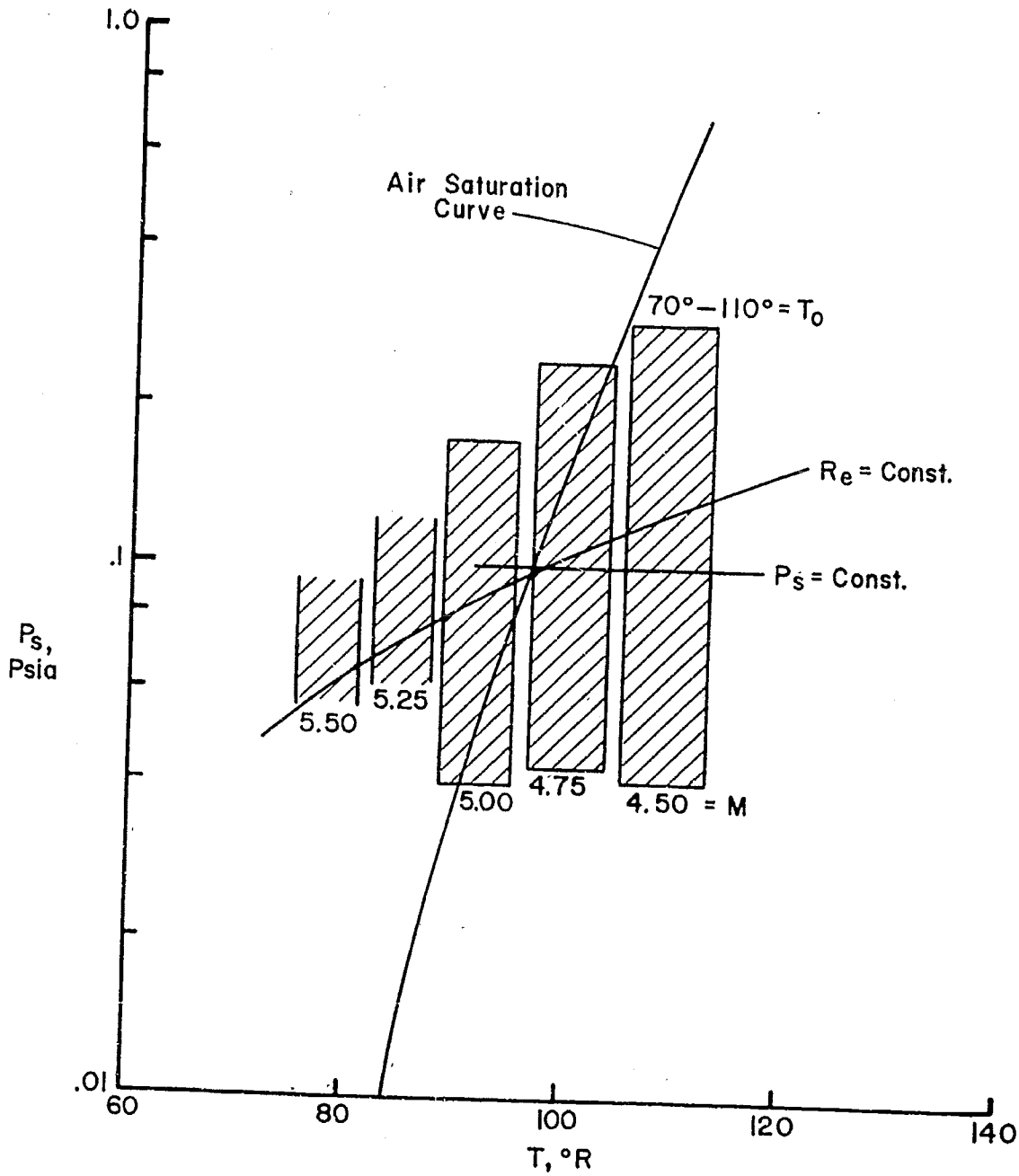

Figure 5a. Supersonic tunnel operating limits

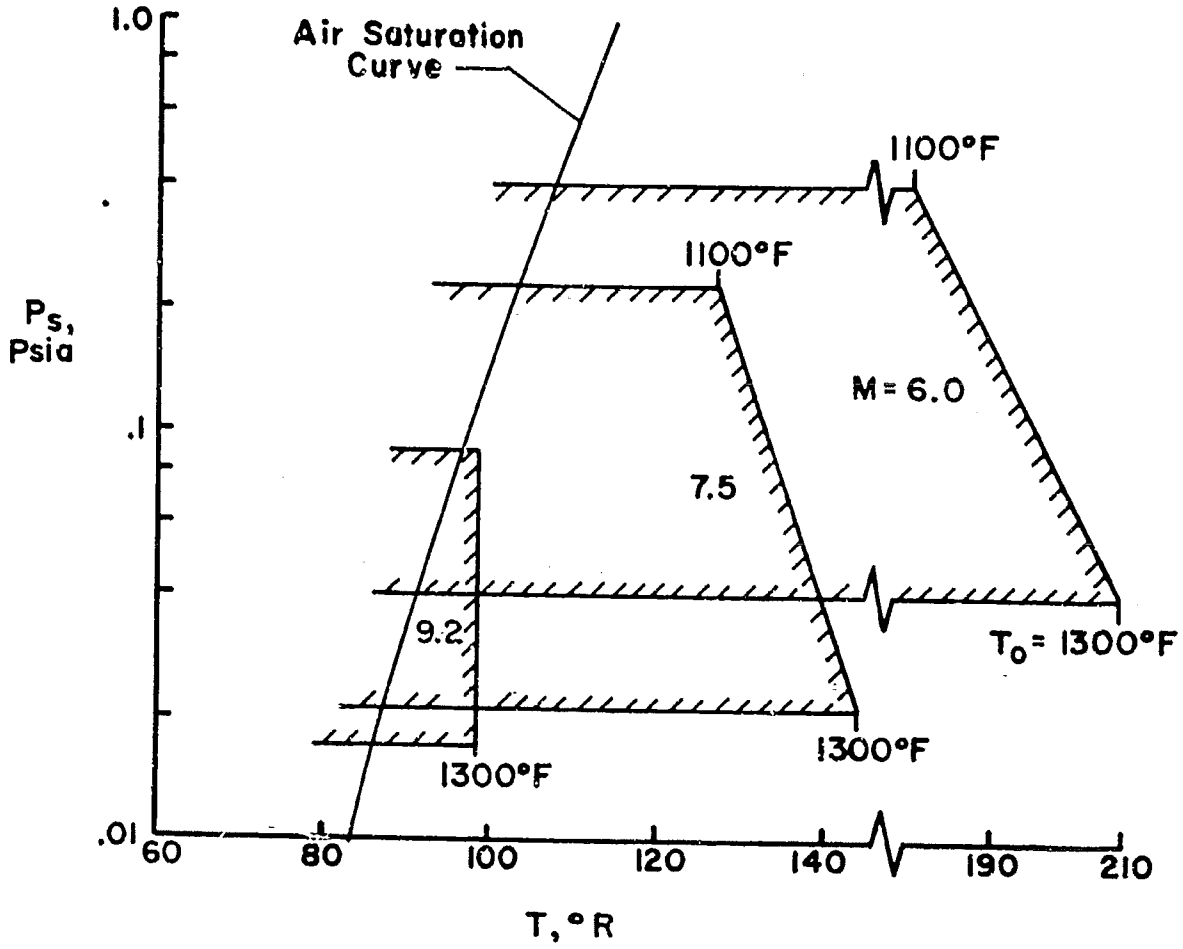

Figure 5b. Hypersonic tunnel practical operating limits

higher temperatures can be reached at M = 9.2 if sufficient time is available; this is the reason for referring to practical limits.) Therefore, the test procedure used in this tunnel was to make static and total head pressure measurements as the temperature was varied at constant stagnation pressure.

In most of the tests the stagnation temperature was varied (either increasing or decreasing) continuously at a rate not to exceed 5 ^{o}F per minute in the supersonic tunnel or 20 ^{o}F per minute in the hypersonic tunnel. Pressure readings were recorded at approximately 10 to 20-degree increments of the stagnation temperature. However, in a few instances and particularly at low pressures, the adequacy of the pressure response time, for the previous method of testing, was checked by stabilizing the temperature for several minutes before recording the data.

4. RESULTS AND DISCUSSION

4.1 Determination of Onset of Liquefaction

Typical experimental pressure measurements as functions of temperature are shown in Figures 6a - 6d for the supersonic and the hypersonic tunnels and may be utilized in describing the method of determining the onset of liquefaction. Additional data of a similar nature were obtained throughout the Mach and Reynolds number ranges of the tunnels, but with emphasis on the hypersonic tunnel.

In the supersonic tunnel (Figure 6a), experimental static pressure measurements made at a fixed location on the tunnel sidewall are compared with the calculated values (without liquefaction) expected for the Mach numbers shown. The onset of liquefaction is defined as the point where the experimental pressures deviate from the calculated values. In this case, as the temperature decreases, the deviation takes the form of an increase in the static pressure over that which was calculated. This increase in pressure, resulting from heat released to the air stream by the liquefaction process, has been observed by other investigators and is predicted by the saturation-expansion theory. It should be noted

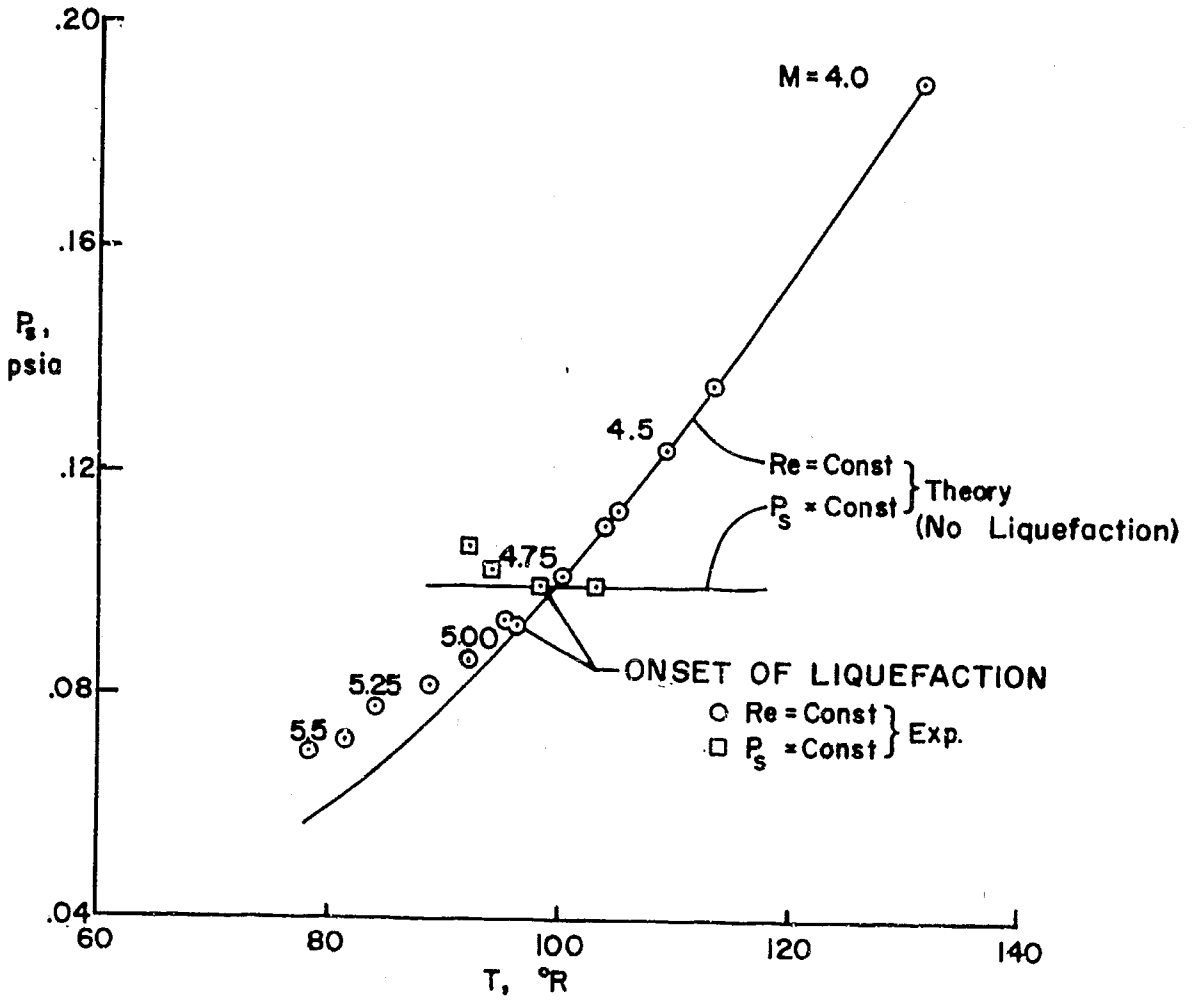

Figure 6a. Determination of onset of liquefaction in the supersonic tunnel

that, while the experimental test section pressures plotted on Figure 6a are actual measured values, the corresponding test section temperatures are computed from the stagnation values using isentropic flow relationships. While this gives valid values for the temperature when no liquefaction occurs, the values in the region of liquefaction are undoubtedly somewhat in error because of the heat added by the liquefaction process. However, since it is the point of onset of liquefaction which is of interest in the present study, this discrepancy is of no particular significance. The use of the calculated temperature values was necessary to provide a common basis for plotting the results from tests at different Mach numbers. It might also be suggested that the changes in Mach number and consequently velocity gradient could affect the interpretation of the results, particularly with respect to any supersaturation present. However, the changes in velocity gradient are relatively small and, as will be shown later, little, if any, supersaturation occurs at the Mach numbers encountered in the supersonic tunnel.

The determination of the onset of liquefaction in the hypersonic tunnel (Figures 6b - 6d) was somewhat more direct as a result of the ability to vary the stagnation temperature sufficiently to conduct the tests at a relatively constant Mach number. The figures show typical experimental static and total head pressure ratios as functions of the measured stagnation temperature at Mach numbers 6.0, 7.5 and 9.2 and stagnation pressures of 600, 644 and 1220 psia, respectively. The static pressure was measured on the top and bottom walls 0.875 inch upstream of the nozzle exit, and the total head probe was located at the same axial position and 5 inches below the centerline of the tunnel. As the stagnation temperature is reduced, the pressure ratios change somewhat (but nearly linearly) as a result of the changes in Reynolds number and the consequent effects on the tunnel nozzle boundary layer. However, when the temperature is reduced sufficiently to encounter liquefaction, a sharp rise in the static pressure ratio is noted. The total head pressure, on the other hand, is sharply reduced at this same temperature.

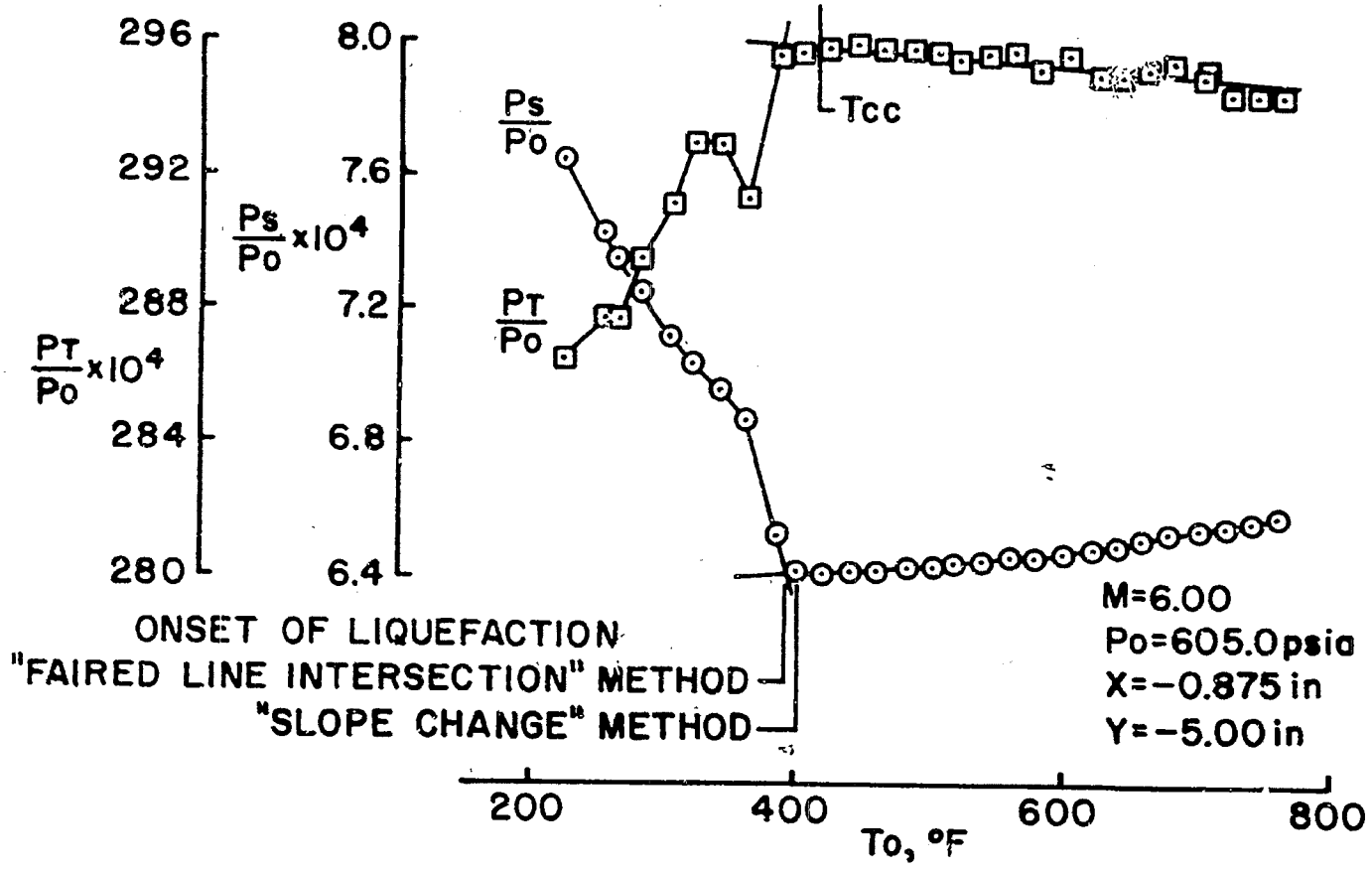

Figure 6b. Determination of onset of liquefaction in the hypersonic tunnel

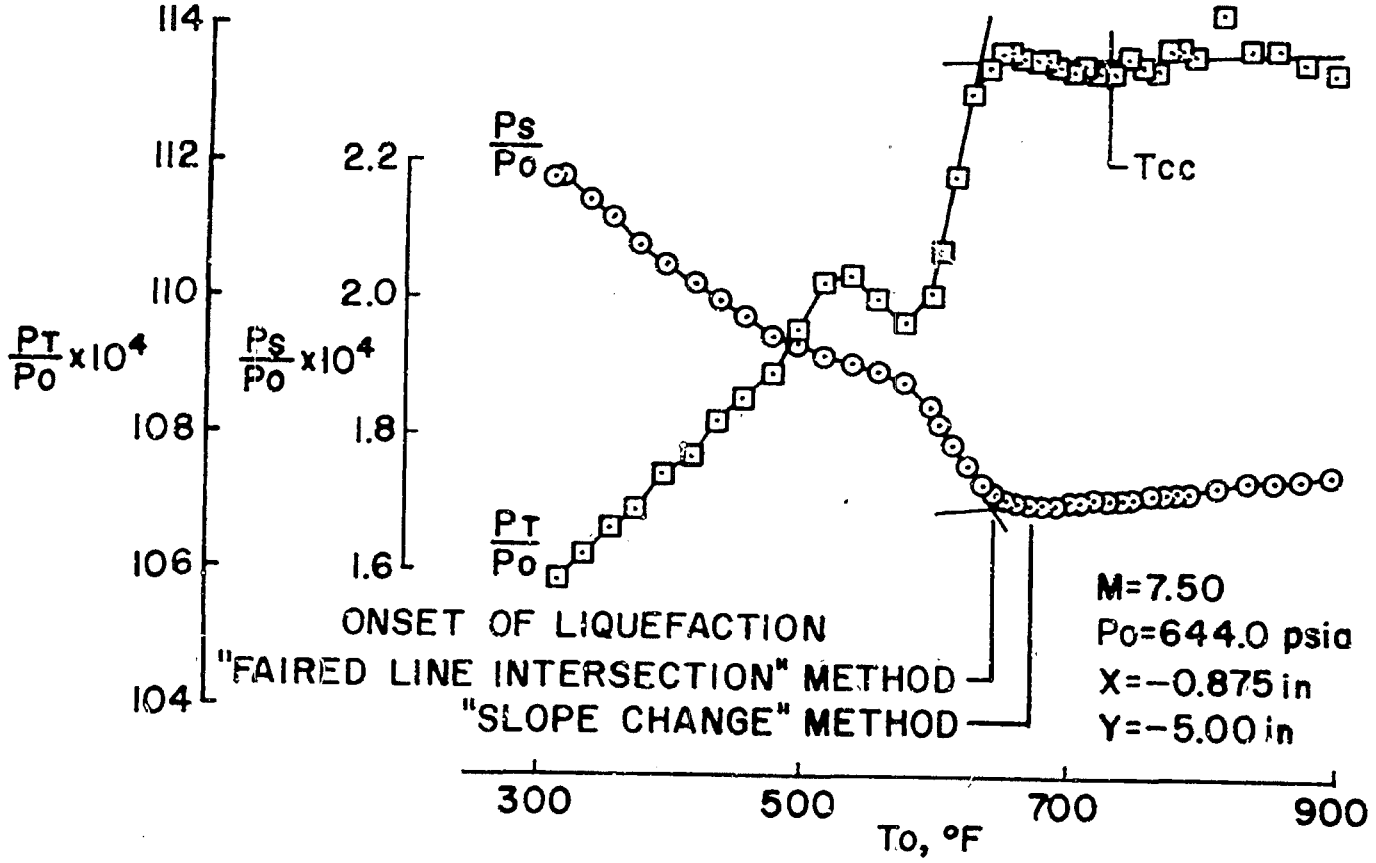

Figure 6c. Determination of onset of liquefaction in the hypersonic tunnel

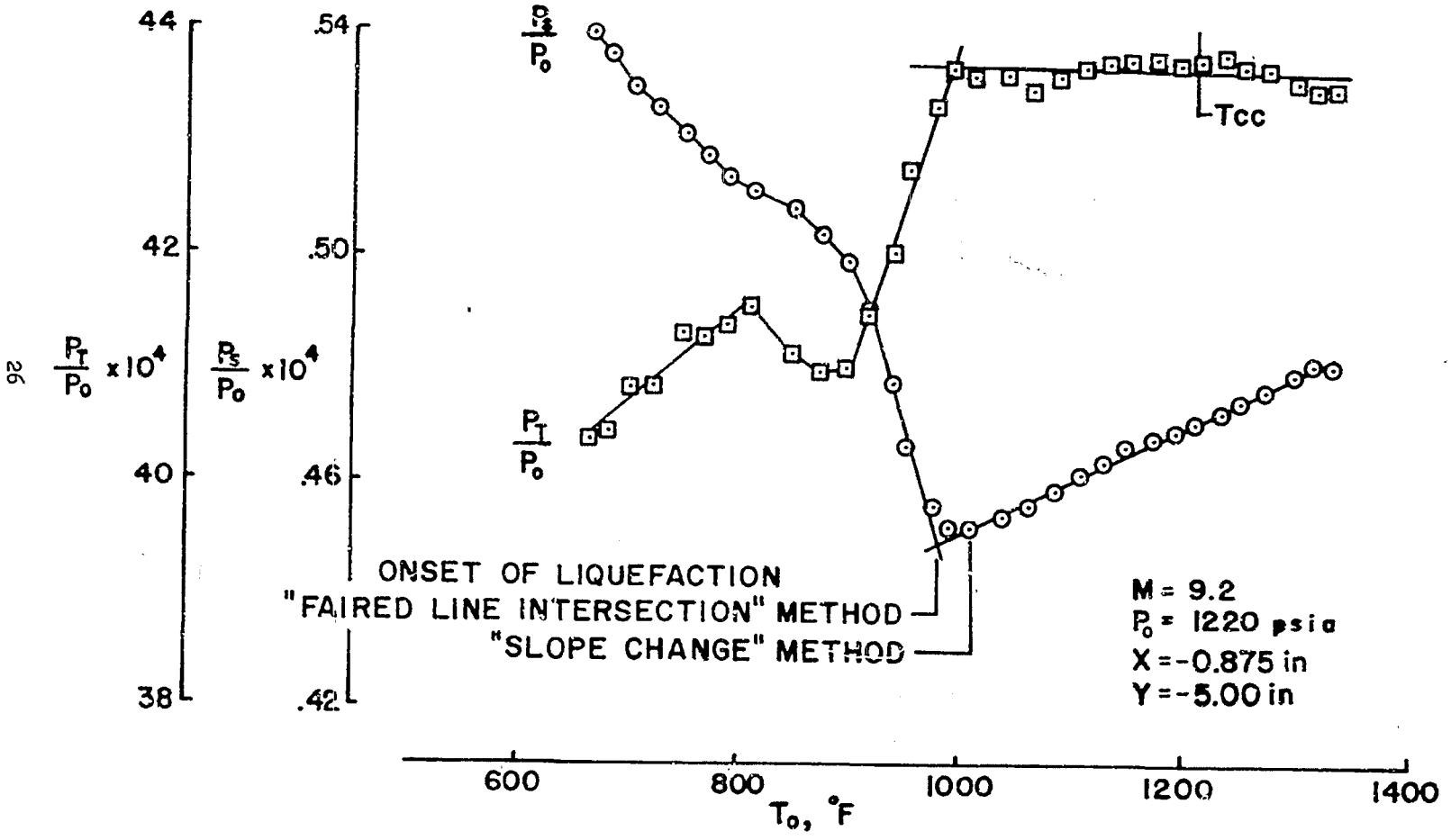

Figure 6d. Determination of onset of liquefaction in the hypersonic tunnel

This reduction was, at first, somewhat surprising since on the basis of Daum's results an increase had been expected. However, as will be shown later, the "characteristic" shape of the total head pressure variation is dependent on the probe position in the flow field. It is noted that the maximum stagnation temperature of the tests is well above that indicated by the theoretical air saturation point in each case as shown by reference to the Clausius-Clapeyron prediction, T_{cc}.

For the hypersonic tunnel tests, the onset of liquefaction is defined in two ways. First, a "faired line intersection" method which consists of fairing straight lines through the relatively linear portions of the data on either side of the region where the pressure ratios change abruptly, and defining the intersection of these lines as the onset of liquefaction. Second, a "slope change" method which defines the onset of liquefaction as the last data point obtained (as the temperature decreases) before the data deviates from the trend established at higher temperatures. An examination of the typical data on Figures 6b - 6d indicates that these two methods can give somewhat different answers, particularly in the case of the static pressure ratio where the slope change method invariably gave a somewhat higher temperature for the onset of liquefaction than did the faired line intersection method. (This difference is more pronounced at M = 7.5 and 9.2 than at M = 6.0.) It is suspected that the slight "rounding off" of the static pressure ratio (and in some cases the total pressure ratio) in the critical area is the result of some undetected characteristics of the instrumentation and test technique, although a similar effect has been noticed by other investigators. Although the points of onset of liquefaction are only labeled on the static pressure ratio plots, the same methods of determination were also applied to the total head pressure ratio plots.

The overall accuracy of a particular determination of the stagnation temperature at the onset of liquefaction is estimated to be approximately $\pm 10^{\circ}$ for M = 4.75 - 6.00 and $\pm 20^{\circ}$ for M = 7.5 and 9.2.

4.2 Effect of Total Head Probe Position on "Characteristic" Pressure Variation

Most of the results in the hypersonic tunnel were obtained with the total head probe near the nozzle exit ($x = -0.875$ inch) and 5 inches below the tunnel centerline, and the sample data just discussed in Figures 6b - 6d are typical of the data trends observed. A few tests were made, however, with the total head probe in different vertical and axial positions to determine whether the results obtained near the nozzle exit were representative of those throughout the test section area. During these tests, it was found that the "characteristic" total head pressure ratio variation persisted only as long as the probe was positioned in the flow outside of the boundary layer, but that when positioned within the boundary layer the trend in this pressure ratio reversed and showed an increase at the onset of liquefaction. This effect of the probe location is shown in Figure 7a where the total head pressure ratios are plotted for several vertical probe positions and for a constant axial position near the nozzle exit. The vertical scale is shown only for the lower plot, and a reference value is provided for the others. The results are for a Mach number of 9.2 and a stagnation pressure of 1464 psia. They clearly show the reversal in the pressure ratio trend at the onset of liquefaction as the probe position varies from the tunnel centerline ($y = 0$) to within the boundary layer. In addition, near the edge of the boundary layer (defined by a decrease in the total head pressure ratio), the variation in pressure ratio is very small and suggests that at a particular location in this vicinity there might be no variation at all.

The reasons for these changes in the total head pressure ratio trends are not entirely clear. However, it might be suggested, that as the probe nears the tunnel wall, the total head pressure ratio behavior at the onset of liquefaction should approach that of the static pressure ratio which exhibits a rise. The reversal and elimination of the total head pressure variation near the edge of the boundary layer is undoubtedly associated with the different characteristics of the free stream and

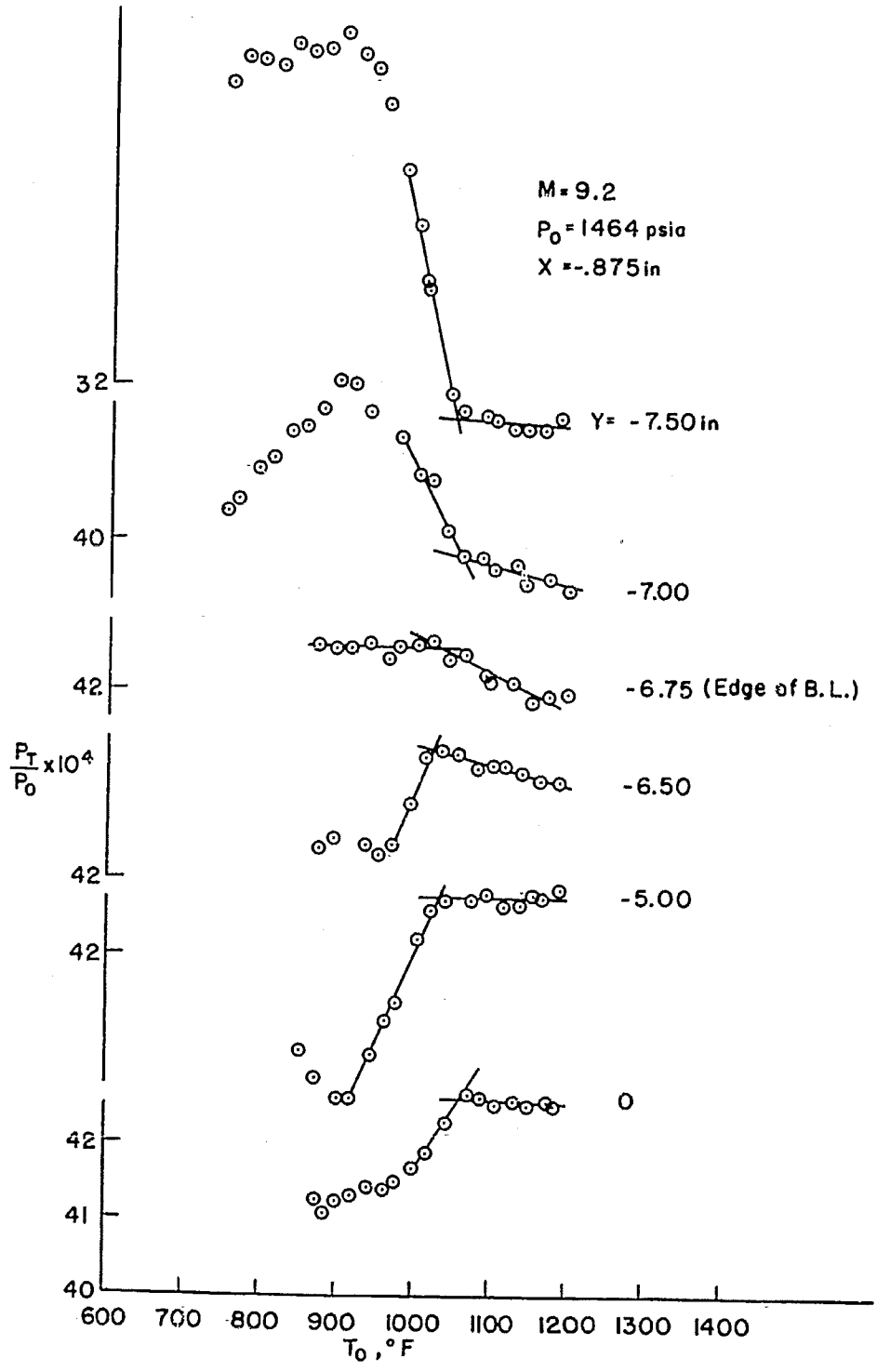

Figure 7a. Effect of probe vertical location on total head pressure variation at the onset of air liquefaction

boundary layer flows. The free stream contains liquid or frozen particles after the liquefaction process commences and the effect of these particles as they pass through the conditions associated with the strong probe bow shock is a complex process with the net result being a total head pressure decrease. The boundary layer flow, however, (because of the higher temperature) has a decreasing concentration of liquefied particles as the boundary layer is penetrated. Then the increase in pressure on the boundary layer (due to heat added by the liquefaction process in the free stream) apparently, at first, offsets and then, nearer the wall, dominates the total head pressure ratio trend.

In any case, the results of Figure 7a clearly show that the "characteristic" total head pressure variation depends on the probe position. It is also obvious that, when using this method of detection for the onset of liquefaction, the total head probe should not be positioned near the edge of the boundary layer because of the lack of sensitivity to the liquefaction process.

Total head pressure ratio variations for the same test conditions but for three different axial positions of the probe, near the nozzle exit (X = -0.875) and at 10-inch intervals downstream, are plotted in Figure 7b for a constant vertical probe position of Y = -5 inches. These data show trends in the total head pressure ratio at the onset of liquefaction similar to those discussed previously in Figures 6b - 6d when the probe was positioned well outside the boundary layer.

4.3 Effect of Probe Position on the Onset of Liquefaction

The stagnation temperature at the point of onset of liquefaction was determined for each of the hypersonic test runs by using one of the two methods outlined previously with emphasis on the "faired line intersection" method applied to the total head pressure ratio variation. Although the majority of the data were taken with a fixed total head probe position, a few runs (the characteristics of which were described in Section 4.2) were made with the probe at different vertical and axial locations in the test section area. The primary purpose of these runs

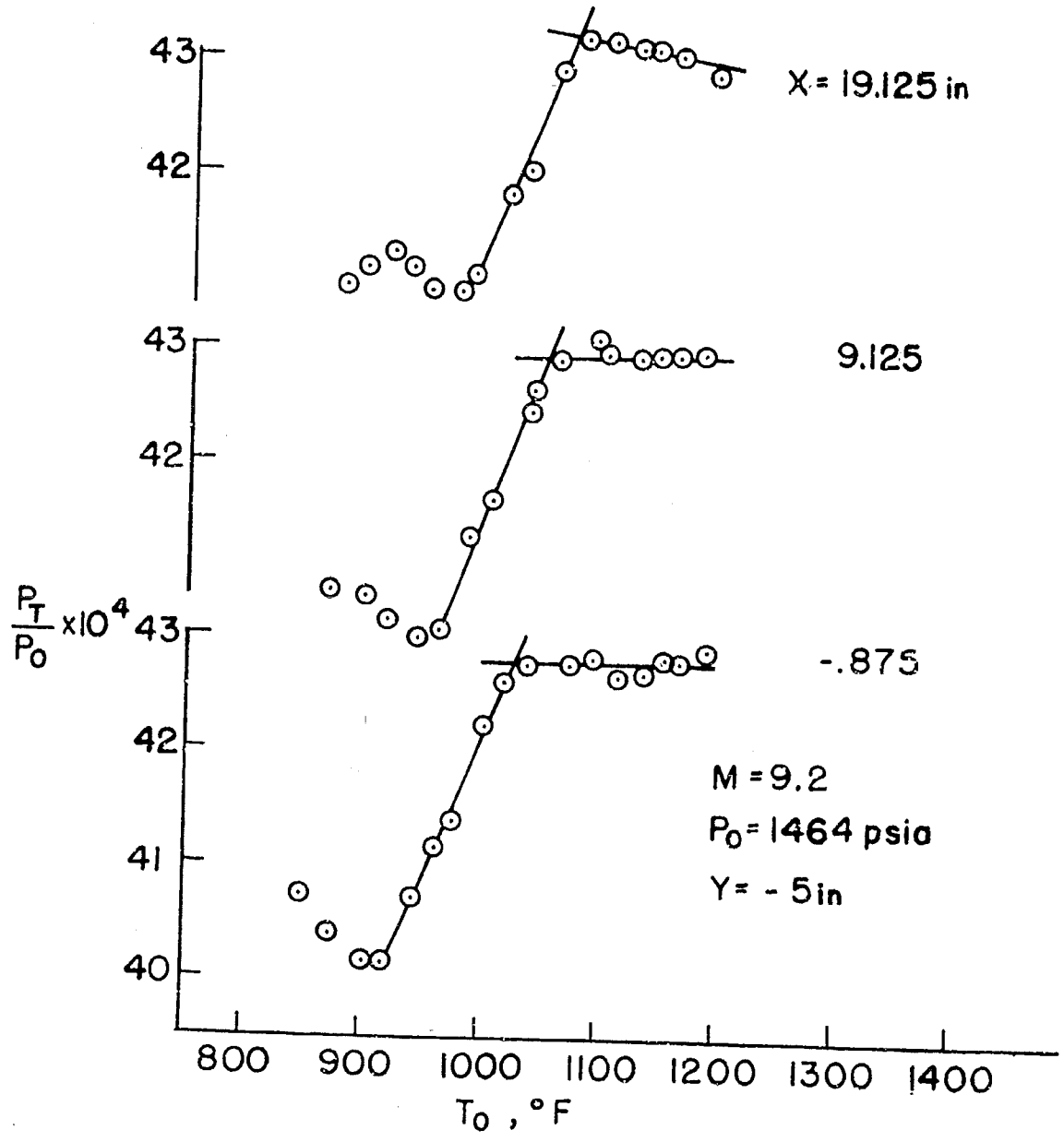

Figure 7b. Effect of probe axial location on total head pressure variation at the onset of air liquefaction

was to determine whether the fixed location data were representative for the test section region in general. The results of these tests are shown in Figures 8a - 8b for Mach numbers of 6.0 and 9.2 and for two different stagnation pressures. Figure 8a shows that, at Mach number 6.0 and at constant P_o, differences in the stagnation temperature at the onset of liquefaction are only slightly greater than the expected data accuracy, and no significant trends are discernible for the three different axial positions, X, and two different vertical positions, Y. In addition, the onset of liquefaction determined from the static pressure ratio at X = 0.875 on the wall agrees well with the total head probe data. There is, of course, a noticeable difference in the critical stagnation temperature values for the two different stagnation pressure levels of 160 and 605 psia, and this will be discussed in a later section. Similar data are shown in Figure 8b for Mach number 9.2, and the results, especially on the centerline Y = 0, are also comparable in that no significant effect of probe position is indicated. This is somewhat surprising at M = 9.2 since there is an appreciable amount of supersaturation present (as will be shown later), and one might expect a collapse of the supersaturated state at a higher temperature after the somewhat greater time interval required to reach the downstream position.

The off-centerline data (Y = -5) for both Mach numbers (Figures 8a and 8b) do appear to show a small but persistent upward trend of the temperature for onset of liquefaction as the probe is moved downstream. However, this trend is only within the range of the data accuracy. (The data in Figure 8b for M = 9.2 and P_o = 1464 psia were obtained from the basic data plot of Figure 7b where, of course, this apparent trend is also noticeable.)

Both of the preceding figures (8a and 8b) present data obtained at different axial positions well outside of the boundary layer. Figure 8c shows results of a vertical survey from the tunnel centerline (Y = 0), to well within the boundary layer. These results were obtained at Mach number 9.2, stagnation pressures of 395 and 1464 psia and near the

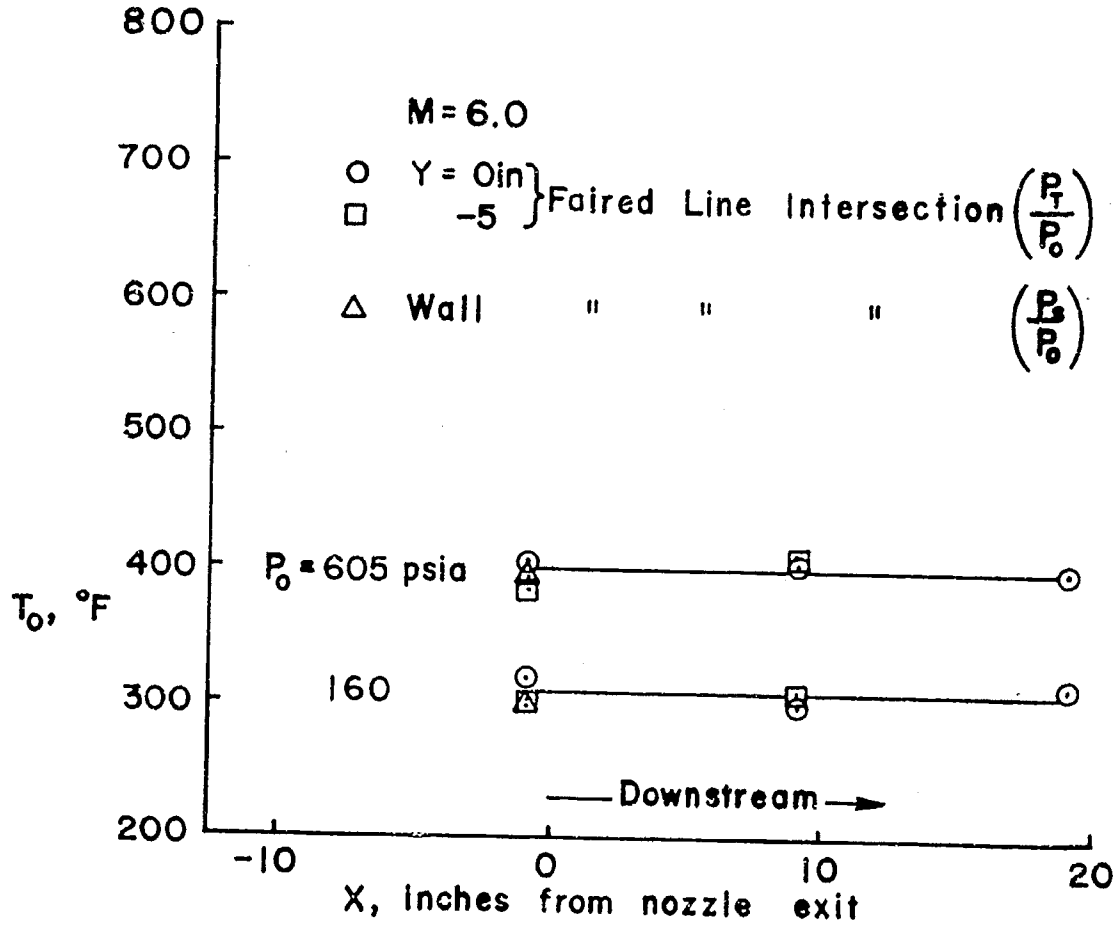

Figure 8a. Effect of probe axial position on stagnation temperature at onset of liquefaction

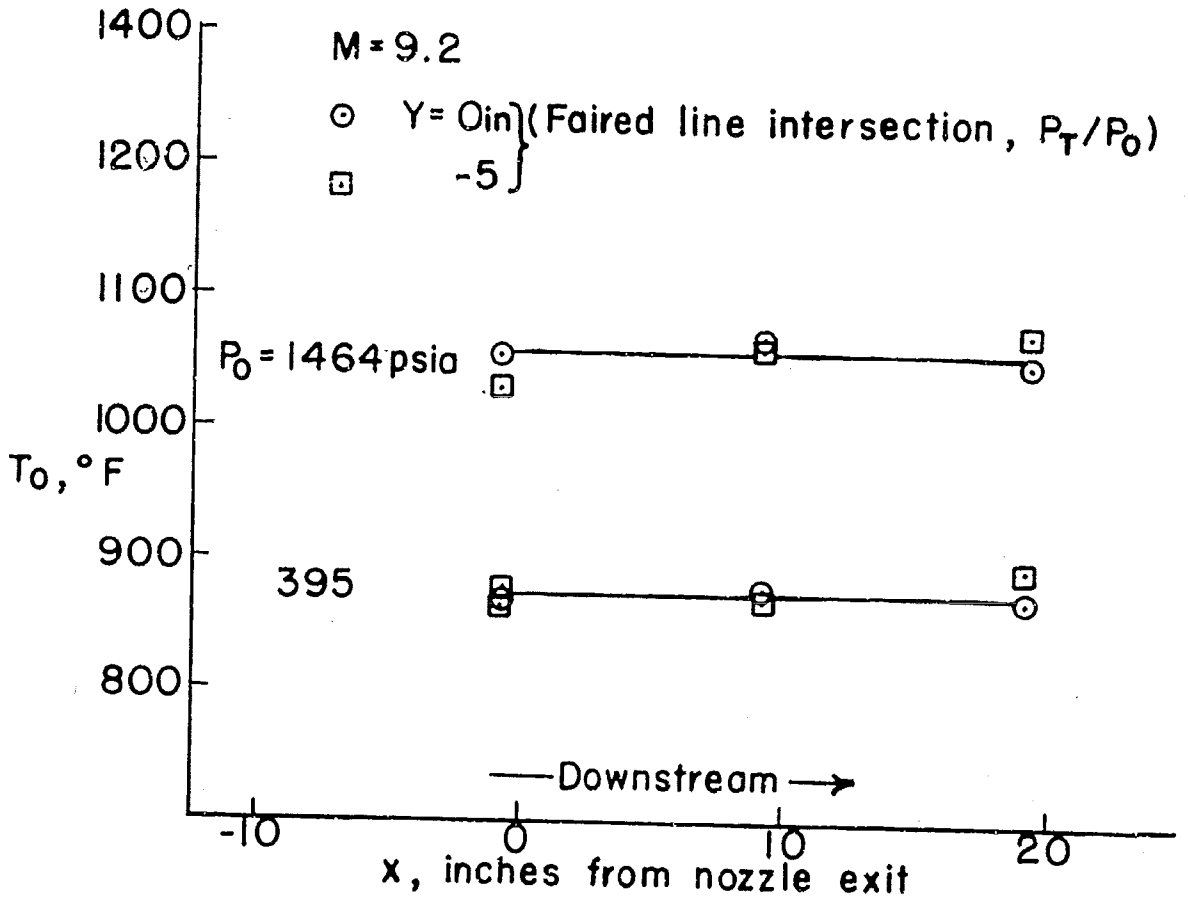

Figure 8b. Effect of probe axial position on stagnation temperature at onset of liquefaction

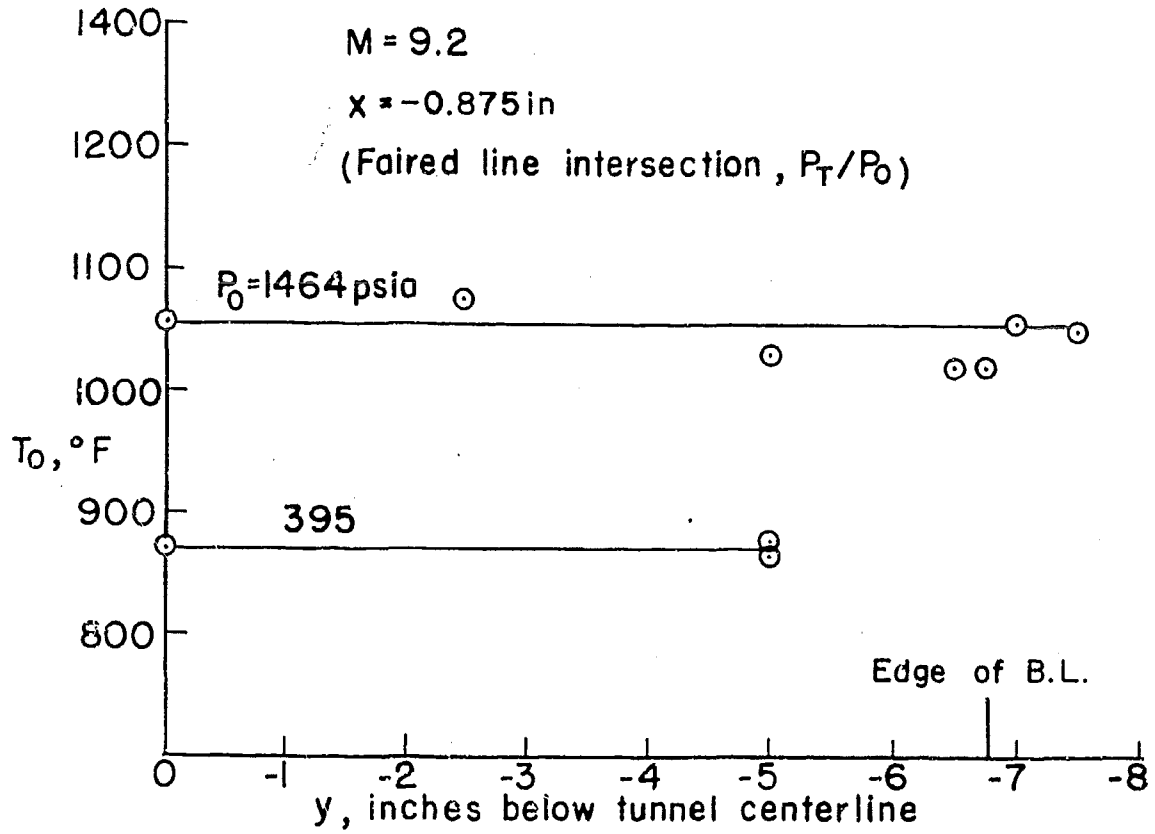

Figure 8c. Effect of probe vertical position on stagnation temperature at onset of liquefaction

nozzle exit (X = - 0.875). (Most of the data in this figure at P_o = 1464 psia were obtained from the basic data plot of Figure 7a.) If the estimated accuracy of the results are taken into consideration along with the previously described difficulty in determining the onset of liquefaction from total head pressures in the vicinity of the edge of the boundary layer (Y ≈ -6.75), the stagnation temperature at the onset of liquefaction again does not show any significant trend with vertical probe position.

Thus, it appears that, for given test conditions, the onset of liquefaction occurs at substantially the same values of the stagnation temperature throughout the test section area and that results at a given location are probably representative, at least within the accuracy of the present test measurements.

4.4 Summary of Results

A summary of the data for the onset of liquefaction in both tunnels and for a wide range of pressures is presented in Figure 9 along with the theoretical air liquefaction curve and Daum's experimental boundary. This figure shows the onset of liquefaction data on a static pressure versus temperature plot so that the results at different Mach numbers can be reduced to a common basis for presentation and comparison. This reduction was accomplished by using isentropic flow relations to calculate the test section temperature corresponding to the measured stagnation temperature at the onset of liquefaction. The assumption was made that these relations would be valid for the conditions just before liquefaction commences. When the onset of liquefaction was determined by the total head pressure measurements in the hypersonic tunnel, it was also necessary to calculate the associated static pressures. This was done by using the measured stagnation pressure and the actual Mach number indicated by the total head to stagnation pressure ratio. The BRL experimental results are plotted with solid or open symbols to indicate the method of determining the onset of liquefaction, i.e., "faired line intersection" or "slope change" method. Only the "slope change" method with the static pressure was used for the supersonic tunnel results. For the hypersonic

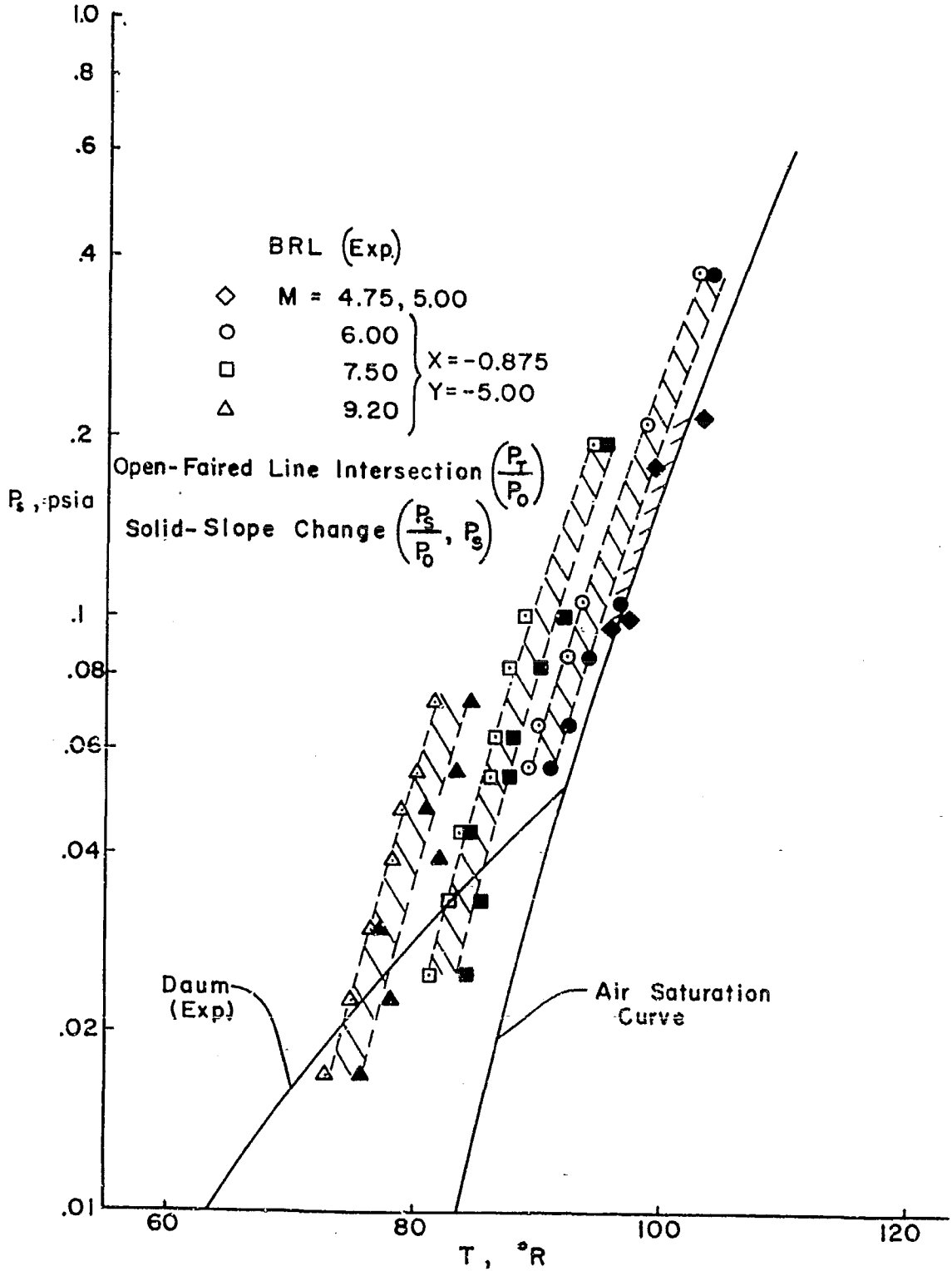

Figure 9. Summary of data for onset of liquefaction

tunnel results, both methods were used and in such a manner as to give the greatest spread in the experimental results. This was done since there is some uncertainty as to just which method and pressure gives the best indication of the actual onset of liquefaction.

The plotted open symbol data show that the "faired line" intersection method (used with total head pressure ratio) consistently indicates a lower temperature at the onset of liquefaction than does the closed symbol "slope change" data using the static pressure ratio and that there is considerably more scatter in the "slope change" data. However, in spite of this area of uncertainty, three distinct experimentally determined bands are clearly defined for the three hypersonic Mach numbers of 6.0, 7.5 and 9.2 for the range of pressures which could be tested. The supersonic tunnel results are grouped around the theoretical air saturation line. Generally, the results show that air liquefaction occurs near the theoretical boundary (Clausius-Clapeyron) for Mach numbers 4.75 and 5.00 with little, if any, supersaturation. However, as the Mach number increases to M = 6.0, 7.5 and 9.2 there is an increase in the amount of supersaturation before liquefaction occurs and, at a given mach number, the supersaturation is about the same at all pressure levels tested. Thus, the experimental air liquefaction boundaries roughly parallel the theoretical boundary.

The BRL experimental results give boundaries for our hypersonic tunnel which are considerably different from those predicted by Daum on the basis of experimental data summarized from several tunnels. This prediction is shown on Figure 9 and indicates that no supersaturation would be encountered at the higher pressure levels but that increasing amounts would occur as the pressure level is reduced. It appears that this prediction does not apply to wind tunnels in general since it is apparently based on a fortuitious grouping of the data which occurred as a result of the general flow characteristics of the several tunnels involved. For example, there is a strong tendency for the static pressure to reduce sharply as the Mach number of a facility increases and thus results in an indication of increasing amounts of supersaturation. As

already pointed out, the experimental boundaries of the present tests not only show appreciable amounts of supersaturation at the higher pressure levels, but also do not, at least for the limited pressure range tested, appear to diverge from the theoretical boundary at the lower pressure levels.

4.5 Application of Results

In making a practical application of the results of the tests which outline the experimental air liquefaction boundaries for the BRL wind tunnels, it is necessary to recall that these boundaries indicate only the regions where the liquefaction of air constituents has an effect on the flow properties in the test section area. No information is provided on the much more complex subject of possible effects on model test results, particularly where local expansion of the flow may cause collapse of the supersaturated state. However, there is some indication that this collapse is time-dependent and that for many model configurations the time scale is too short for liquefaction to occur locally if it does not already exist in the flow prior to encountering the model. With this information in mind, the operating charts for Mach numbers 7.5 and 9.2 in the hypersonic tunnel are presented in Figure 10. These charts show the experimental boundaries of Figure 9 and the theoretical air saturation curves at stagnation conditions of pressure and temperature. The chart for M = 9.2 indicates an appreciable reduction, of approximately 150 - 200 ^{o}F, in the experimentally determined stagnation temperature required to prevent liquefaction in the tunnel flow, from that indicated by theory. If further tests also show no effects on models, the stagnation temperature requirements may be relaxed sufficiently to speed up test runs significantly at M = 9.2. A smaller reduction in the stagnation temperature of approximately 50 - 70 ^{o}F could also be applied to the M = 7.5 tests, but adequate stagnation temperature is easily available at this Mach number (see Figure 5b), and the practical advantage would be negligible. This is also true at Mach number 6.0 where there is little difference between the experimental and theoretical boundaries. In the supersonic tunnel, where no heater is available, during typical

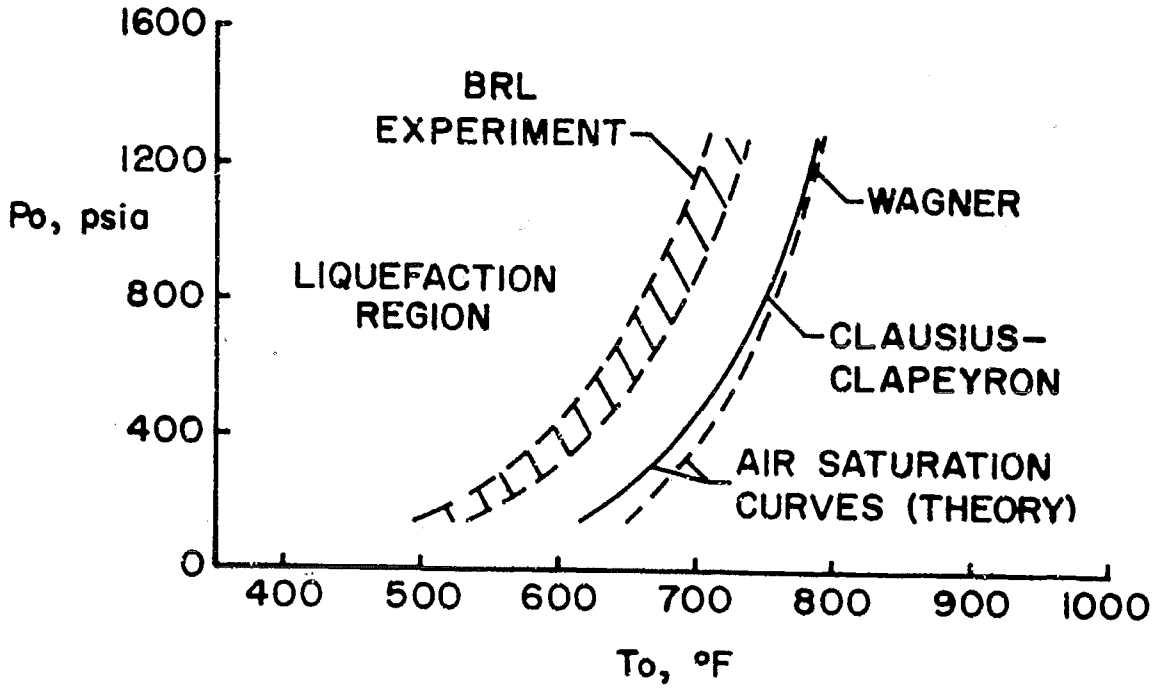

Figure 10a. Operating chart for M = 7.5

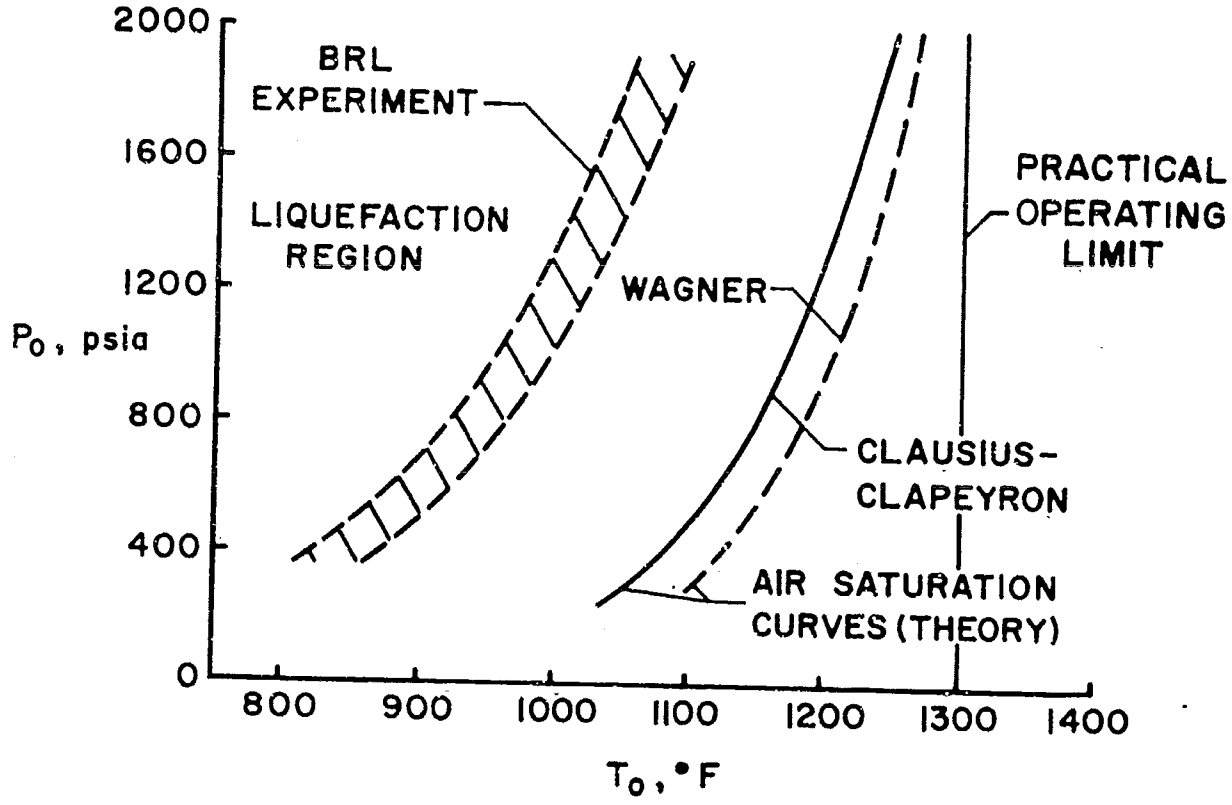

Figure 10b. Operating chart for M = 9.2

runs with 90 °F stagnation temperature we can expect to encounter the effects of air liquefaction in the tunnel flow near the theoretical boundary, or at M = 4.75 at high Reynolds numbers, and at M = 5.0 at intermediate Reynolds numbers (see Figure 5a). By utilizing the present 110 °F maximum temperature output from the compressor plant for the supersonic tunnel, the effects of air liquefaction on the tunnel flow can only be delayed to Mach number 5.0 at the higher pressures.

5. CONCLUSIONS

The experimental boundaries indicating the regions where liquefaction of the air constituents has an effect on the flow properties in the test section of the moderate size BRL wind tunnels have been determined, with emphasis on the hypersonic tunnel.

Static and total head pressure measurements as a function of temperature are adequate indicators of the onset of liquefaction.

The "characteristic" variation in the total head pressure at the onset of liquefaction is a function of probe position with respect to the boundary layer. This pressure increases at the onset of liquefaction when in the boundary layer, decreases when outside the boundary layer, and is insensitive to the liquefaction process when near the outer edge of the boundary layer.

Onset of liquefaction data at a given location in the test section appeared generally representative for the test section region.

Air liquefaction occurs near the theoretical boundary in the supersonic tunnel at Mach numbers 4.75 and 5.0 with little, if any, supersaturation.

Some supersaturation becomes evident at Mach number 6.0, and increases as the Mach number increases to 7.5 and 9.2.

The difference between the theoretical and experimental temperature at the onset of liquefaction is about the same at all pressure levels tested for a given Mach number.

The present data do not verify Daum's prediction which apparently does not apply to wind tunnels in general.

The supersaturation which exists at M = 9.2 may allow us to decrease our stagnation temperature requirements significantly at this Mach number.

Additional experiments are required to determine the effects, if any, on models tested in the supersaturated tunnel flow regime from near the theoretical boundary to the experimental boundary.

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13. ABSTRACT

The boundaries for the onset of air liquefaction have been experimentally determined for the Ballistic Research Laboratories' (BRL) Wind Tunnels. These boundaries indicate the regions where the liquefaction of air constituents has an effect on the flow properties in the test section. The boundaries were determined by making static and total head pressure measurements (with varying temperature) throughout the appropriate Mach and Reynolds number ranges of both the supersonic and hypersonic wind tunnels. The results show that air liquefaction occurs near the theoretical boundary (Clausius-Clapeyron) for Mach numbers 4.75 and 5.00 with little, if any, supersaturation. However, as the Mach number increases to 6.0, 7.5 and 9.2, there is an increase in the amount of supersaturation before liquefaction occurs, and at a given Mach number, the difference between the experimental and theoretical temperature at the onset of liquefaction is about the same at all pressure levels tested. These results may allow a relaxation of our stagnation temperature requirements by an amount which would be of considerable operational significance at M = 9.2.

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Supersonic						

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