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5.1 Some Methods for Reducing Wing Drag and Wing-Nacelle Interference

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Introduction

This paper summarizes the results of efforts directed toward drag reduction which are underway within the Transonic Aerodynamics Branch at NASA-LRC. Three areas of research which will be discussed are: (1) The development of both supercritical and subcritical families of airfoils (see, for example, references 1 to 3); (2) The development and application of vortex diffusers (or, more popularly, winglets) to reduce induced drag (reference 4); and (3) The application of supercritical wings to executive-type aircraft and the reduction of severe wing-pylon-nacelle interference problems which were identified during these investigations (reference 5).

It should be noted that this is not a summary of the total NASA-Langley effort devoted to drag reduction, but rather a discussion of several selected areas which would be of interest.

Work at Langley is continuing in several additional areas including the reduction of turbulent skin friction through the use of compliant surfaces, reductions in so-called "crud" drag through the application of various surface coverings, reductions in induced drag using over the wing blowing (see reference 6), tip-mounted engines (reference 7), favorable power interference effects, and the use of thick supercritical wings to achieve higher aspect ratios. Finally, the possibility of obtaining practical laminar flow control is also under consideration.

Airfoil Development

Supercritical airfoils - This new type transonic airfoil was developed by Dr. R.T. Whitcomb at NASA-Langley about 10 years ago. At that time, theoretical approaches for supercritical flows were non-existent and much of the early work in developing the airfoils was intuitive in nature.

Figure 1 presents two-dimensional wind tunnel results for several ten percent thick airfoils at a section lift coefficient of 0.7. The conventional airfoil results presented are for the NACA 64A-410. Comparison of the results for this airfoil with those for the supercritical airfoils illustrates the significant gain in drag-rise Mach number achieved by use of the supercritical section. The increase in drag-rise Mach number is approximately 0.1. These results also indicate the presence of drag creep which was characteristic of all of the early supercritical airfoils. The drag creep, which results from increases in pressure drag associated with the onset of supercritical flows on the airfoil upper surface, was noted in the early flight test results for the F8 and T-2C research airplanes which employed supercritical wings having these early-type airfoils.

Much of the recent work at Langley has been devoted to the elimination of this undesirable drag creep, and the solid curve of Figure 1 shows the result of these efforts. Refinements to the airfoil were involved primarily with changes which resulted in a more favorable flow recompression over the forward upper surface and the elimination of a region of flow overexpansion near the three-quarter chord location also on the upper surface. A slight loss in force-break or drag-divergence Mach number is noted (about 0.01) as a result of slightly increased wave losses at the higher Mach numbers, but this compromise is felt to be of little consequence relative to the gains achieved in eliminating drag creep. It should be noted that, unlike the early work, the shaping changes used in the design of the recent airfoil, were guided by the use of the analytical program developed recently by Korn and others (reference 8) in achieving desired pressure distributions for the various cases.

Figure 2 indicates the status of the current supercritical airfoil development program. As is evident, the main effort is ambitious, and covers a broad range of design lift coefficients for airfoils ranging in thickness ratio from 6 percent to 22 percent. Solid symbols on the figure indicate airfoils which have been designed and tested. Open symbols represent airfoils which are currently under design using the analytical program noted earlier, and the crossed symbols indicate airfoils which are considered to have important applications and which are planned for design in the future.

Subcritical airfoils - The Langley work on supercritical airfoils led to a renewed interest on the part of NASA in developing airfoils designed for subcritical speeds. The first of these, designated the GA(W)-1, was a 17-percent airfoil designed specifically for the single-engine climb requirements for light twin-engine aircraft. Initial wind-tunnel results for this airfoil encouraged the design of several other airfoils for use at subcritical speeds.

Figure 3 presents a comparison of two-dimensional results obtained recently for the 13-percent thick GA(W)-2 airfoil and the older NACA 651-213 airfoil. Results for both airfoils were obtained in the Langley low turbulence pressure tunnel using the narrow fixed transition strip technique. Assuming section lift coefficients of 0.4 and 1.0 for the cruise and climb cases, respectively, reductions in section drag coefficient on the order of 3 percent and 17 percent, respectively, are achieved for the newer airfoil. Significant gains at the higher lift coefficients are indicated.

Figure 4 corresponds to the earlier supercritical family figure and indicates the current status of the subcritical airfoil family development. All of the airfoils developed thus far have been designed for a lift coefficient of 0.4, having thickness ratios of 13, 17, and 21 percent. An additional airfoil in this group is being designed with a thickness ratio of 9 percent. Also in design are two 17-percent airfoils having design lift coefficients of 0.2 and 0.7. Planned for future development are two 13-percent airfoils with design lift coefficients of 0 and 1.2.

Vortex Diffusers

A sizeable effort is currently underway at NASA-LRC directed toward the reduction of induced drag. One phase of this effort, which has received wide notice, involves the use of vortex diffusers, or winglets as they are more popularly called, mounted at the wing tips. Unlike end plates, the vortex diffusers are designed with the same careful attention to local flow conditions as would be utilized in the design of the wing itself. The placement of the vortex diffuser within the rotational flow field of the wing tip results in forward inclinations of the lift (or side force) vectors for the vortex diffusers, producing a thrust component which increases with increasing lift. The action is analogous to the force which propels sailboats, of course.

Figure 5 shows the geometric characteristics of the semispan model used for the vortex diffuser development. The wing planform represents an early version of a wide-body transport configuration. The two tip configurations tested, shown in the right side of the figure, represent the basic tip configuration and the vortex diffuser configuration which was tested assuming the "soft tip" portion of the basic wing panel could be removed. This resulted in a reduction in the basic panel span of about 2.5 percent. The vortex diffuser geometry is shown on the left side of the figure. The upper vortex diffuser span is about equal to the basic wing tip chord; the leading edge sweep is equal to the wing leading edge sweep and the vortex diffuser root chord extends over the aft 60 percent of the wing tip chord. This particular arrangement was selected in order to avoid superimposing the high local velocities occurring on the wing upper surface and on the vortex diffuser upper surface, which faces inboard. This upper diffuser is canted outward about 18° from the vertical. The lower diffuser is reduced considerably in span to provide ground clearance, extends over the forward 40 percent of the wing tip chord, and is canted outboard about 36°. The upper and lower vortex diffusers were separated to avoid mutual interference effects.

Figure 6 presents incremental drag results associated with the vortex diffusers as a function of lift coefficient for three Mach numbers. Incremental drag is defined as the drag coefficient for diffusers on minus the drag coefficient for diffusers off so that negative values of this parameter represent gains or, thrust.

Near zero lift, a net penalty results as would be expected. At a lift coefficient of about 0.26 the diffusers are carried with no penalty, and above this lift coefficient, favorable effects are obtained which increase with increasing lift. For the case presented, the cruise lift coefficient is about 0.53 at a Mach number of 0.80, resulting in a gain of about 15 drag counts ($C_D = 0.0015$). In full-scale terms this would represent an increase in L/D of about 5 percent, which, of course, is significant.

Figure 7 indicates the effect of the vortex diffusers on the wing pitching-moment and root-bending-moment coefficients. These results are for the cruise Mach number of 0.80, and show relatively small effects of the diffusers, for example, a two percent increase in root bending moment at the highest lift coefficient tested. Also, early wind tunnel flutter tests have indicated relatively small reductions in flutter dynamic pressure resulting from addition of the diffusers. It was also concluded that these effects were associated with structural characteristics rather than any unsteady aerodynamic interaction.

Figure 8 illustrates one proposed application of vortex diffusers. NASA is currently involved in a joint program with the USAF to determine the possibility of adding vortex diffusers to both the C-141 and the KC-135. Tests of both configurations are scheduled for this fall in the 8-foot Transonic Pressure Tunnel. This model photograph depicts vortex diffusers installed on the C-141.

Wing-Nacelle Interference

In an effort to provide access to supercritical wing technology for the general aviation manufacturers, NASA has entered into several cooperative endeavor agreements with members of the industry whereby NASA provides expertise in the areas of aerodynamic design and application of supercritical wings to this class of aircraft and also provides limited wind tunnel testing for configurations which are under design. The remainder of this discussion will present some results obtained recently which relate to the problem of wing-nacelle interference which occurs at high subsonic speeds and which is characteristic of configurations where fuselage-mounted engines overhang the wing rearward upper surface. A representative configuration is shown in Figure 9. This is a photograph of a one-ninth scale model of an executive-type aircraft under test in the Langley eight-foot transonic pressure tunnel. This particular investigation was conducted to determine the aerodynamic feasibility of replacing the original wing with one having supercritical sections of increased thickness, the thickness ratio being increased on the average from about .09 to .12. Because the wing was intended to be retrofitted, other configuration changes were to be kept to a minimum, therefore most of the tailoring or "tuning" changes were associated with the wing itself although some changes to the pylons were also made.

Figure 10 illustrates the severity of the interference problem which was found to exist between the wing and the engine-pylon arrangement for the modified configuration. These results are for a lift coefficient of 0.25 and are presented as an incremental drag coefficient versus Mach number, where M = 0.60 is used as a reference drag level for each configuration. It should be emphasized that all of the results presented are for the configuration with a supercritical wing. No comparisons are presented with the basic wing.

The data for the initial supercritical wing configuration, shown by the solid curve, indicate noticeable drag creep and an early drag rise. Reasons for these effects will be discussed later. Removal of the engines and pylons resulted in significant reductions in drag-creep, and the force-break or drag-rise Mach number was increased by about 0.02 to 0.03 as indicated by the dashed curve. Modifications to the wing root section, the addition of a wing glove and some reshaping of the pylon provided the results indicated by the long-short dashed curve. As can be seen, the drag creep was reduced considerably (about 75 percent at a Mach number of 0.80).

Figure 11 presents wing upper-surface oil flow photographs for a Mach number of 0.825 and a lift coefficient of about 0.35. The photograph on the left of the figure is for the initial configuration with nacelles and pylons and shows dramatically, the effect of the nacelle and pylon presence in forcing the uppersurface shock wave forward on the inboard wing region. The presence of a second wave which originates in the channel formed by the upper surface of the wing and the nacelle-pylon combination is also apparent. Examination of local pressure distributions for this case indicates the second wave and the adverse pressure gradients associated with it caused extensive separation in the "channel" region. The center photograph, for the case of the nacelles and pylons removed, shows what could be termed an expected supercritical wave location for this thickness ratio on the upper surface with little or no separated flow in evidence.

The final photograph of Figure 11 illustrates the upper surface condition for the tuned configuration. The main wave appears somewhat weaker compared to that for the initial configuration, and no evidence of the second wave is seen. Modifications to the configuration were accomplished through a number of steps. Figure 12 shows a comparison of the initial wing root and pylon lines with those for the final configuration tested. Most of the changes noted were made to eliminate what was essentially a converging-diverging channel formed by the wing-pylon-nacelle combination. Initially, material was removed from the aft region of the wing upper surface. Then, in order to reduce the upper surface velocities entering the channel, a glove was added and the forward portion of the resulting airfoil was increased in thickness. Finally, the lower surface of the pylon was thickened in order to provide for a relatively constant area in the channel. All of the noted changes represented an application of the area rule in a local sense, since the induced velocities approached and exceeded sonic values in the region.

The results just discussed were obtained using an executive-type aircraft model which employed turbojet engines. It might be expected, therefore, that replacement of the turbojet engines with the newer and larger turbofan engines would serve to aggravate the interference problem which was noted and some recent wind tunnel results indicate this to be the case.

Figure 13 presents results for an executive-type aircraft very similar to the one previously discussed. Again, results are presented in the form of an incremental drag coefficient versus Mach number; however, the reference Mach number in this figure is 0.50. Because an interference problem was anticipated, provision was made on the model to allow translation of the engine-pylon combination to several longitudinal locations. The results given in Figure 13 are for the proposed initial location (identified in Figure 13 as the production location), the most rearward location possible, which corresponded to a full-scale rearward shift of 18 inches and for a final "tuned" configuration with the engines aft. For this span location, and neglecting the glove, the leading edge of the nacelle moved from about the 55-percent chord location to the 70-percent location. This relocation was made in three steps of 6 inches each, full scale, and the results indicate that further gains could be achieved by additional rearward movement of the nacelle. Obviously, however, airplane balance problems would impose some practical rearward limit to the nacelle relocation. As with the earlier results, noticeable additional gains were made through so-called "tuning" which, in this instance, involved primarily changes in the inboard airfoil shape.

Concluding Remarks

Efforts underway within the Transonic Aerodynamics Branch at NASA-LRC have been directed toward drag reduction in several areas. Primary efforts have been involved with the design of both supercritical and subcritical families of airfoils, the reduction of induced drag through the use of vortex diffusers, and the reduction of interference drag for executive-type aircraft.

The results of many of these efforts are felt to be applicable to the design of general aviation aircraft.

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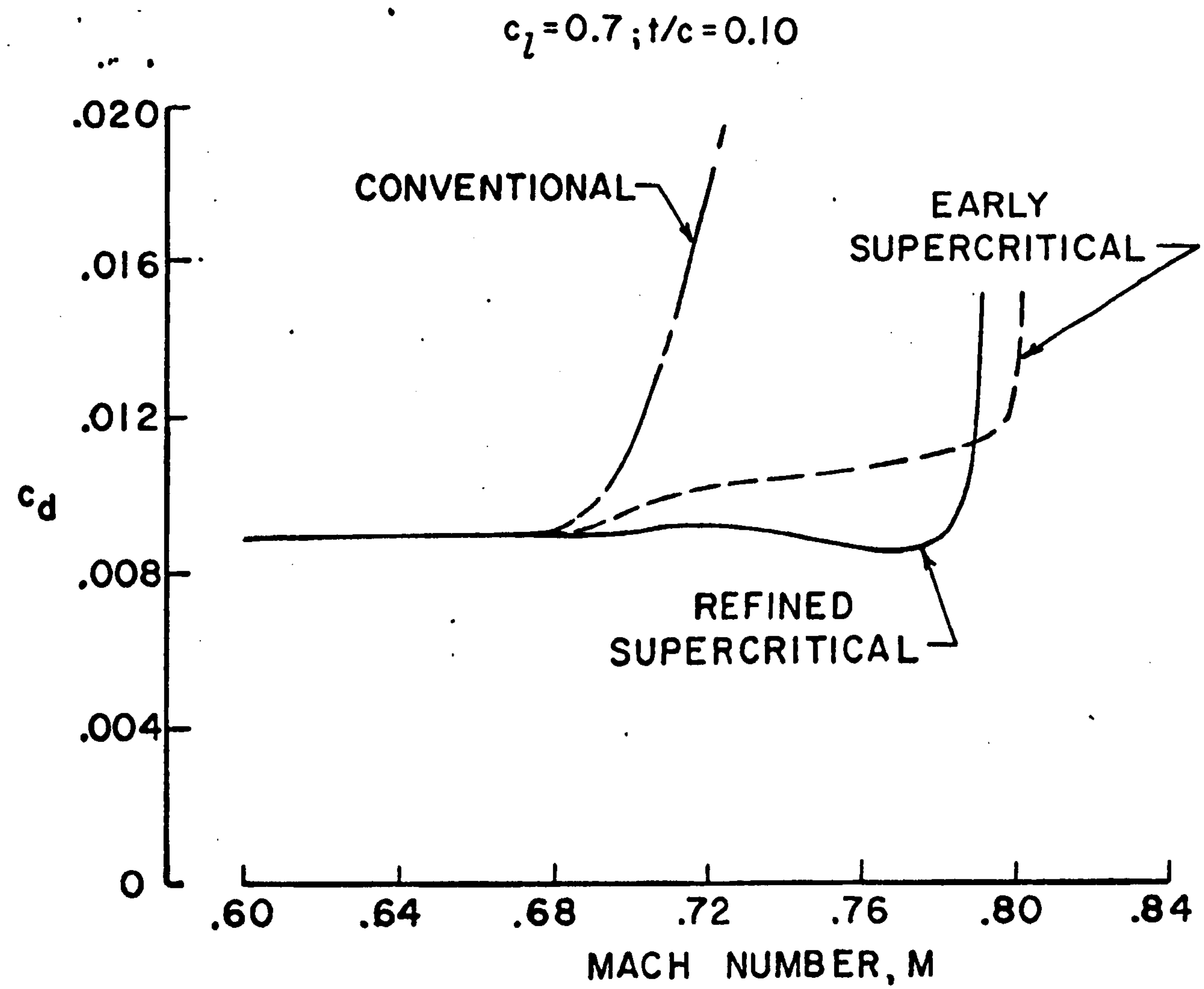


Figure 1. Supercritical Airfoil Improvements

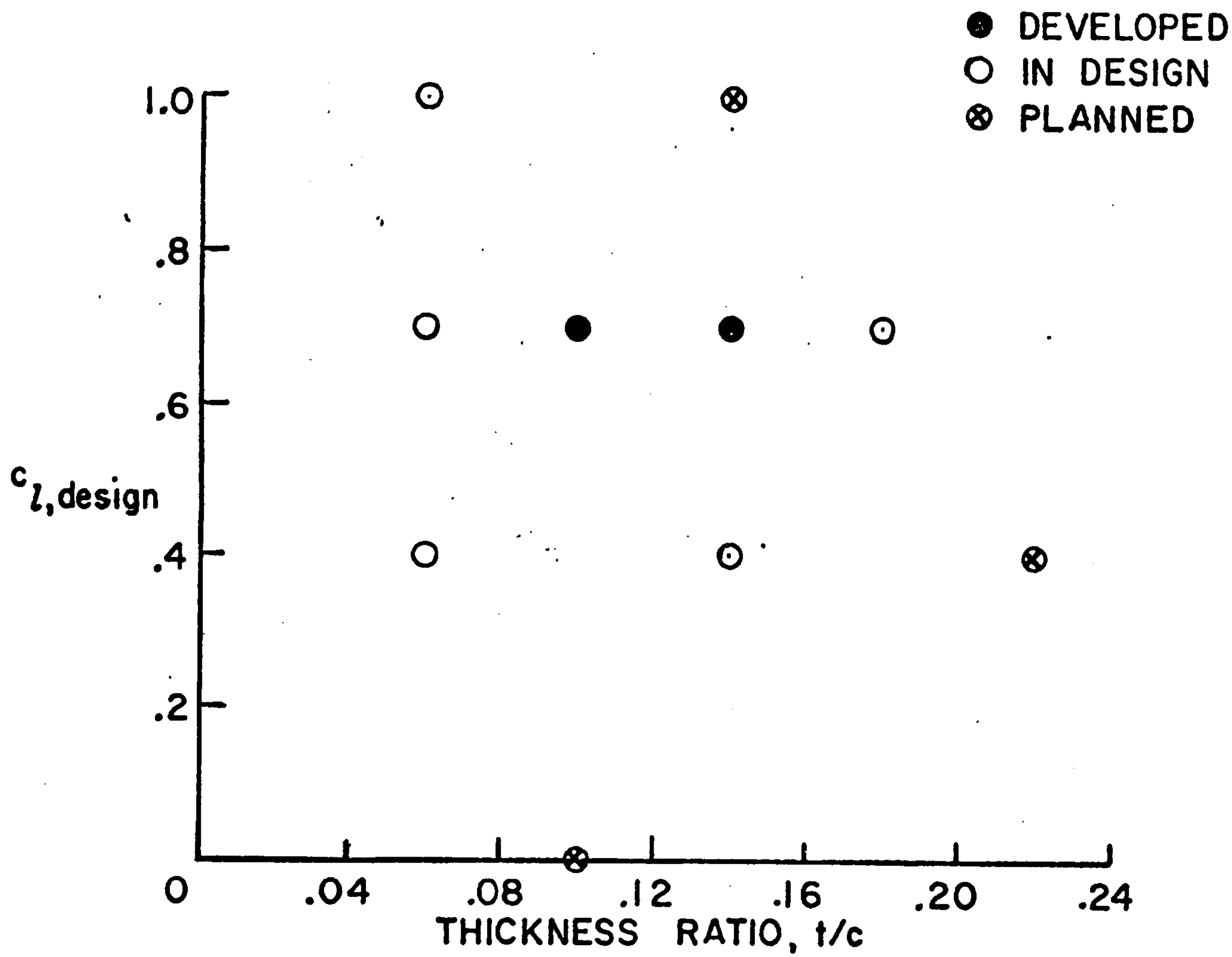


Figure 2. Supercritical Airfoil Family

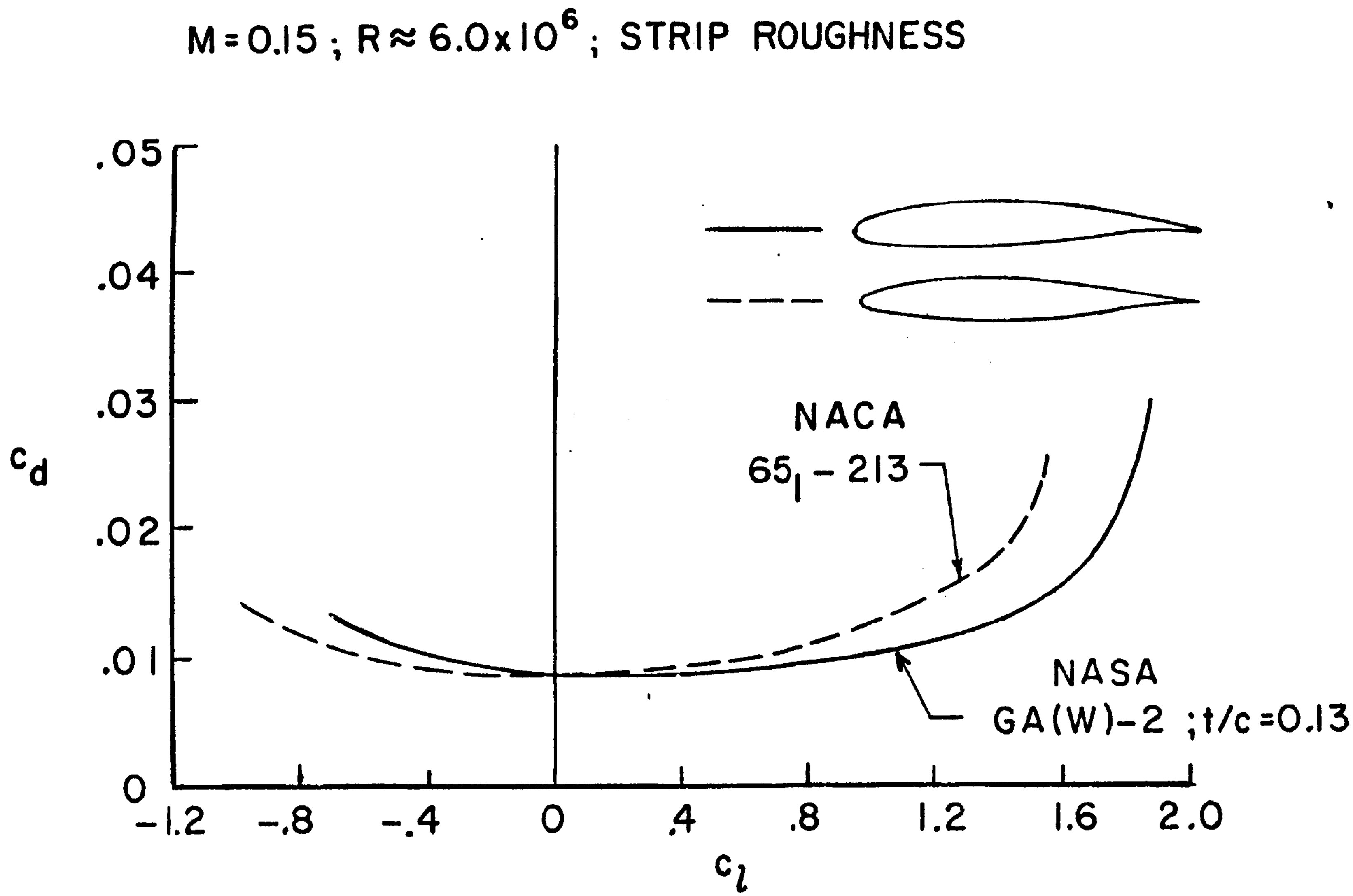


Figure 3. Subcritical Airfoil Improvements

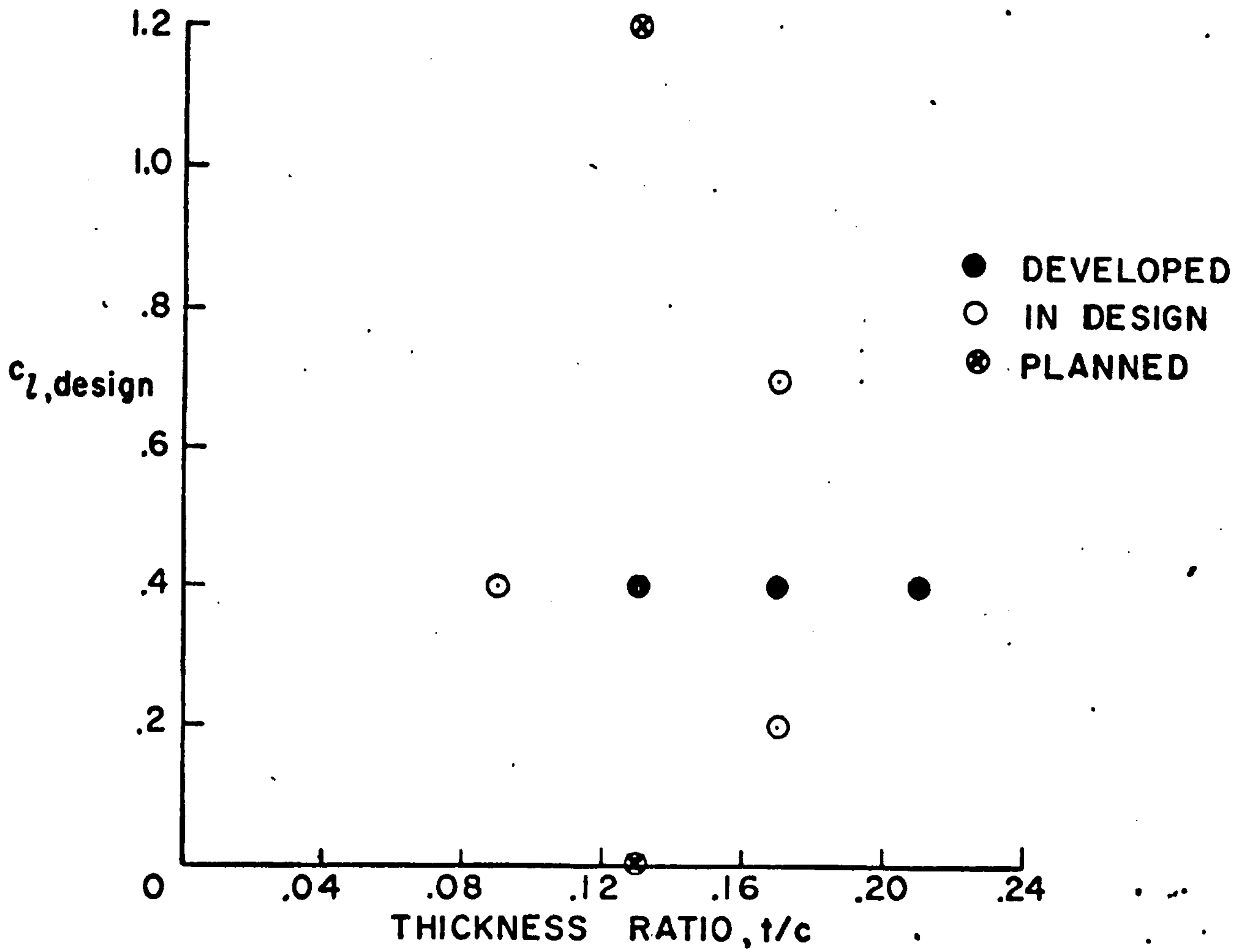
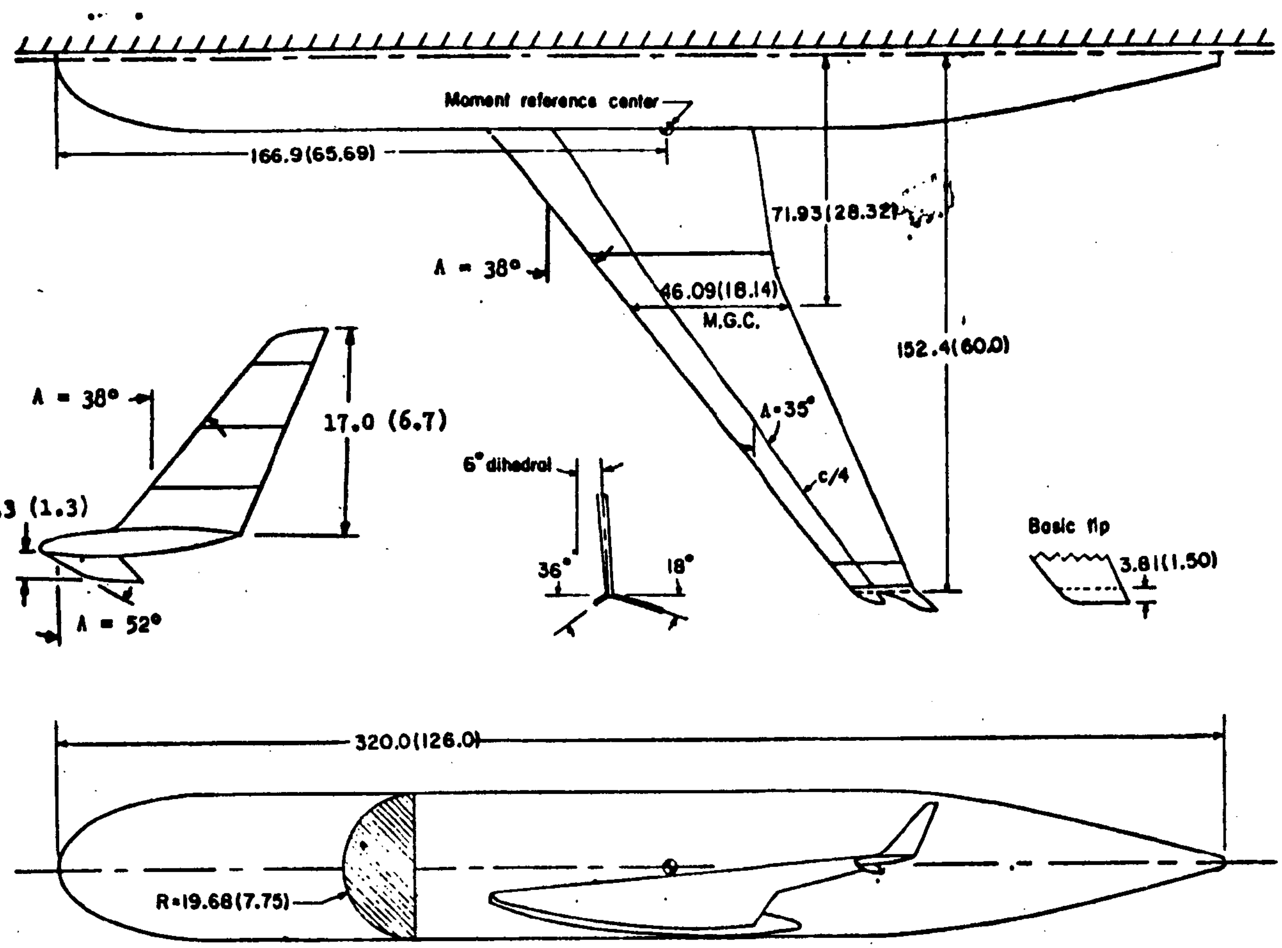


Figure 4. Subcritical Airfoil Family



Dimensions in centimeters (inches).

Figure 5. Vortex Diffuser Model

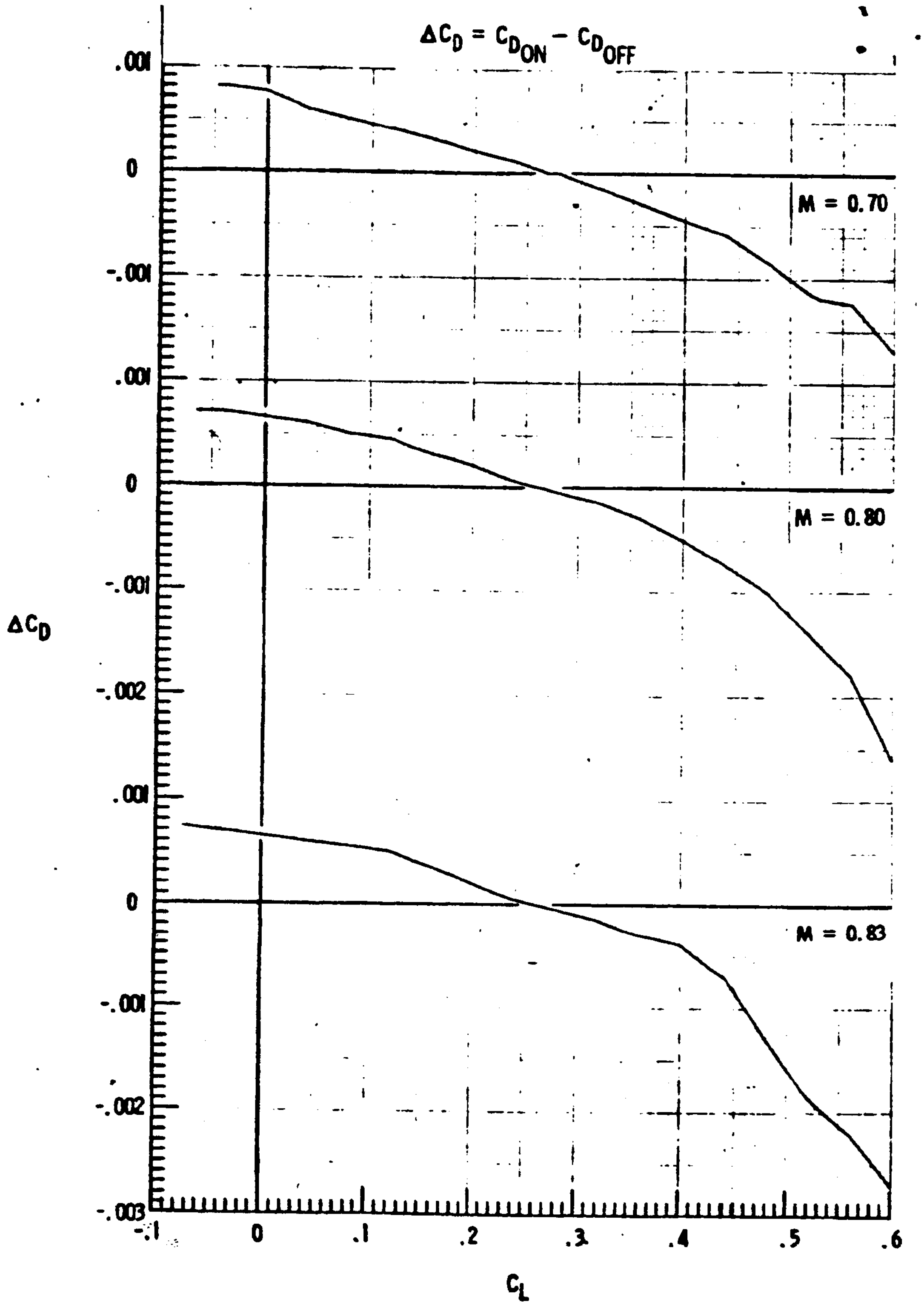


Figure 6. Vortex Diffuser Effects on Drag Coefficient

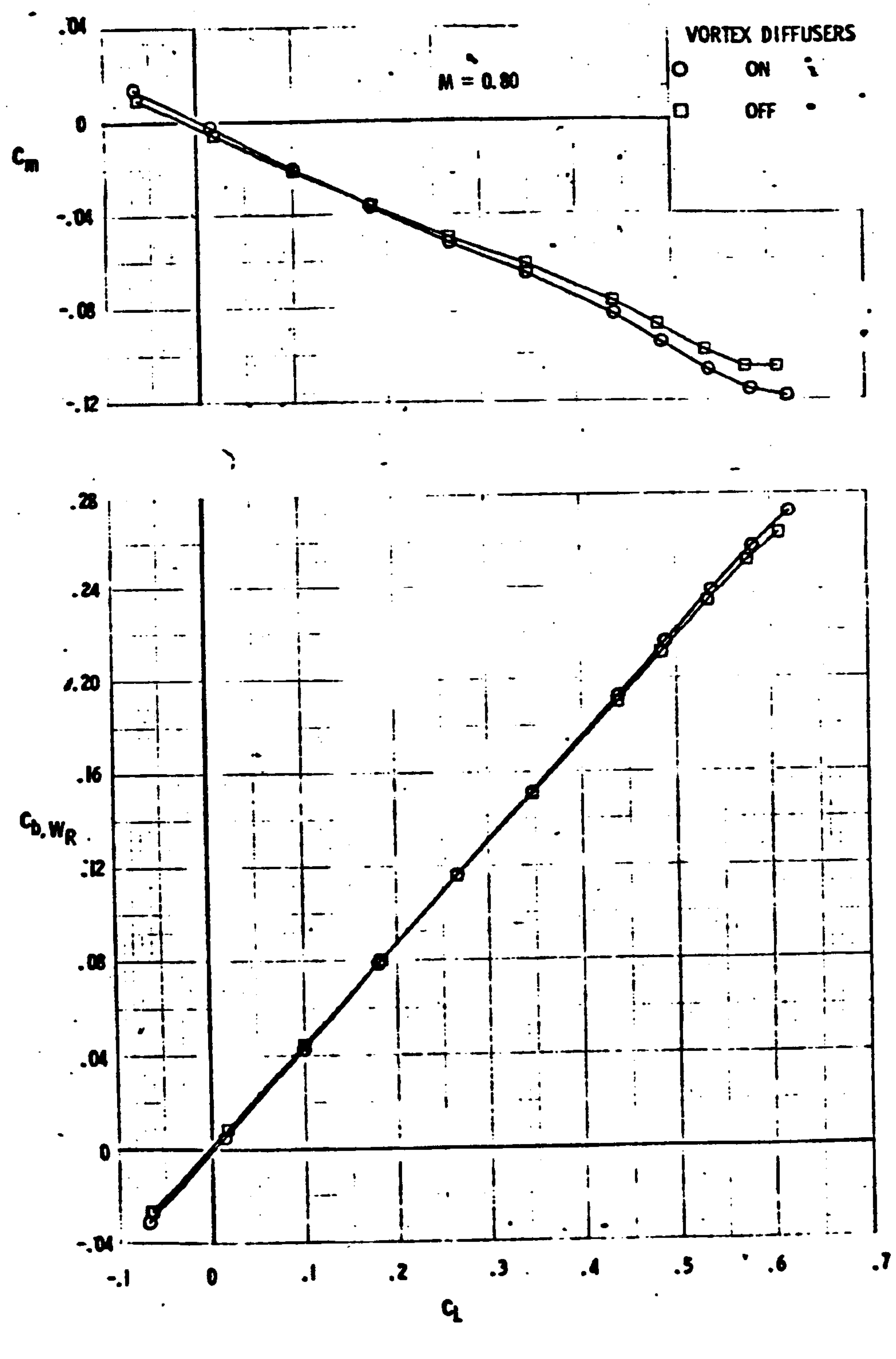


Figure 7. Vortex Diffuser Effects on Pitching-Moment Coefficient and Wing Root Bending-Moment Coefficient

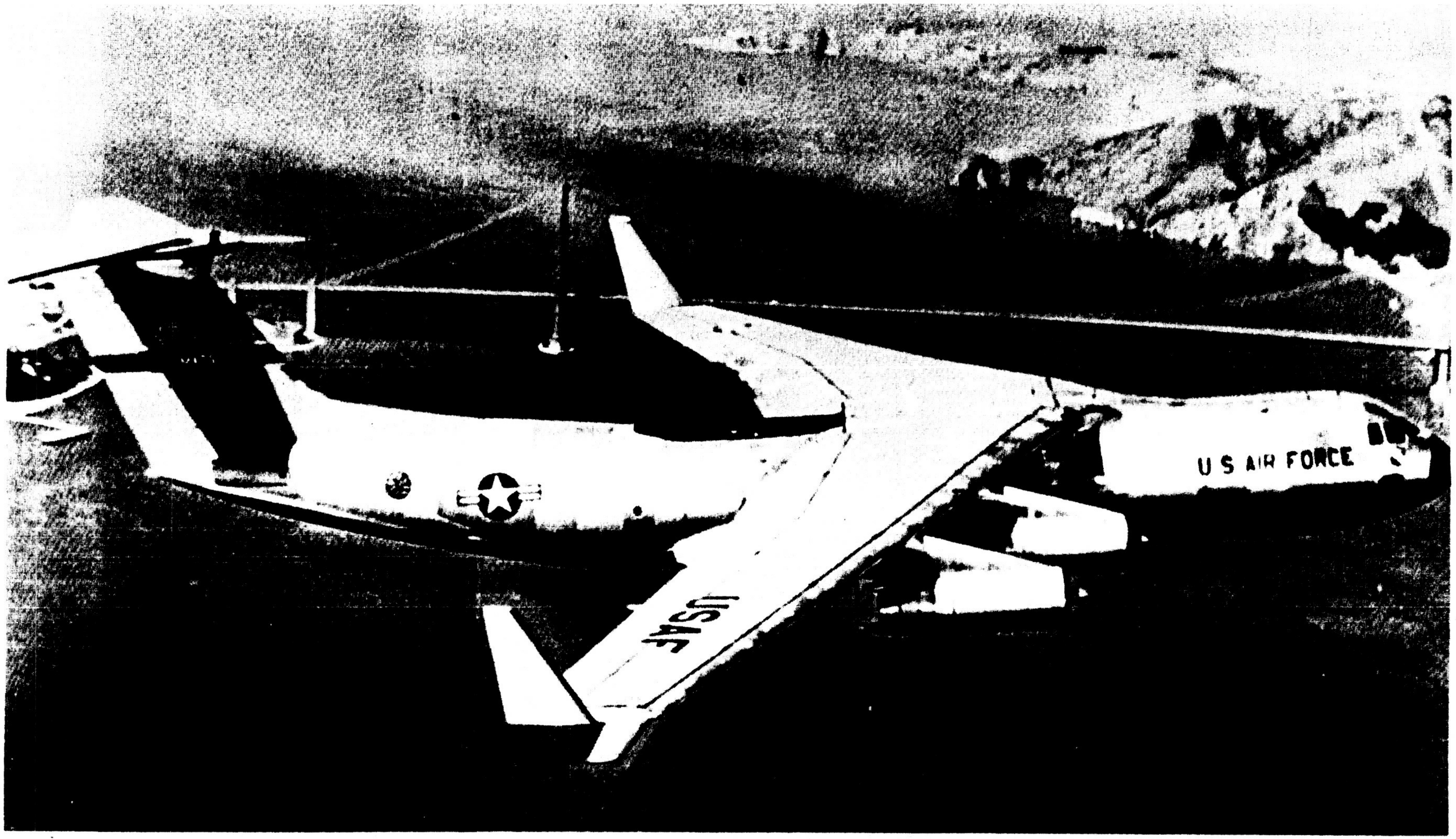


Figure 8. Lockheed C5A with Winglets

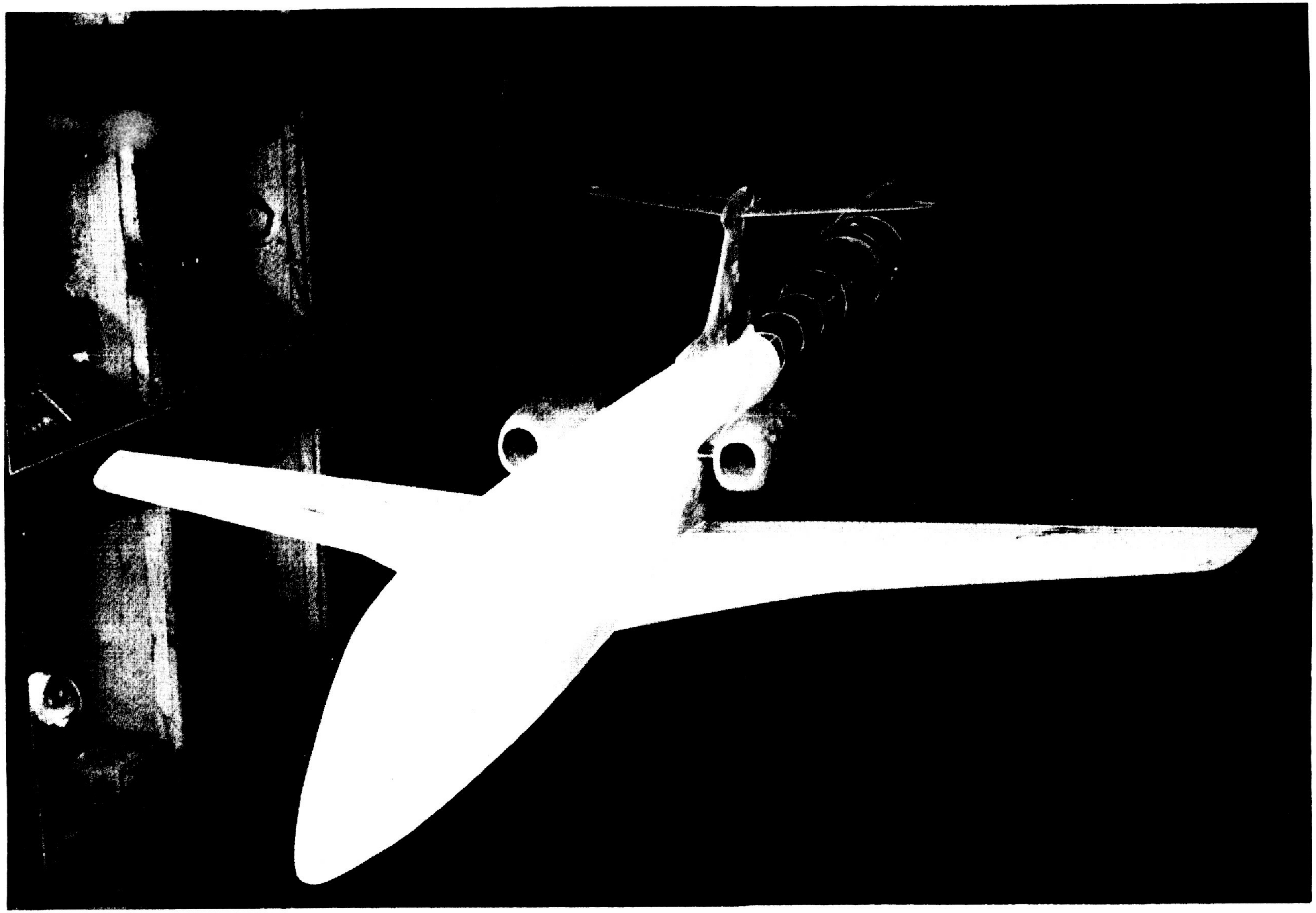


Figure 9. Typical Configuration Illustrating Wing-Nacelle-Fuselage Interference Problem

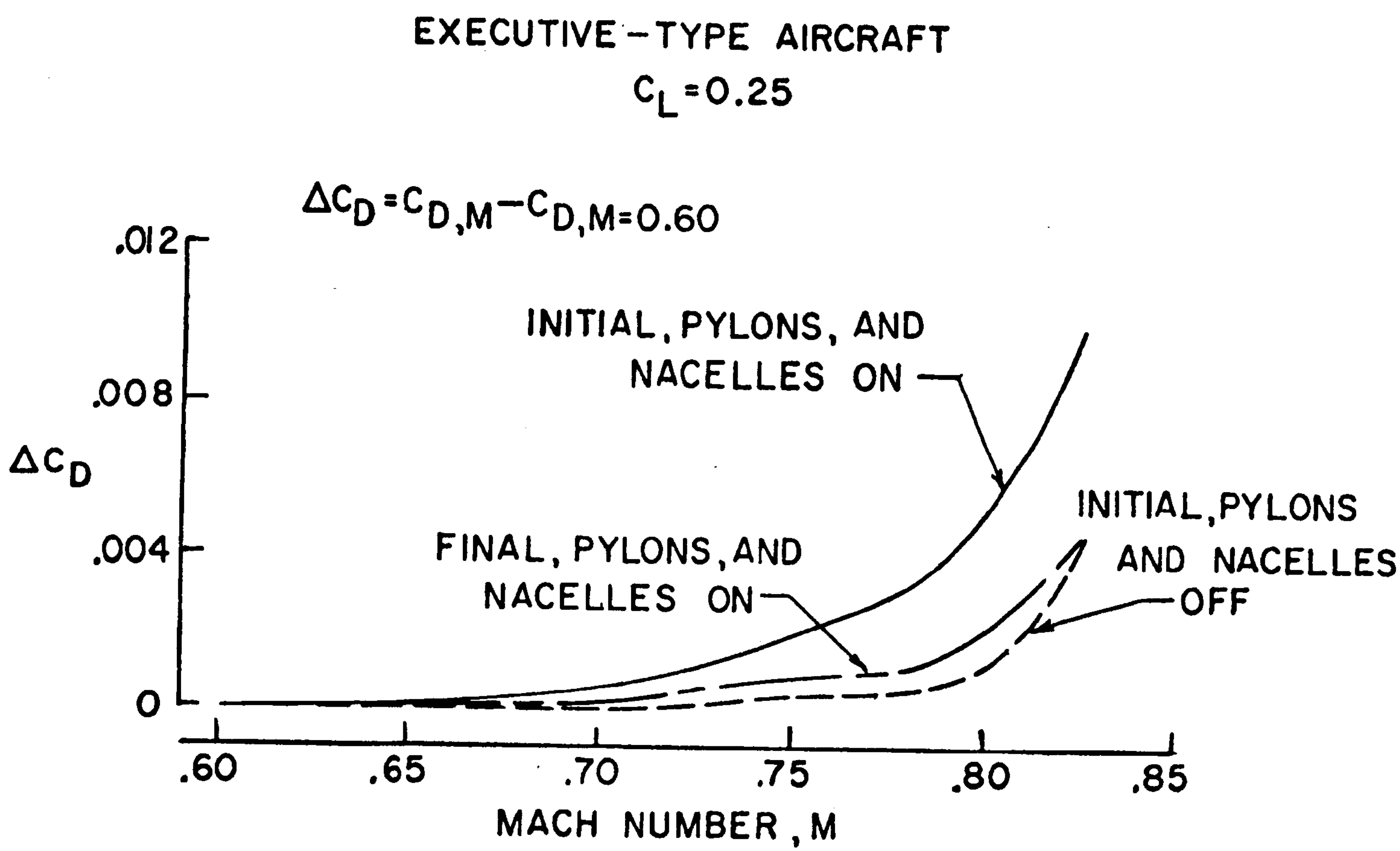


Figure 10. Effects of Wing-Root and Pylon Modifications

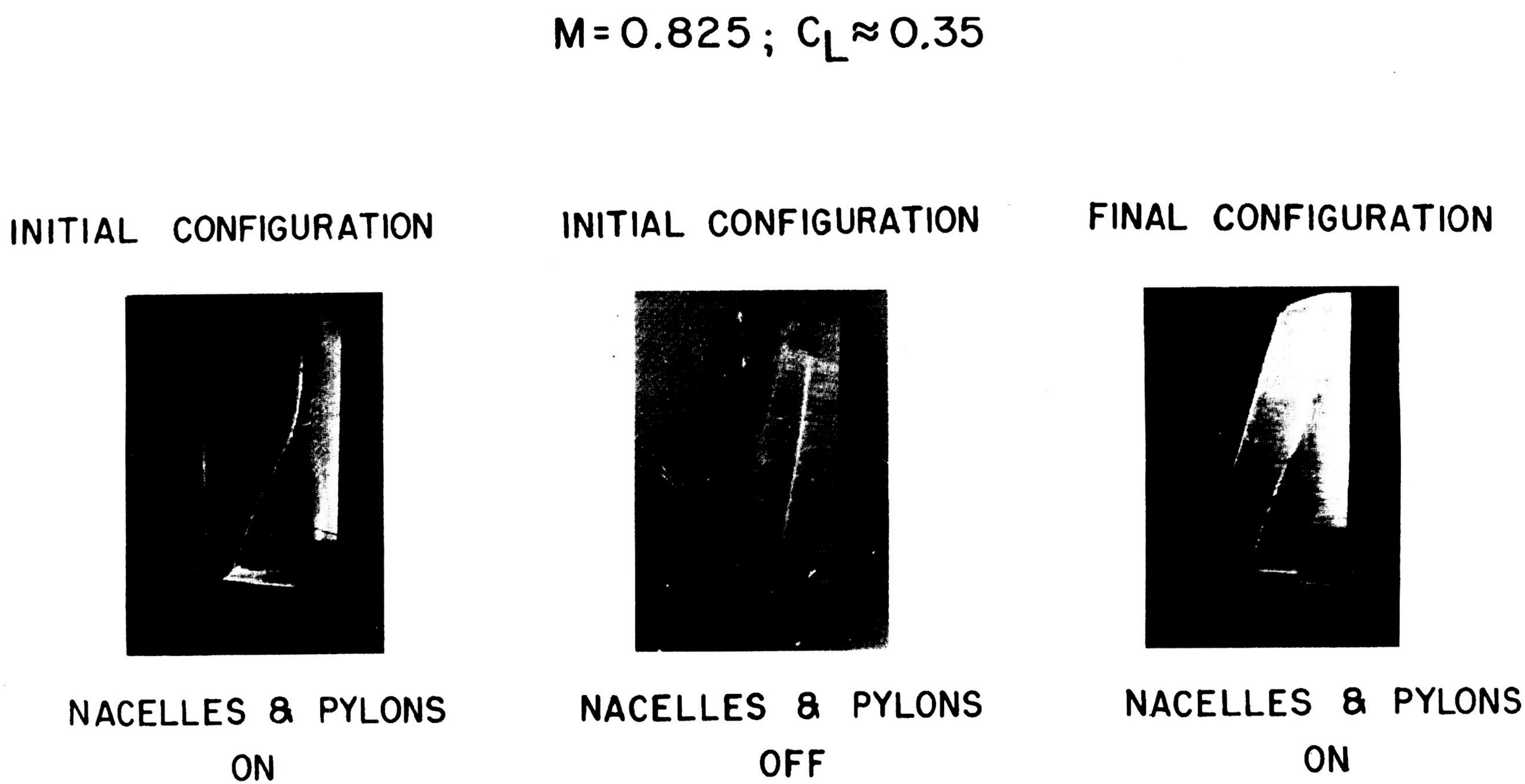


Figure 11. Wing Upper-Surface Oil Flows

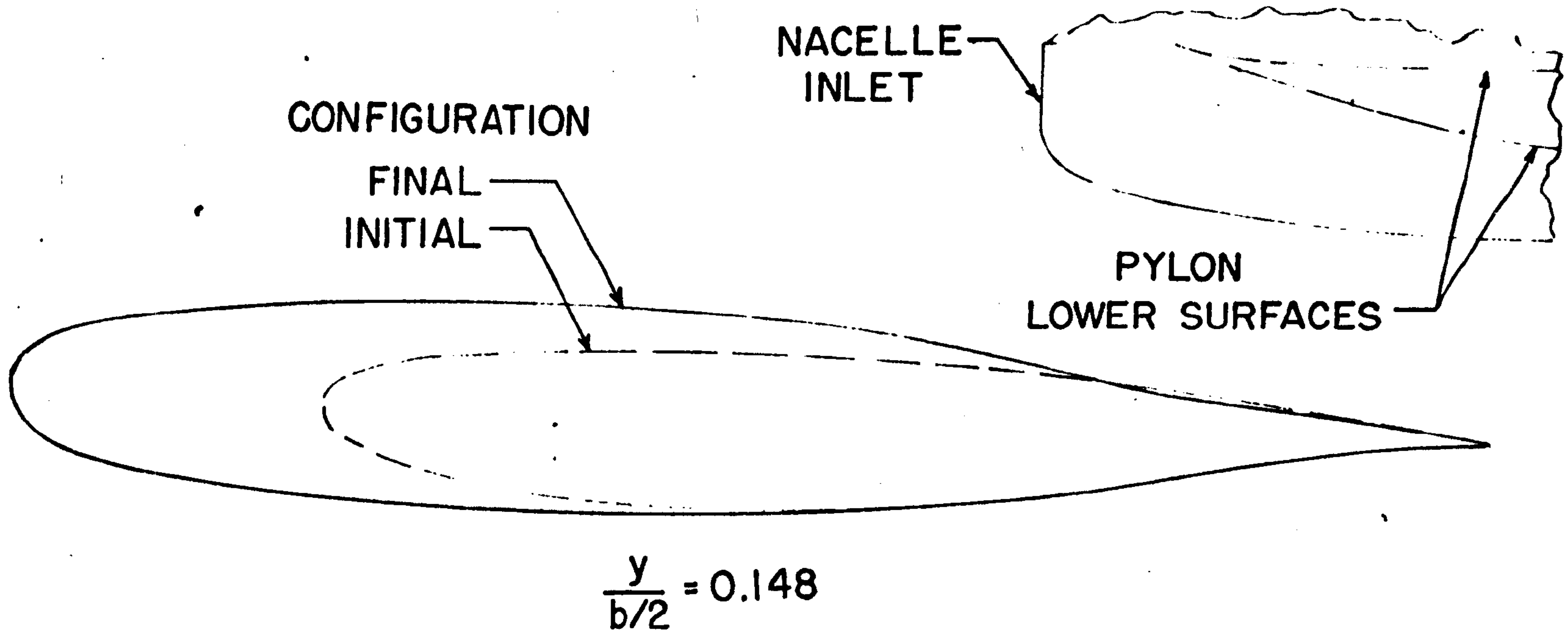


Figure 12. Wing-Root Airfoil and Pylon Modifications

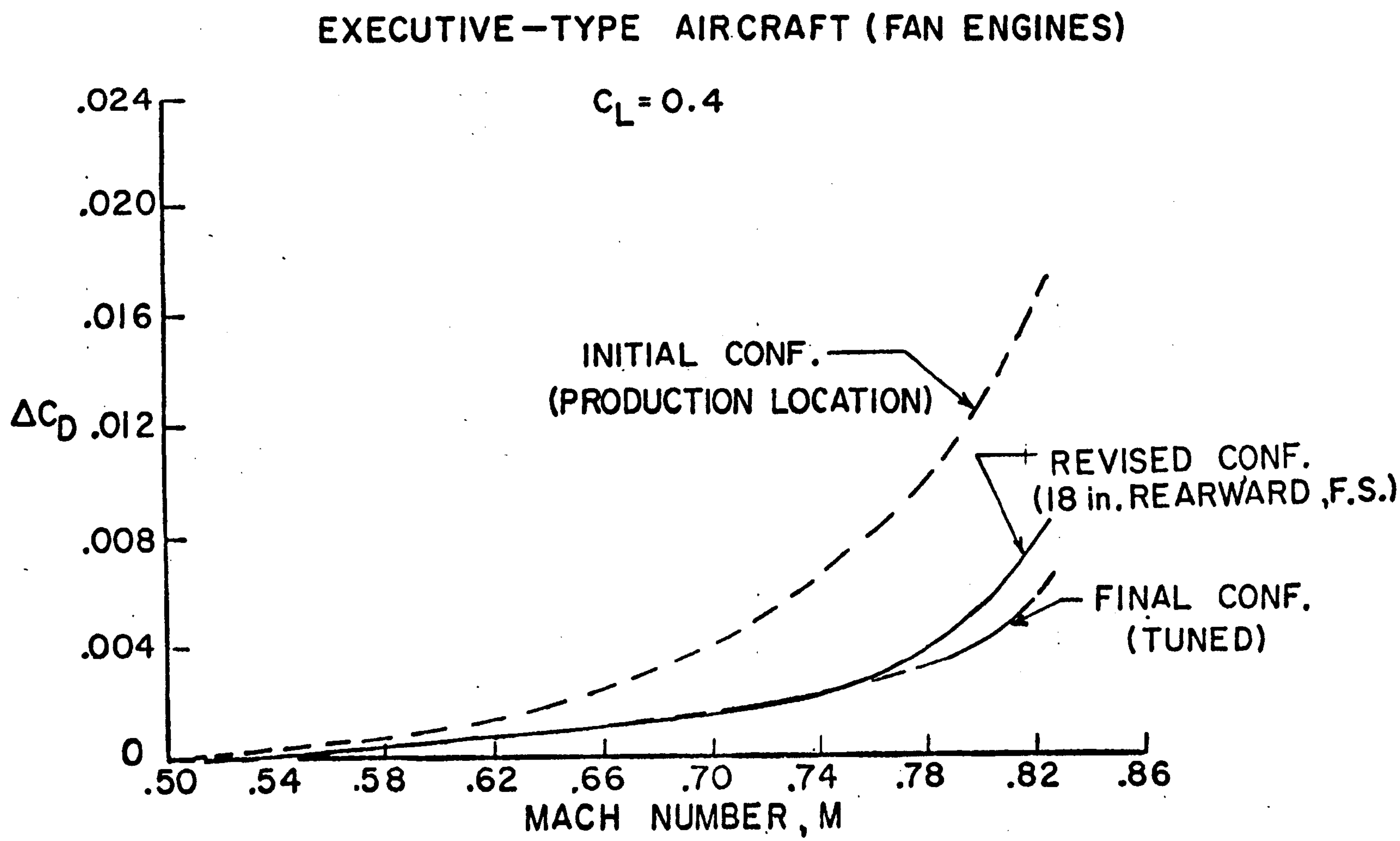


Figure 13. Effect of Engine Nacelle Translation