

30. CONSIDERATIONS REGARDING THE EVALUATION AND REDUCTION
OF SUPERSONIC SKIN FRICTION

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SUMMARY

A comparison is made between previously published experimental data for supersonic turbulent boundary-layer skin friction and the skin-friction predictions obtained by using the Sommer and Short T' and Spalding and Chi methods. Also, various methods for reducing skin friction on the supersonic transport are discussed.

INTRODUCTION

Although the wave drag and the drag due to lift of the proposed supersonic transport configurations have been greatly reduced as the design has progressed, the skin-friction drag has remained relatively constant. Because the skin-friction drag of a typical supersonic transport is a large part of the total drag, reduction of the skin-friction drag is potentially a good means of obtaining drag reductions.

Figure 1 shows a breakdown of the drag of a typical supersonic transport cruising at a Mach number of 2.7 and an altitude of 65 000 ft. As can be seen, skin friction accounts for about 40 percent of the total drag. Since a typical transport has about 100 counts of total drag at cruise, the skin-friction drag is about 40 counts. For each count that the drag can be reduced, the lift-drag ratio can be increased by about 0.1.

Several methods which can be used to reduce the skin-friction drag on a supersonic transport will be reviewed in this paper. In addition, methods for calculating skin-friction drag will be reviewed.

SYMBOLS

b	wing span
c	wing chord
C_D	drag coefficient
$C_{D,F}$	drag coefficient due to skin friction

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$\Delta C_{D,F}$	increment in drag coefficient due to skin friction
C_F	average skin-friction coefficient
$C_{F,aw}$	adiabatic wall average skin-friction coefficient
$C_{F,injection}$	average skin-friction coefficient with air injection
$C_{F,no injection}$	average skin-friction coefficient without air injection
$C_{F,n=0}$	average skin-friction coefficient for $n = 0$
c_f	local skin-friction coefficient
$c_{f,i}$	incompressible local skin-friction coefficient (see section "Methods of Evaluating Skin Friction")
h	altitude
M	Mach number
\dot{m}	injection-air mass-flow rate
n	planform exponent (see fig. 10)
R_l	Reynolds number based on distance from leading edge
R_x	Reynolds number based on distance from virtual origin of turbulent boundary layer
S	reference surface area
T_{aw}	adiabatic wall temperature
T_w	wall temperature
V_∞	free-stream air velocity
w	injection-air weight-flow rate
y	distance from center line in spanwise direction
η_r	recovery factor
ρ_∞	free-stream air density

Subscripts:

exp experimental value
theor theoretical value

DISCUSSION

Methods of Evaluating Skin Friction

Several years ago, a comparison between the various theories of supersonic skin friction in use at that time and the available experimental data showed that the Sommer and Short T' method generally gave the best prediction of compressible turbulent boundary-layer skin friction (ref. 1). A new method for the prediction of compressible turbulent skin friction has since been developed by Spalding and Chi (ref. 2). Also, some new experimental data for supersonic skin friction at high Reynolds numbers have extended the range of Reynolds numbers over which experimental results are available (refs. 3 to 9). In all of these references except reference 9, local skin friction was measured. Therefore, comparisons herein will be made by using local rather than average skin-friction measurements.

Figures 2 to 7 show comparisons between presently available experimental data and the skin-friction predictions of Sommer and Short (figs. 2, 4, and 6) and Spalding and Chi (figs. 3, 5, and 7). (The experimental data presented in the figures were obtained from references 3 to 8 and 10 to 12.) The skin friction is presented in the form of the ratio $\frac{c_f}{c_{f,i}}$, where the value of $c_{f,i}$ is predicted by the method involved. As will be shown, neither method gives completely satisfactory results over the entire range of Reynolds numbers.

In figures 2 and 3 are shown the experimental variations of $\frac{c_f}{c_{f,i}}$ with M for a value of R_x of 10×10^6 compared with the predictions of Sommer and Short (fig. 2) and Spalding and Chi (fig. 3). The curves and data shown are all for adiabatic wall temperatures. There is some scatter in the experimental data, but generally the Sommer and Short T' prediction agrees slightly better with the data at this Reynolds number than the Spalding and Chi prediction.

When the new experimental data for skin friction at higher Reynolds numbers of 50×10^6 and 100×10^6 are used in the same type of comparison, the results are not the same, as shown in figures 4 and 5. (The data of Hopkins and Keener were obtained for a Reynolds number based upon momentum thickness. These data are converted in figures 4 and 5 to values for R_x by using the method of reference 1.) For these conditions, the data agree better with the Spalding and Chi prediction and lie above the Sommer and Short T' prediction curve.

The reason for the agreement of the data with the Sommer and Short T' prediction at low Reynolds numbers and with the Spalding and Chi prediction at high Reynolds numbers can be shown by plotting the skin-friction ratio as a function of Reynolds number for a constant Mach number. The Sommer and Short T' curve is shown in figure 6 and the Spalding and Chi curve is shown in figure 7. The data were all obtained for Mach numbers between 2.20 and 2.95 and transformed to values for a Mach number of 2.7 by using the equation

$$\frac{c_f}{c_{f,i}} = \left(\frac{c_{f,exp}}{c_{f,theor}} \right)_{M_{exp}} \left(\frac{c_{f,theor}}{c_{f,i}} \right)_{M=2.7}$$

The values obtained for $\frac{c_f}{c_{f,i}}$ by using this equation are not the same for the two methods since the parameter $c_{f,theor}$ is dependent upon the particular method involved. Therefore, the values of the ratio $\frac{c_f}{c_{f,i}}$ are slightly different in figures 6 and 7. However, this procedure allows a direct comparison to be made between the data and the predicted curves by preserving the relation of experimental values to predicted values. It appears from these data that the skin-friction ratio is almost independent of Reynolds number. Both methods predict some variation of the skin-friction ratio with Reynolds number and, therefore, neither prediction curve matches the data over the entire range of Reynolds numbers. In order to predict the average skin friction, it is important that the method give accurate results for the local skin-friction level at all Reynolds numbers up to the Reynolds number of interest, since the average is obtained by integrating the local values. Therefore, even though the Spalding and Chi method gives accurate results for the local skin friction at high Reynolds numbers, it does not necessarily give accurate results for the average skin friction at these Reynolds numbers. There is also some doubt as to the validity of the Spalding and Chi method for use at the high temperature levels encountered on a supersonic transport, since the constants in this method were obtained by comparison with wind-tunnel data and no provision was made to account for the effect of temperature level on the viscosity ratio of air. Most other methods of predicting skin friction, including the Sommer and Short T' method, do have such a provision.

As can be seen, only a limited amount of experimental data is available for the very high Reynolds numbers encountered by a supersonic transport. More data are needed to increase confidence in the prediction of skin friction at high Reynolds numbers.

The effect of wall temperature on the average skin friction at $M = 3.0$ and $R_x = 94 \times 10^6$ is shown in figures 8 and 9 for an ogive-cylinder body of revolution (ref. 9). The variations of $\frac{C_F}{C_{F,aw}}$ with $\frac{T_w}{T_{aw}}$ are presented for experiment and theory, where T_{aw} is based on a recovery factor η_r of 0.89 and the value of $C_{F,aw}$ is obtained by extrapolating the experimental values to adiabatic conditions. A comparison of these figures shows that the Sommer

and Short T' method better predicts the effect of wall temperature on skin friction at Mach 3. However, the heat-transfer correlations in reference 13 indicate that the Spalding and Chi method is more accurate at hypersonic speeds.

It is apparent that there is much room for improvement in the accuracy of predictions of turbulent skin-friction drag. However, the Sommer and Short T' method is considered to provide the best predictions of skin friction under conditions encountered by the supersonic transport. Therefore, this method is used to calculate skin friction in the rest of this paper.

Methods of Reducing Skin Friction

Most of the methods discussed in this paper for reducing the skin friction on a supersonic transport have been presented before in various conference papers and NASA reports. These methods are presented herein without regard to the design considerations involved, or the effects they might have on other characteristics of the aircraft. Application to a supersonic transport will require careful and ingenious design in order to obtain favorable overall results.

Configuration changes and blending.- One way to reduce skin friction is to take advantage of the fact that skin friction is low at high Reynolds numbers. (See ref. 14.) Figure 10 illustrates the changes in skin friction which occur as the wing planform is changed so as to remove areas from the tips and add areas in the center, where they will be in high Reynolds number flows. The skin friction was calculated at a Mach number of 2.7 and an altitude of 65 000 ft for a wing with a planform area of 8000 ft² and an aspect ratio of 1.7. The wing chord was determined by a power-law formula, and the midchord sweep of the wing was held constant at 50°. As can be seen, the areas near the tips are progressively moved toward the center of the wing. This process results in a reduction in the total skin friction, even though the total area and the aspect ratio of the wing remain the same.

Another obvious way of reducing skin friction is decreasing the wetted area of the aircraft. The method used to decrease the wetted area, which is called blending, is accomplished by deforming the aircraft into a shape that is as close as possible to a body of revolution. Such a shape, of course, would have the least surface area for a given volume distribution. Although this type of blending is used to reduce skin friction only, it is not incompatible with the type of blending which can be used to reduce wave drag and structural weight.

An example of a configuration shape which resulted from blending and changing the planform of a delta-wing type supersonic transport is shown in figure 11. The wing planform has been changed to remove areas near the tips and add areas near the center in such a way that the total area and the wing aspect ratio are constant. The wing and tail have been blended into the fuselage with large fillets; the nacelles have been blended together and a splitter plate used to separate the inlets. The data of reference 15 show that a

splitter plate prevents mutual interference between inlets when they are unstarted. The nacelle inlets have not been blended into the wing because such blending would have produced problems of diverting the wing boundary layer around the inlets.

The skin-friction-drag reductions that might be obtained by these configuration changes are shown in table I. The reductions due to planform changes result only from removing areas in low Reynolds number flows and replacing them in high Reynolds number flows. There is no change in the total wetted area. The skin-friction-drag reductions due to blending result from changes in the total wetted area which occur as the components of the aircraft are blended. Changes in the skin friction caused by three-dimensional effects in the corners were neglected in these calculations. Although each individual increment is small, the total increment can be a significant reduction in the skin-friction drag. For an aircraft with 40 counts of skin-friction drag, the total reduction shown in table I amounts to about 2 counts.

Effects of emissivity on wall temperature and skin friction.- As shown before, the wall-temperature ratio has a large effect on skin friction. Both the theory and the experimental data showed that the skin friction increased as the wall-temperature ratio decreased. This trend is shown in figure 12, where the skin-friction drag is plotted as a function of the wall-temperature ratio for a typical supersonic transport flying at a Mach number of 2.7 and an altitude of 65 000 ft. Also shown in the figure are vertical dashed lines at the temperature ratios corresponding to the equilibrium wall temperatures for various wall emissivities. (See also ref. 16.) The range of emissivities being considered for presently proposed supersonic transports is shown as the crosshatched region. As is well known, radiation of heat from the wall caused by high emissivities reduces the wall temperature. For this particular configuration, an emissivity of 0.5 reduces the wall-temperature ratio to about 0.95, and an emissivity of 1.0 reduces it to about 0.91. It can be seen that increasing the emissivity reduces the wall temperature but increases the skin-friction drag. Low emissivities have the opposite effect of increasing the wall temperature and reducing the skin-friction drag. Therefore, low values of the emissivity, which can be controlled to a certain extent by the choice of paint or surface coating used, reduce the skin-friction drag of a supersonic transport. Determination of the best wall emissivity to use will depend on the exact configuration and structural design chosen.

Boundary-layer control.- The ideal way to reduce the skin friction on a supersonic transport, of course, would be with laminar-flow control. Research on laminar-flow control, however, is still continuing and very little practical experience has been obtained so far. Therefore, laminar-flow control does not appear feasible for the first-generation supersonic transport.

Theoretically, it is possible to obtain about 2 feet of natural laminar flow on unswept leading edges, such as the engine nacelles, and about 1.2 feet of natural laminar flow on swept leading edges, such as the wing and tail (ref. 17). With these amounts of laminar flow, the skin-friction drag could be reduced by about 3 percent. However, large extents of natural laminar flow on the supersonic transport appear unlikely, since this condition would require very

accurate construction, extensive maintenance, and some method of avoiding insect contamination during service.

There is, however, a method of reducing the turbulent skin-friction drag. It has been shown experimentally that the turbulent skin friction can be reduced by injecting air into the boundary layer through rearward-inclined flush slots in the surface (refs. 18 and 19). The effect of air injection on the drag is shown in figure 13, in which the model drag coefficient is plotted as a function of the injection mass-flow parameter. The lower curve presents the variation of the measured values of C_D with the rate of air injection through a rearward-inclined flush slot at $M = 3.0$. These measured values of C_D include the reduction in skin friction as well as the thrust recovered from the injected air. The upper curve represents the calculated values of C_D that could be obtained if the momentum thrust of the same air were recovered with a convergent nozzle. The difference in the levels of the two curves indicates that a reduction in skin friction occurred. The physical process behind this skin-friction reduction is not yet fully understood.

A possible application of air injection to one of the supersonic transport configurations is presented in figure 14. The abscissa is the injection-air weight-flow rate through inclined flush slots. The air for injection can be obtained from the inlet bleed air, which is already available for use onboard the airplane. The ordinate is the ratio of the average airplane skin-friction coefficient with air injection to the average skin-friction coefficient without air injection. The flow rate of the inlet bleed air is estimated to be about 80 lb/sec. With this amount of air, the skin friction can be reduced by 5 percent.

Recently published boundary-layer surveys behind flush slots (ref. 19) have suggested that perhaps even larger reductions in skin friction could be obtained from two or three slots distributed along the surface, instead of one slot near the leading edge. This hypothesis requires experimental verification, however, before it can be used. The feasibility of using air injection to reduce skin friction depends upon many considerations. The point to be made, however, is that the skin-friction reductions shown in figure 14 indicate that further study of the use of air injection on the supersonic transport is warranted.

CONCLUDING REMARKS

In summary, a comparison between theory and the latest experimental results for compressible turbulent skin friction shows that more data are needed to increase confidence in the prediction of skin friction at supersonic speeds and high Reynolds numbers.

Planform changes and configuration blending can significantly change the total skin-friction drag of a supersonic transport. Also, the wall emissivity of a supersonic transport can have a large effect on the skin-friction drag.

The reduction in turbulent skin friction obtainable with air injection through rearward-inclined flush slots indicates that further study is warranted.

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TABLE I

CALCULATED SKIN-FRICTION-DRAG REDUCTIONS
 DUE TO CONFIGURATION CHANGES
 M=2.7; h = 65 000 FT

	$\frac{\Delta C_{D,F}}{C_{D,F}}$
<u>PLANFORM CHANGES</u>	
WING.....	-0.5 %
TAIL	-0.1 %
	TOTAL -0.6 %
<u>BLENDING</u>	
WING-FUSELAGE JUNCTURE.....	-3.1 %
VERTICAL-TAIL-FUSELAGE JUNCTURE	-0.3 %
NACELLES.....	-1.3 %
	TOTAL -4.7 %
TOTAL CHANGE IN SKIN-FRICTION DRAG DUE TO CONFIGURATION CHANGES.....	<u><u>-5.3 %</u></u>

DRAG BREAKDOWN OF A TYPICAL SUPERSONIC TRANSPORT
 $M=2.7; h=65\ 000\ \text{FT}$

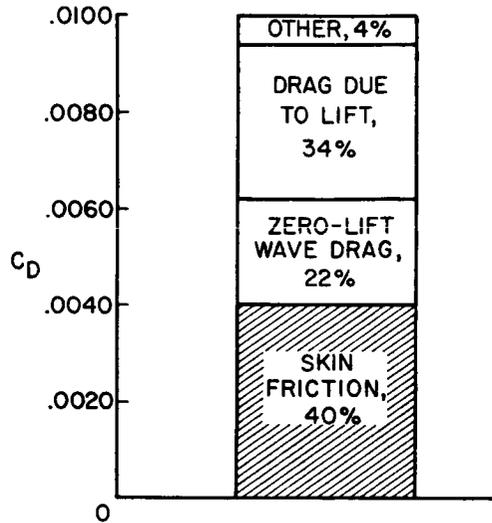


Figure 1

EFFECT OF MACH NUMBER ON TURBULENT SKIN FRICTION
 SOMMER AND SHORT T' METHOD; $T_w/T_{aw}=1.0$

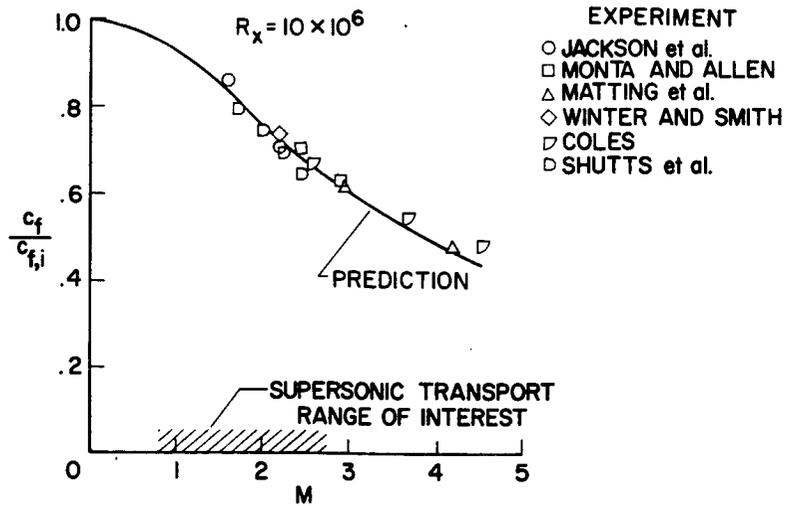


Figure 2

EFFECT OF MACH NUMBER ON TURBULENT SKIN FRICTION
 SPALDING AND CHI METHOD; $T_w/T_{aw} = 1.0$

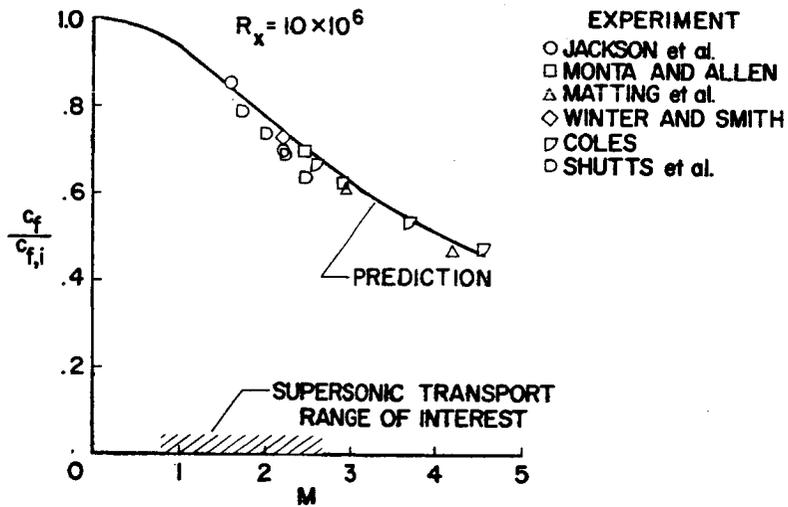


Figure 3

EFFECT OF MACH NUMBER ON TURBULENT SKIN FRICTION
 SOMMER AND SHORT T' METHOD; $T_w/T_{aw} = 1.0$

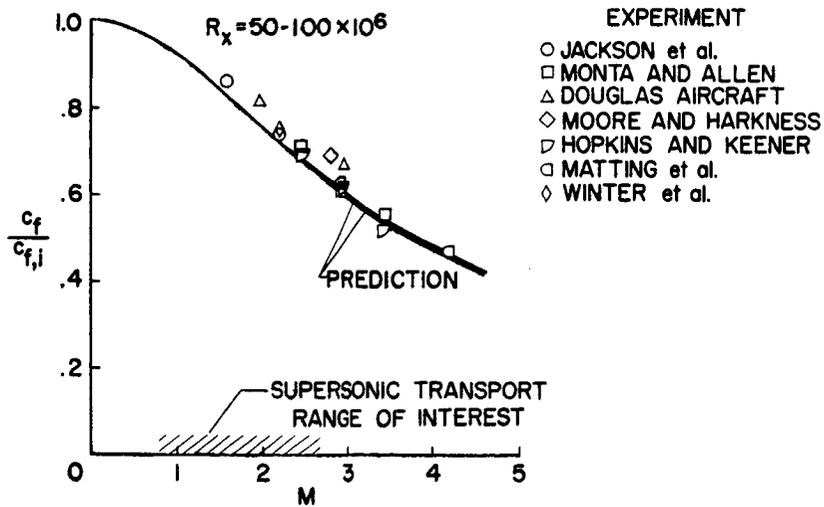


Figure 4

EFFECT OF MACH NUMBER ON TURBULENT SKIN FRICTION
 SPALDING AND CHI METHOD; $T_w/T_{aw} = 1.0$

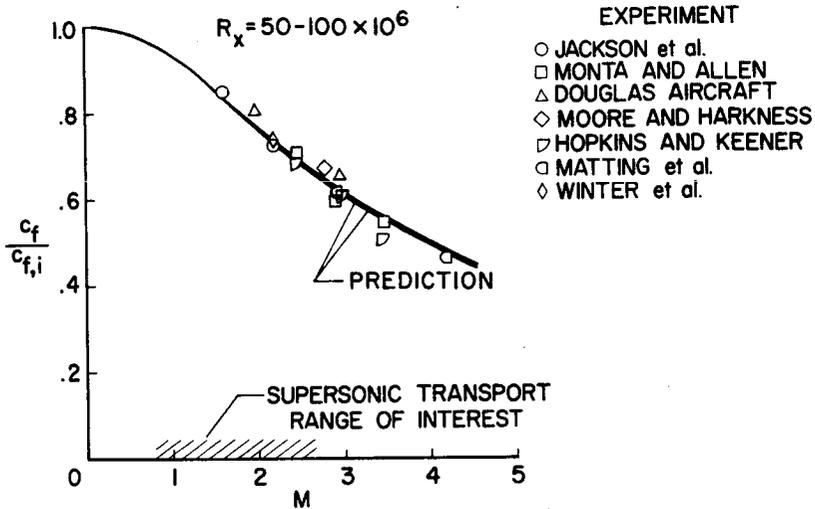


Figure 5

EFFECT OF REYNOLDS NUMBER ON TURBULENT SKIN FRICTION
 SOMMER AND SHORT T' METHOD; $M = 2.7$; $T_w/T_{aw} = 1.0$

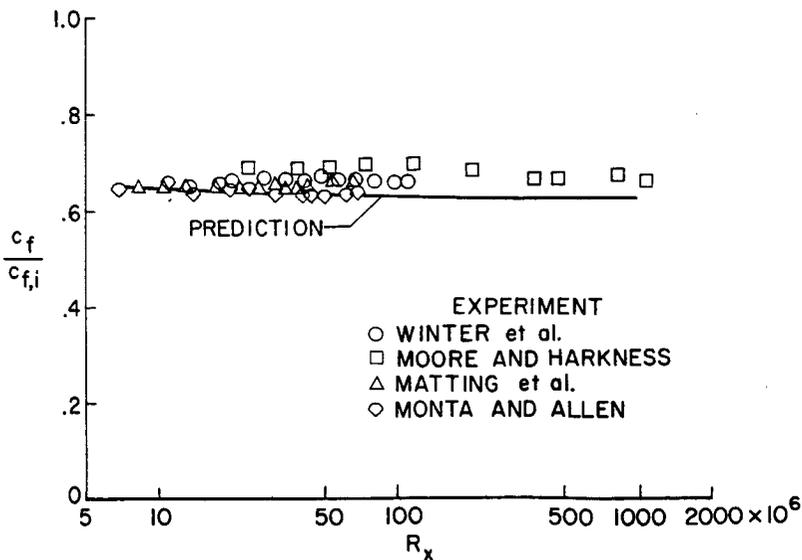


Figure 6

EFFECT OF REYNOLDS NUMBER ON TURBULENT SKIN FRICTION
 SPALDING AND CHI METHOD; $M=2.7$; $T_w/T_{aw}=1.0$

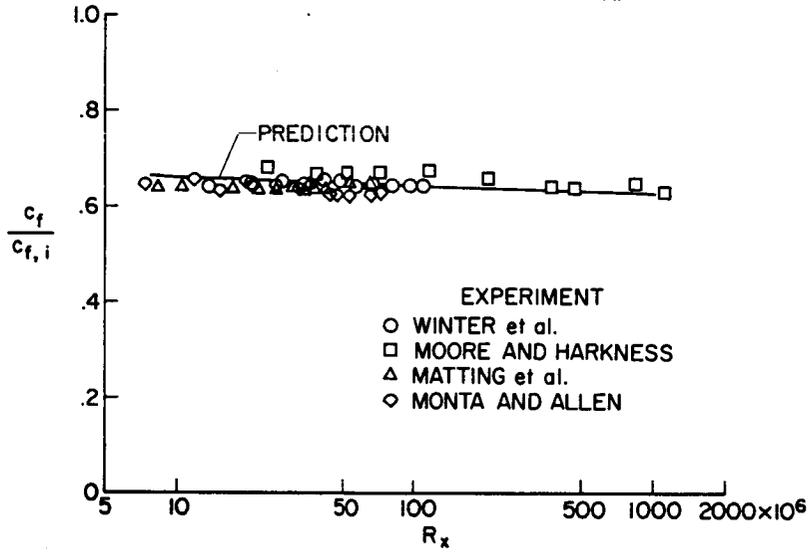


Figure 7

EFFECT OF WALL TEMPERATURE ON TURBULENT SKIN FRICTION
 SOMMER AND SHORT T' METHOD; $M=3.0$; $R_x=94 \times 10^6$

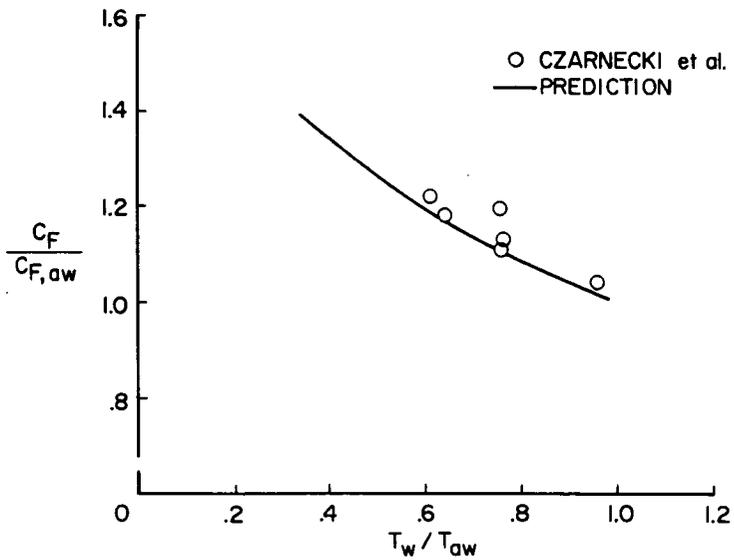


Figure 8

EFFECT OF WALL TEMPERATURE ON TURBULENT SKIN FRICTION
 SPALDING AND CHI METHOD; $M=3.0$; $R_x=94 \times 10^6$

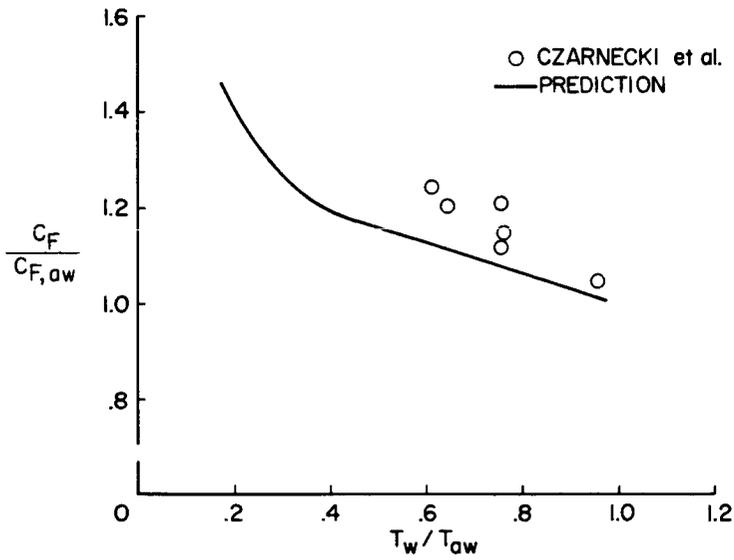


Figure 9

EFFECT OF WING PLANFORM ON SKIN FRICTION
 WING AREA AND ASPECT RATIO CONSTANT

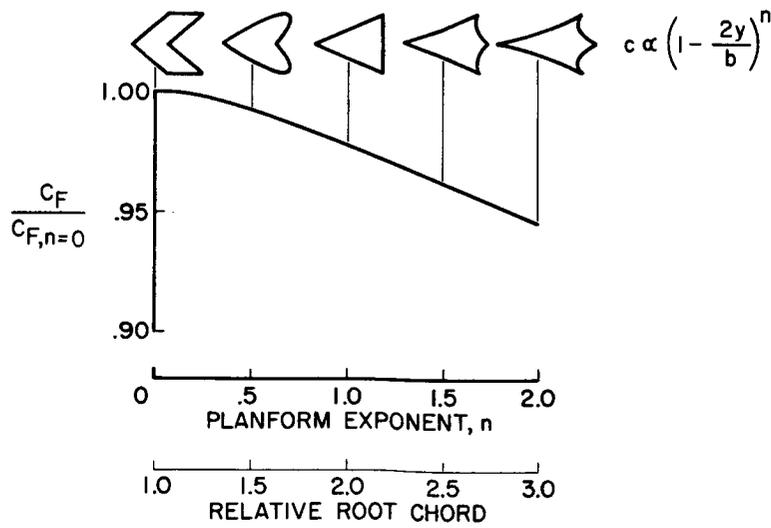


Figure 10

CONFIGURATION CHANGES TO REDUCE SKIN FRICTION

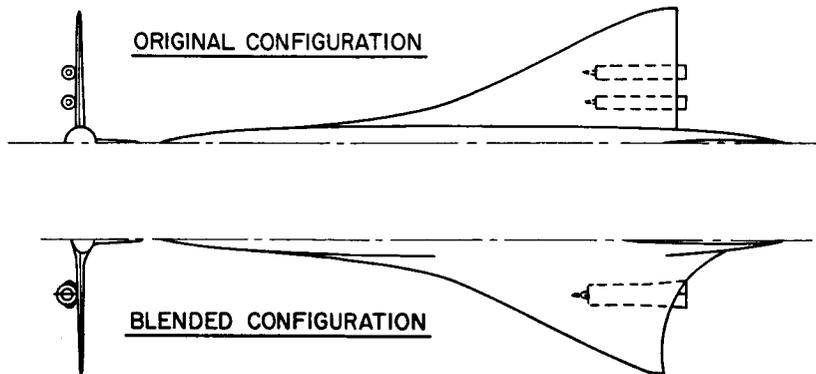


Figure 11

EFFECT OF EMISSIVITY ON WALL TEMPERATURE AND SKIN FRICTION

M=2.7; h=65 000 FT

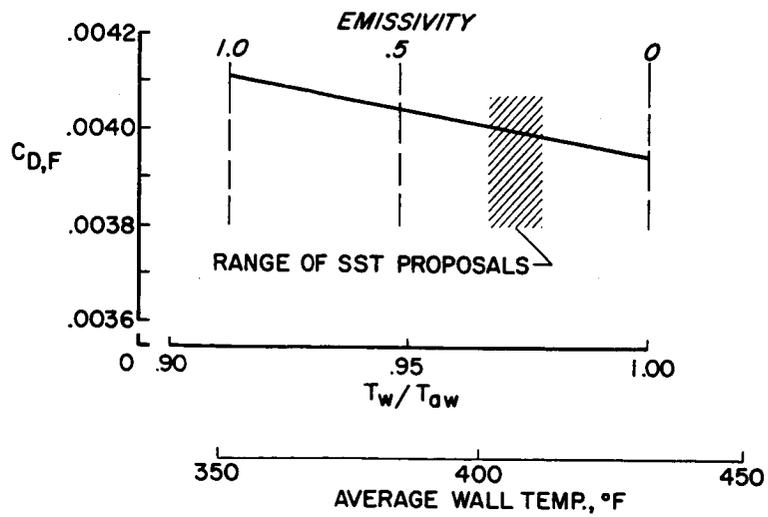


Figure 12

EFFECT OF AIR INJECTION ON DRAG

$M=3.0; R_L=16 \times 10^6$

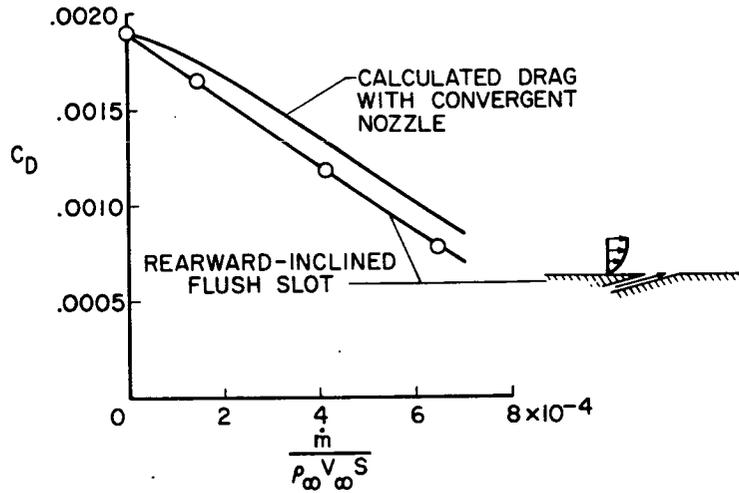


Figure 13

POSSIBLE SKIN-FRICTION REDUCTION ON AN SST WITH AIR INJECTION

$M=2.7; h=65\,000\text{ FT}$

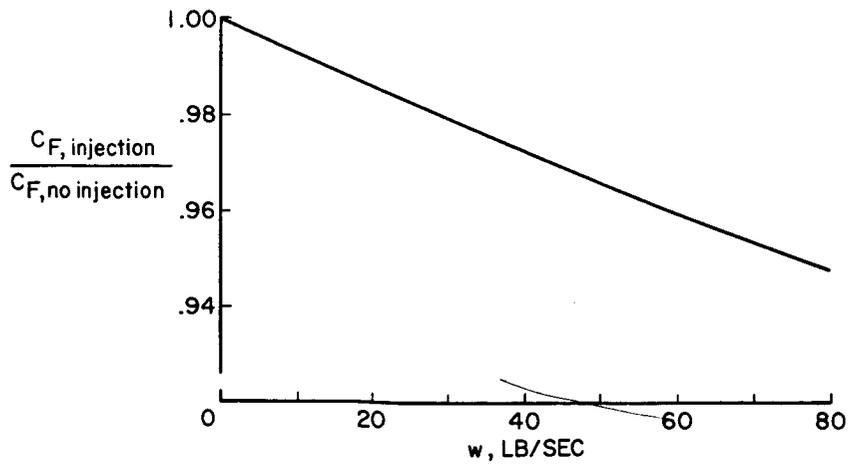


Figure 14