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5.6 Wing Tip Vortex Drag

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Introduction

The drag of a wing may be classified as composed of pressure drag, induced drag and skin friction drag. The induced drag which is the result of producing lift is induced by the vortex system set up around the finite three dimensional wing. By decreasing the strength of the trailing vortices, the induced drag may be reduced. The basic problem is to decrease the vortex without increasing the pressure and skin friction drag so that the total is decreased, or maximizing L/D.

The actual induced drag in pounds is:

$$D_i = \frac{W^2}{\pi b^2 q e}$$

By changing planform e may be varied up to the value for the ideal of the elliptical span loading. However, a two dimensional equivalent wing requires a maximum value of circulation of only $\pi/4$ that of the maximum for an elliptical wing loading. Thus, if the shed vortex could be reduced by this amount, the induced drag would be reduced 21 percent. Since induced drag accounts for 25 percent to 40 percent of the total aircraft drag, this would mean a total reduction of 5 percent to 8 percent over the elliptical loading. A number of methods such as wing tip end plates, tip tanks and winglets have been used or tested to provide an effective increase in aspect ratio and achieve a more two dimensional wing loading. In order to control the wing tip vortices the basic vortex characteristics need to be considered.

Basic Vortex Characteristics

The basic characteristics of the vortex are shown in the tornado(1), Figure 1. The core flow region and the free vortex region are clearly evident. Laboratory investigations(2) have shown that the strength of an unconfined vortex such as the wing tip vortex is a direct function of the vorticity present and the sink pressure and the area to create a core flow to organize the vorticity into a vortex. The circulation type vortex is shown in Figure 2, large diameter with little axial flow. Introducing an axial pressure differential, Figures 3, 4, and 5 show the development into a strong compresible flow vortex, Figure 6. Figure 7, the circulation is continued with a large decrease in axial pressure differential. Vortex breakdown occurs. Figure 8 shows the continuation of the compressible flow vortex with pressure differential only. The rotation of the cage has been stopped. The basic vortex is unstable and wanders around. Figure 9 shows the pressure trace at a fixed point as the compressible core, Figure 6, moves over and around the point. Idealizing the compressible flow vortex the core flow, pressure and density are shown in Figure 10. Figure 11 shows the formation of two compressible flow vortices shown in Figure 12. Using neutrally buoyant helium bubbles the compressible core flow is evident in Figures 13 and 14. Continuing circulation and decreasing the axial pressure differential, the core flow breaks down, Figures 15 and 16.

The vorticity shed in producing lift and the sink provided by the negative pressure region on the upper surface must both be minimized and/or neutralized to decrease the induced drag. Laboratory tests have shown that the introduction of pressure in the core will stop the core flow and dissipate the vortex. An obstruction screen or splines can be introduced into the core flow to attenuate the vortex. Counter vorticity likewise is effective in reducing the vortex. In a number of tests the introduction of turbulence by various means has set up instabilities in a vortex which has hastened its decay. Thus, there are a number of avenues available for some measure of vortex control.

Wing

The basic object is to maximize the wing L/D for a particular operating condition for a given aircraft. Most of the research to date on the wing-tip vortex has been conducted for the purpose of attenuating the vortex downstream of the aircraft, Figure 17. A drogue device properly positioned downstream of the wing tip causes breakdown, Figure 18. A jet engine simulator at the tip with a high-energy jet blast produces the same results.

To increase L/D by decreasing the induced drag the two basic parameters of the vortex must be controlled:

1. The vorticity shed by the wing must be minimized.
2. The low pressure region on the top of the wing must be blocked from the shed vorticity. It is the wing-tip vortex core flow (or deficit flow) that is largely responsible for producing the induced drag.

The vorticity may be reduced by plates, tip-tanks, winglets and counter vortex flow which effectively increase the aspect ratio of the wing. The general effect of these on L/D are shown in Figures 19, 20, and 21. It will be noted that there is a particular angle of attack at which the device offers the largest advantage. It would be expected that any one of these could be optimized further as to size, shape, angle and contour for a given angle of attack of the wing.

Efforts to use a jet have been directed at reducing vorticity downstream. Figure 22 shows the effectiveness of various jet strengths on the dissapation of vorticity. Obviously the upstream jet is not effective in reduction of L/D. The proper use of the downstream jet may be part of the answer. Again the size, location and strength must be optimized for maximum L/D.

The Method of Approach

The method of approach for optimization of L/D through minimizing induced drag should be through a detailed flow study together with force, pressure and vorticity measurements. Flow visualization with neutral helium bubbles, Figure 23 and 24, provides an excellent means of observing the effects of configuration changes. A systematic wind tunnel investigation of a large number of configuration changes should be made. The study should explore all avenues which appear promising as the study progresses even though it may lead to the rebirth of the biplane or triplane.

References

1. Muirhead, V.U., "Compressible Vortex Flow," AIAA Paper No. 73-106, 11th Aerospace Science Meeting, New York, New York, January 1973.

2. Eagleman, J.R.; Muirhead, V.U.,; Willems, N., Thunderstorms, Tornadoes, and Building Damage, Lexington Books, D.C. Heath and Company, Lexington, Mass., 1975.

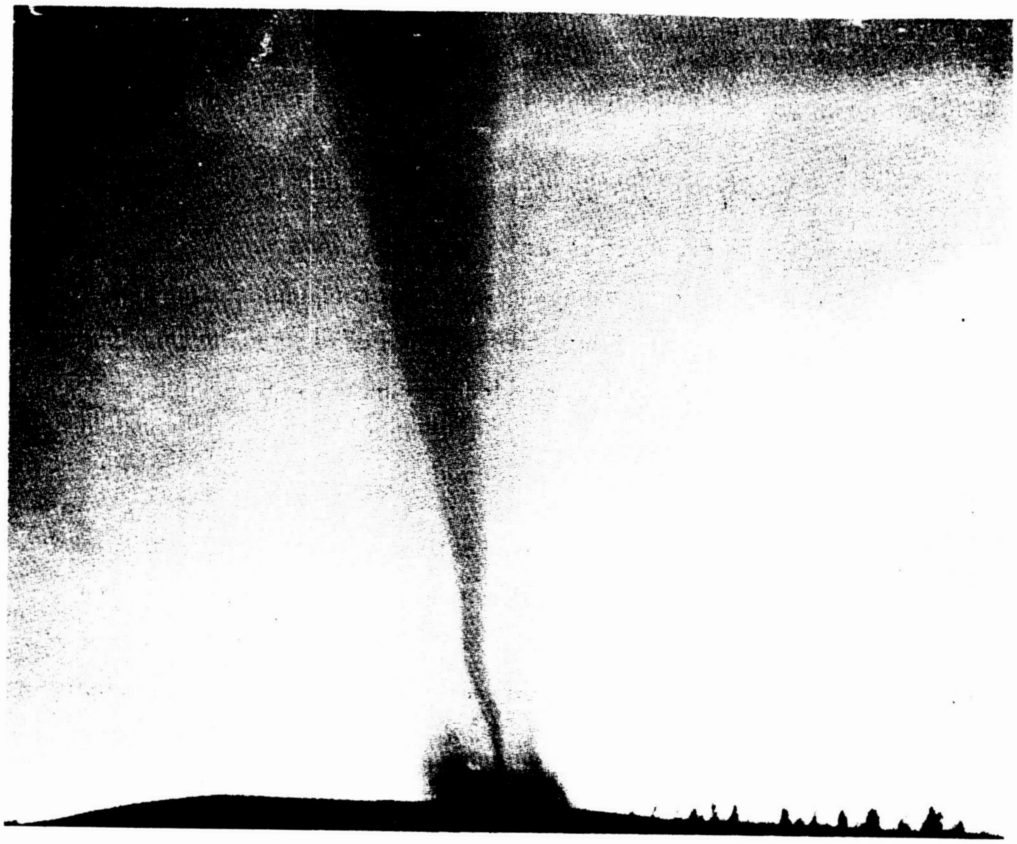

Figure 1. Tornado

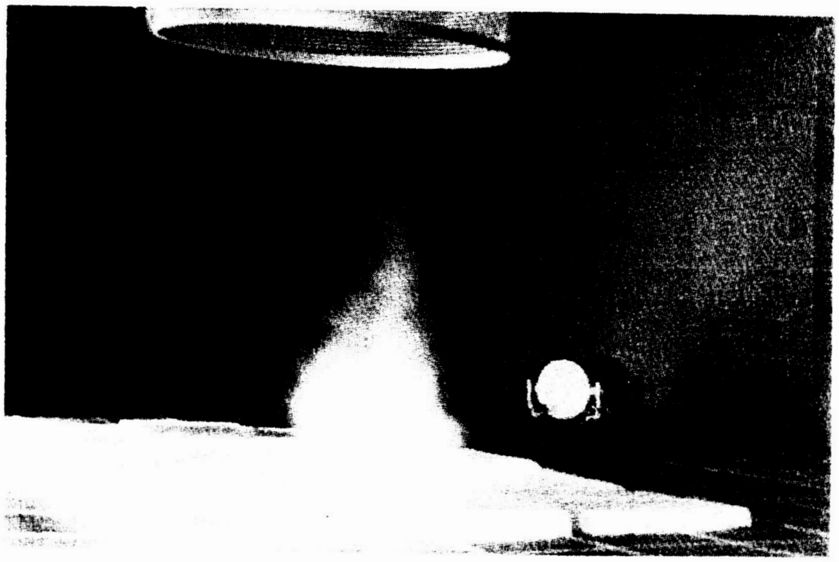

Figure 2. Circulation Vortex

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Figure 3. Introduction of Axial Pressure Differential

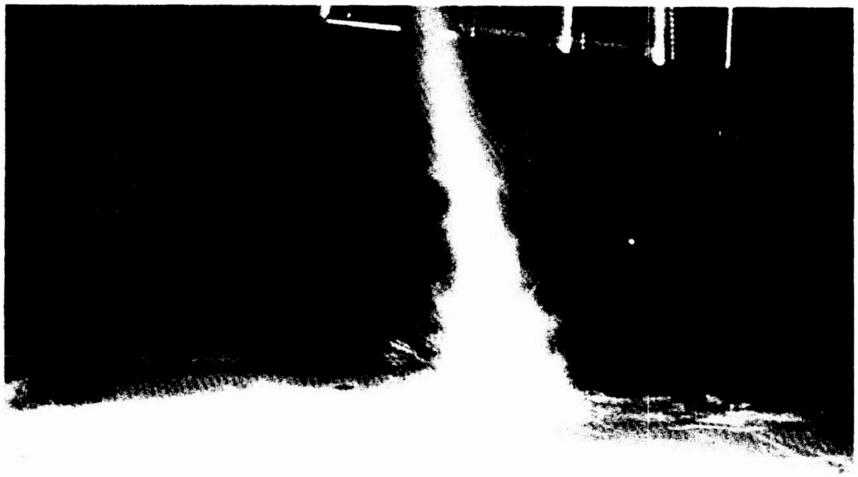

Figure 4. Early Vortex Development

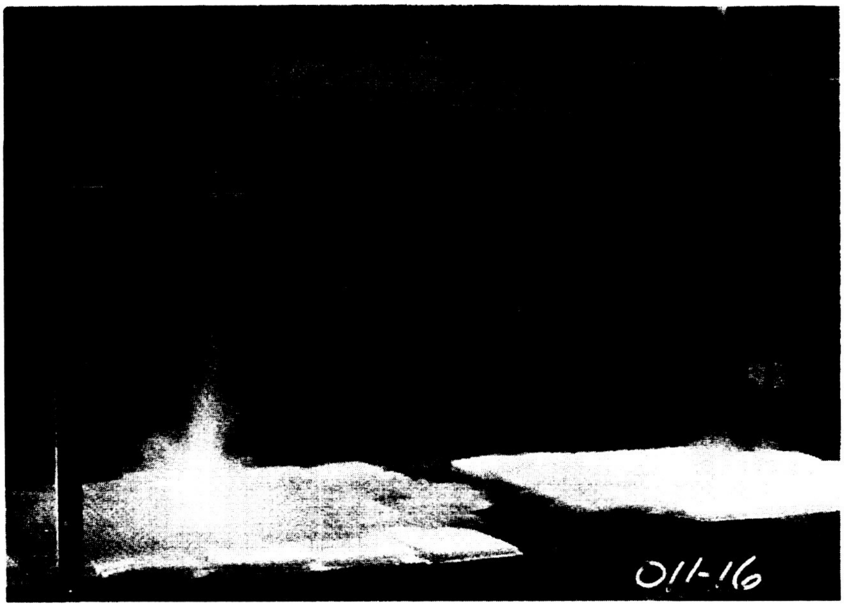

Figure 5. Vortex Development - Spiral Vortices

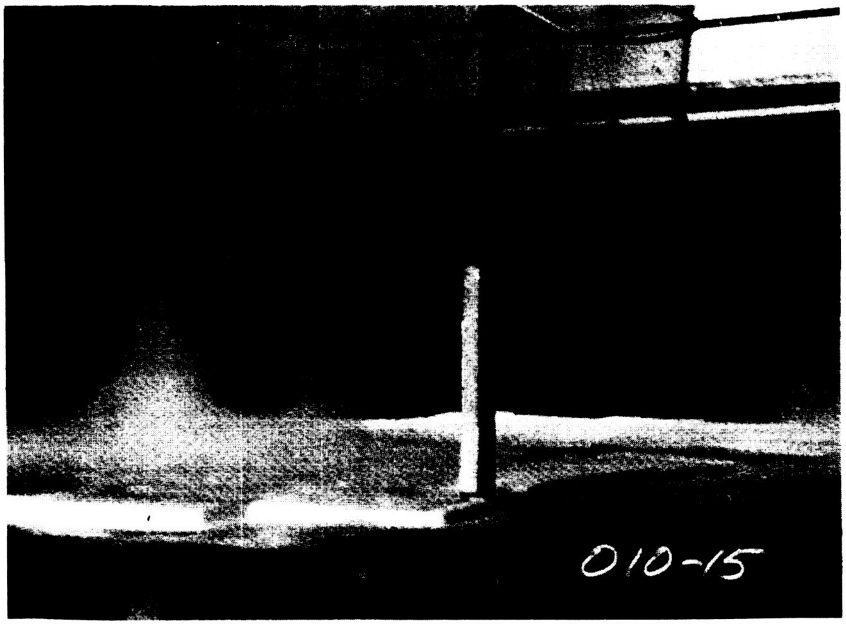

Figure 6. Compressible Vortex Flow

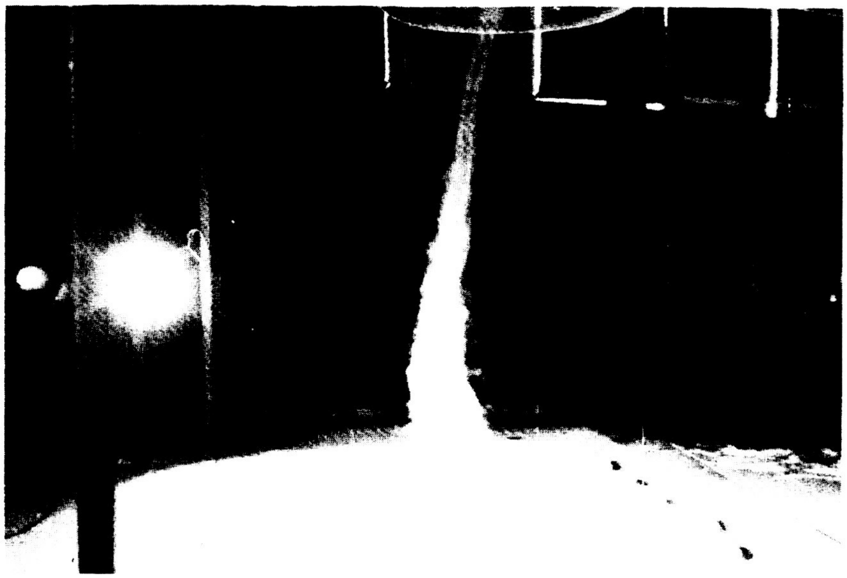

Figure 7. Vortex Breakdown - Circulation with Decreasing Axial Pressure Differential

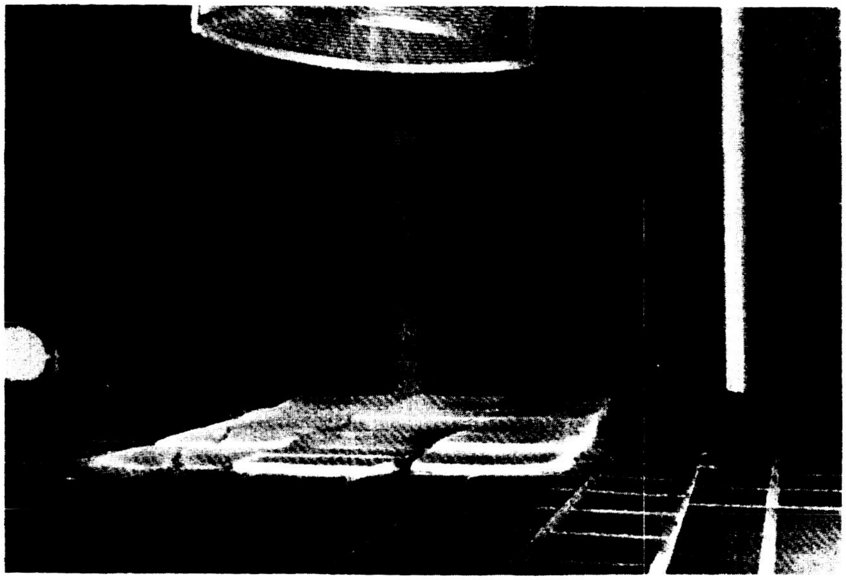

Figure 8. Vortex Sustained by Axial Pressure Differential

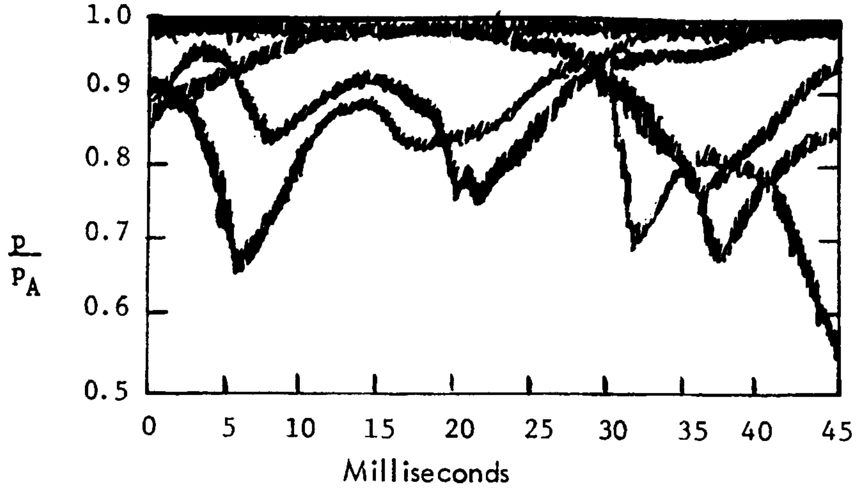

Figure 9. Pressure Traces

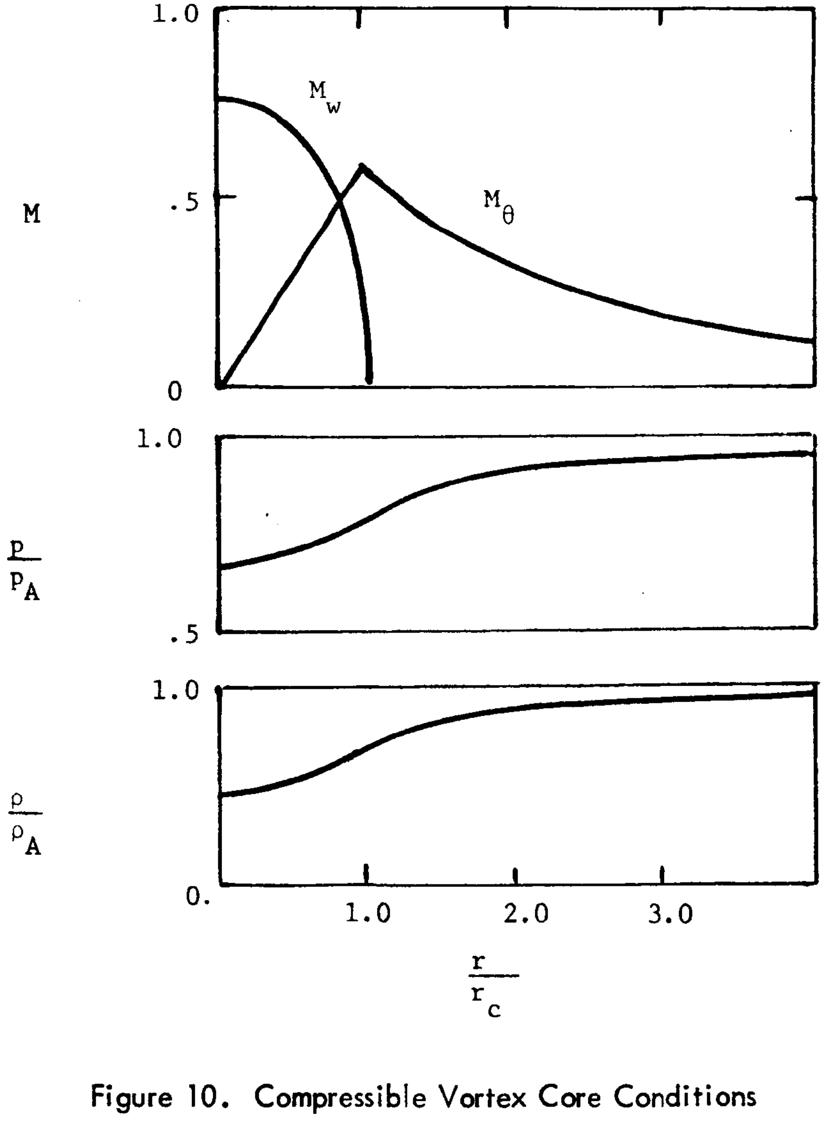

Figure 10. Compressible Vortex Core Conditions

Figure 11. Two Vortices Forming

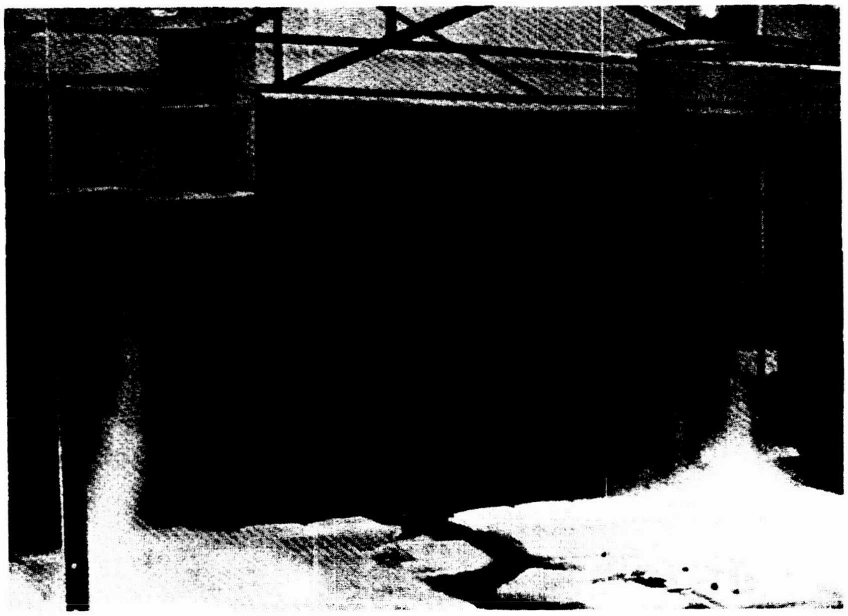

Figure 12. Two Strong Compressible Vortices

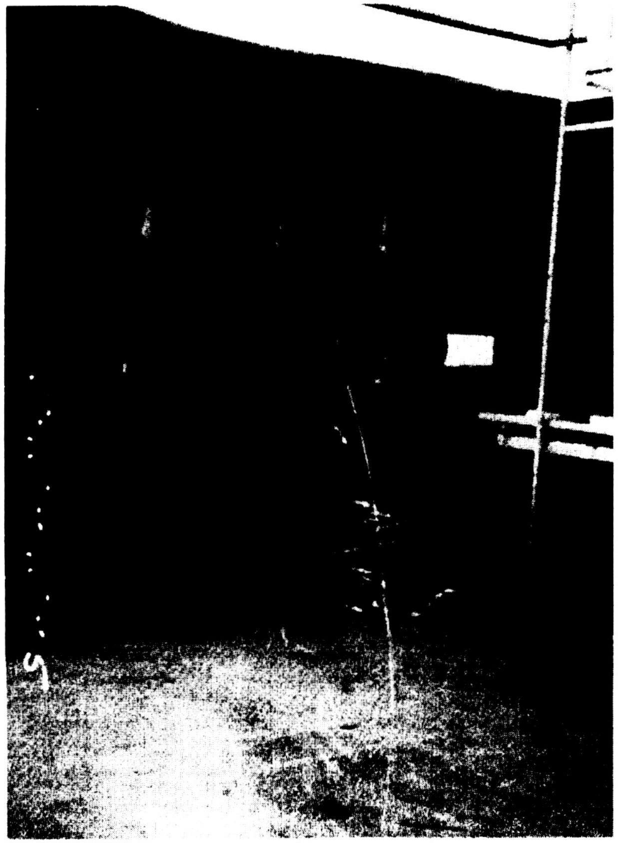

Figure 13

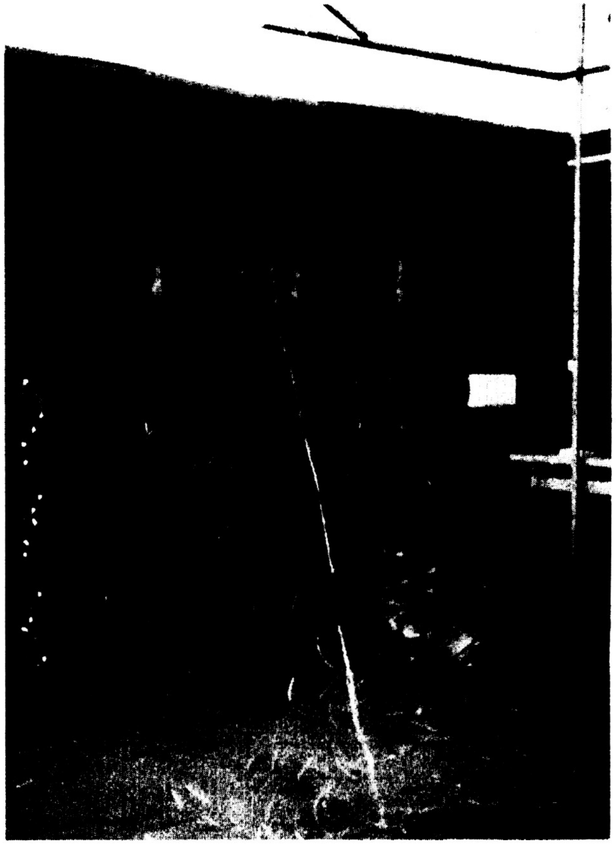

Figure 14

Visualization of Compressible Core - Helium Bubbles

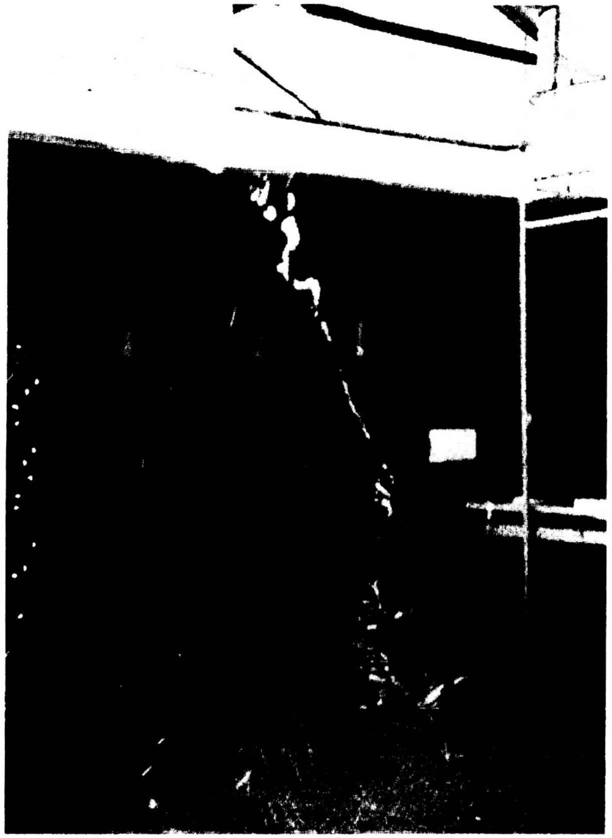

Figure 15

Figure 16

Vortex Breakdown – Helium Bubbles

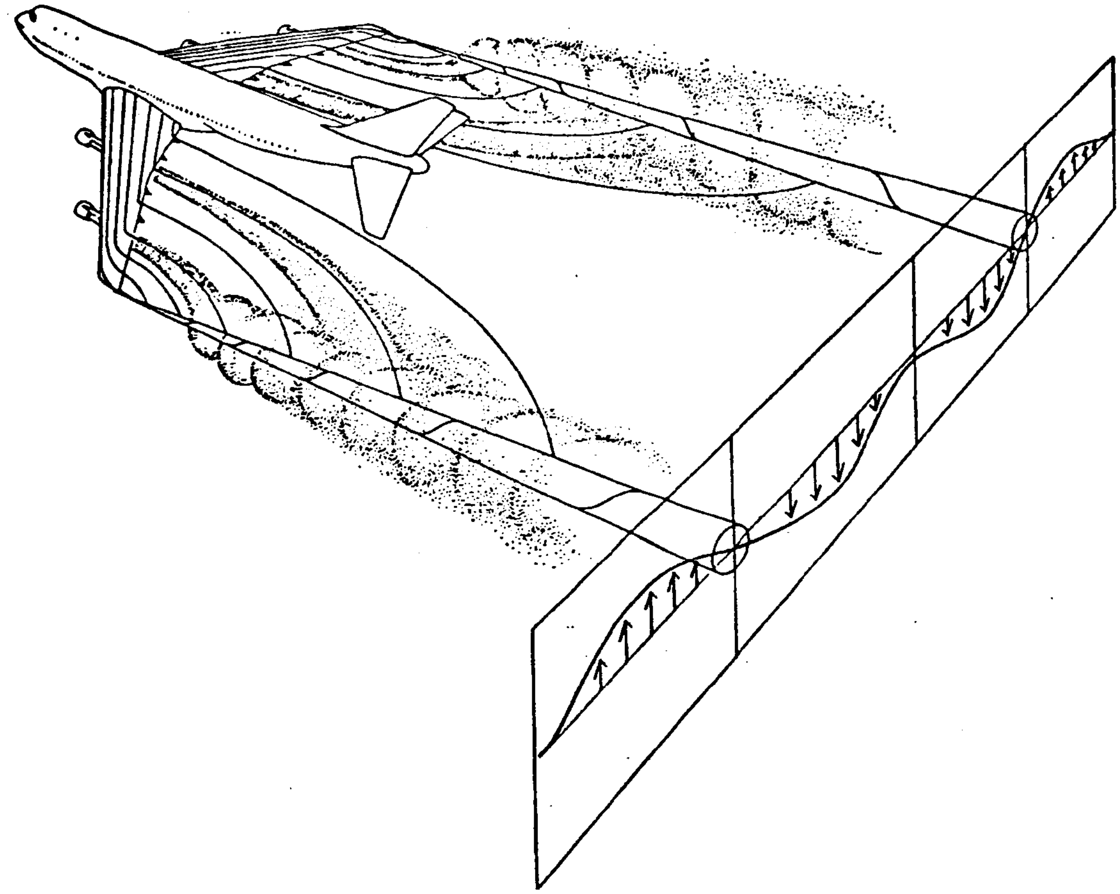

Figure 17. Vortex System

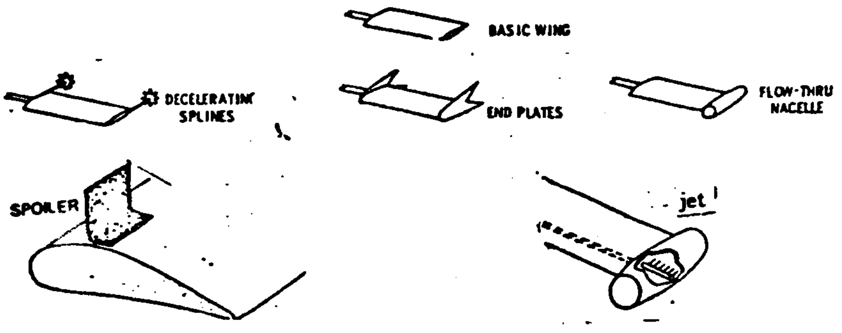

Figure 18. Attenuation Methods

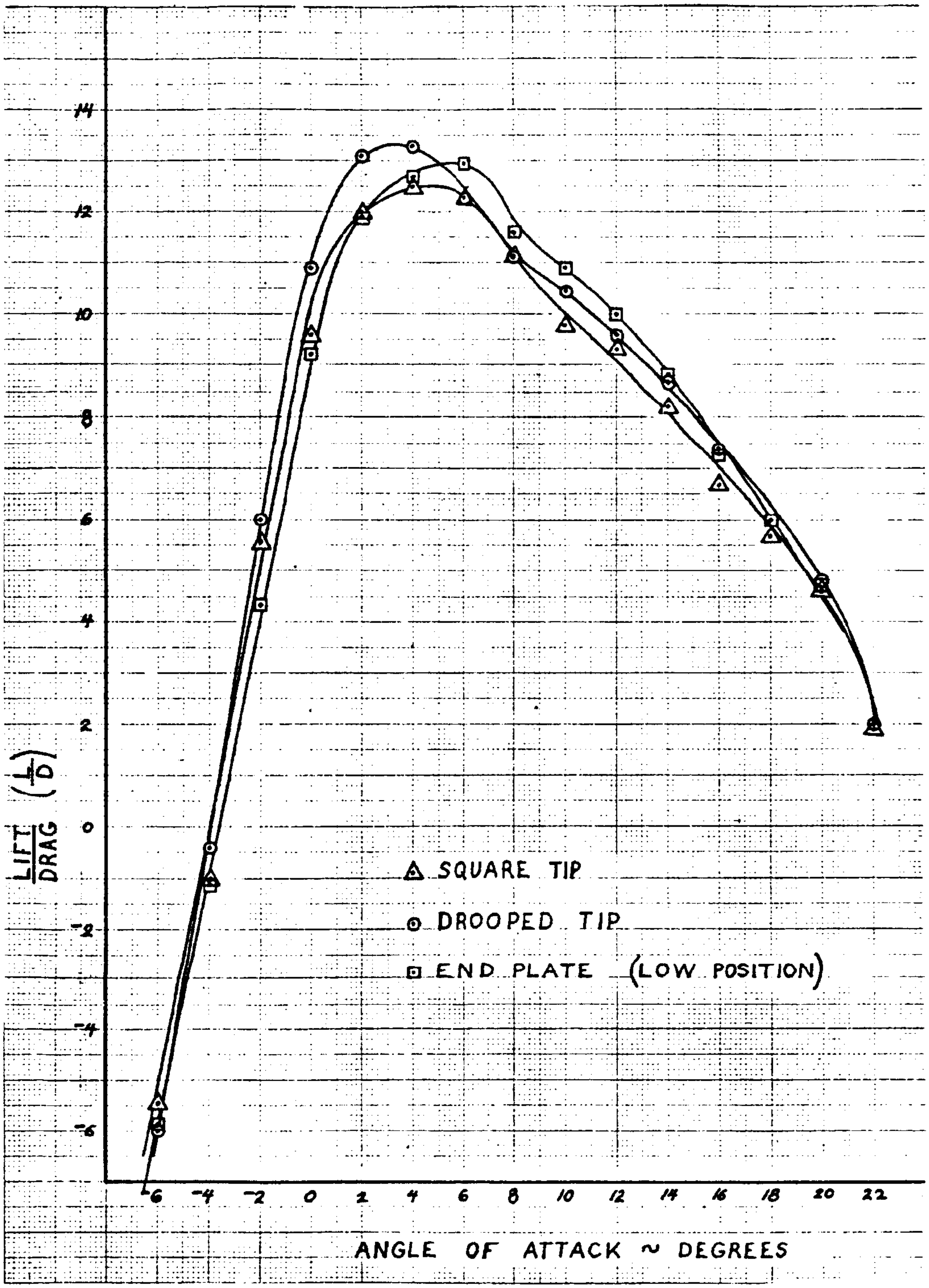

Figure 19. L/D of Wing Tip Configurations

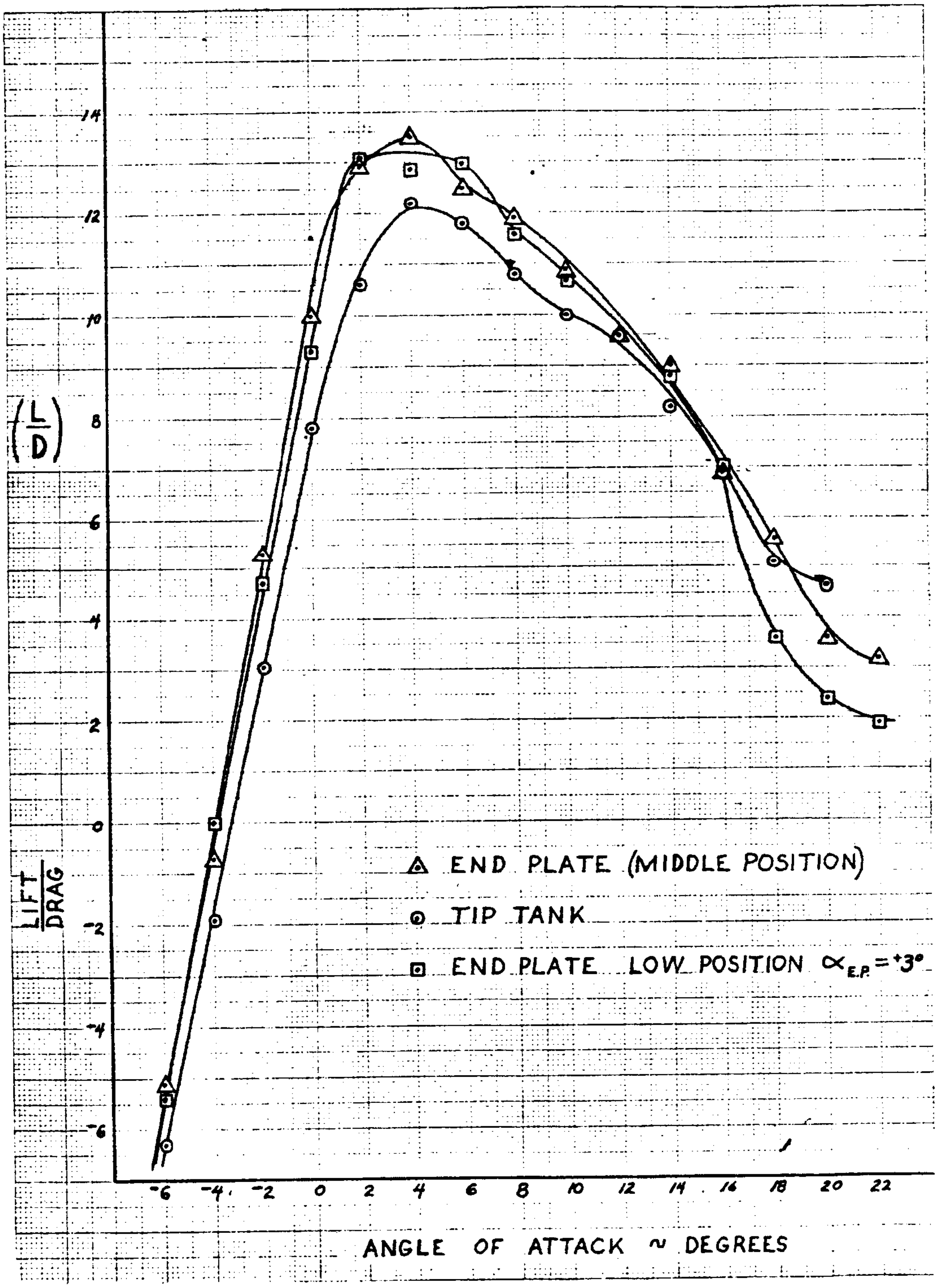

Figure 20. L/D of Wing Tip Configurations

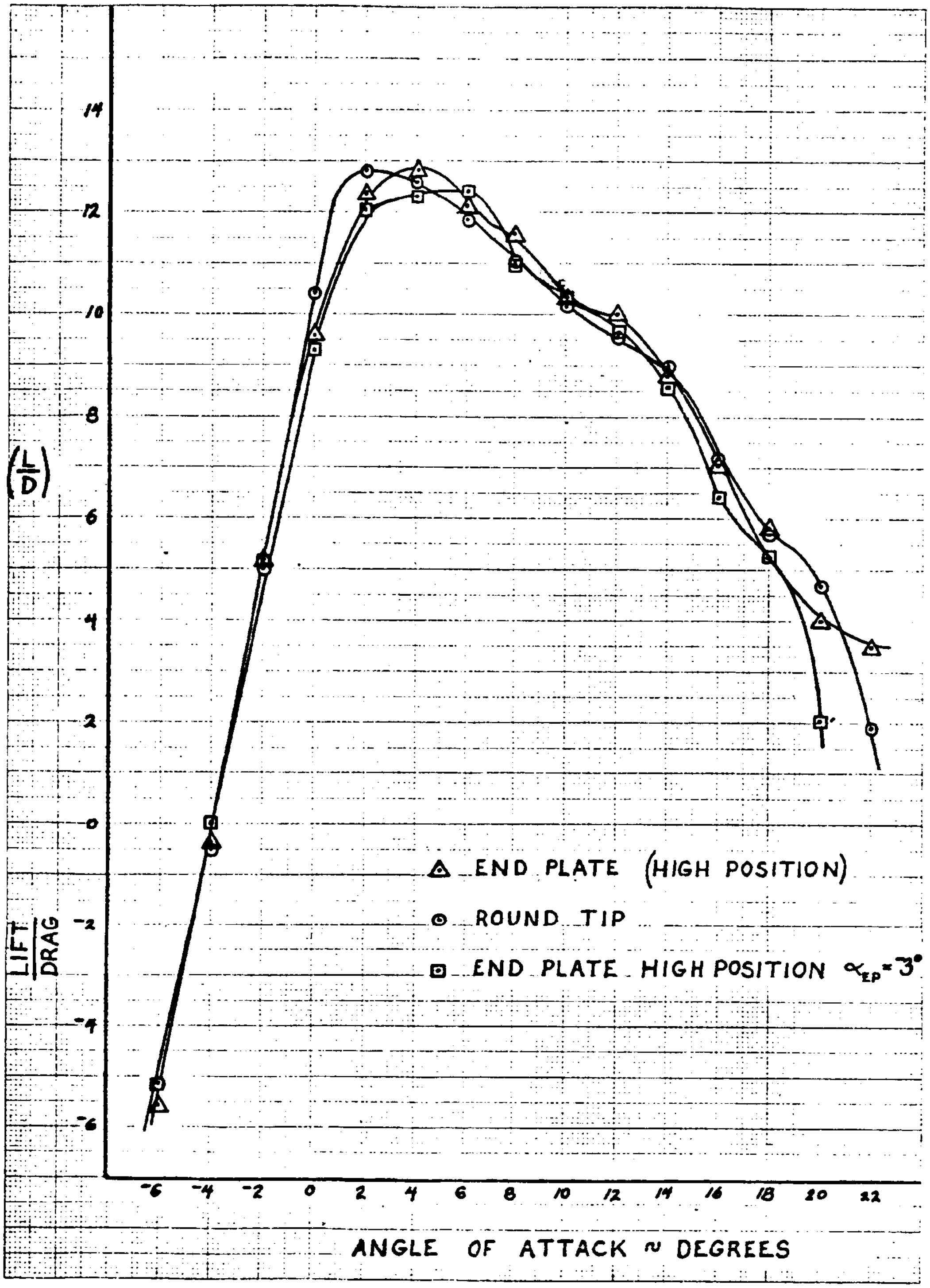

Figure 21. L/D of Wing Tip Configurations

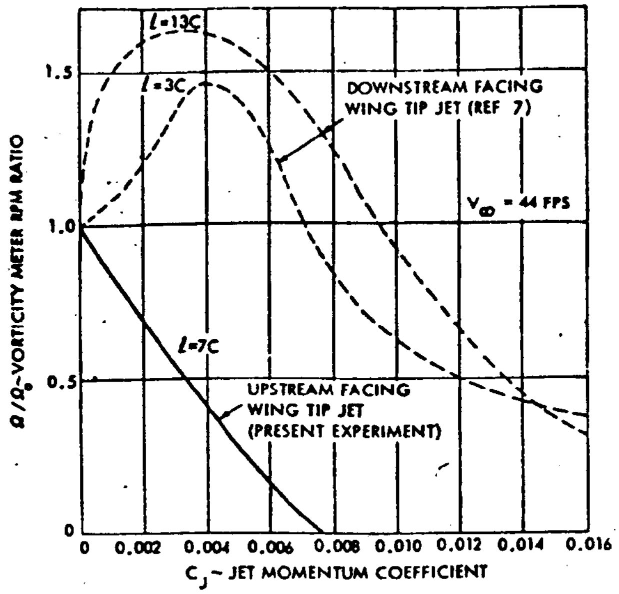

Figure 22. Jet Effect on Wing Tip Vortex

Figure 23. Rounded Wing Tip - Flow Visualization

Figure 24. Wing Tip Plate - Flow Visualization

6. PAPERS OF SESSION IV - EXTERNAL DRAG AND INTERFERENCE DRAG

6.1 Overview of External Nacelle Drag and Interference Drag
R. D. Neal, Gates Learjet Corporation

6.2 Installation Drag Considerations Other than External Nacelle and Interference Drag as Related to Turboprop and Turbofan Engines
G. Burnett, Garrett AiResearch Manufacturing Company of Arizona

6.3 Nacelle Drag Reduction: An Analytically Guided Experimental Program
F. Smetana, North Carolina State University

6.4 Cooling Drag Associated with General Aviation Propulsive Systems
E. J. Cross, Jr., Mississippi State University

6.5 Propellers of Minimum Induced Loss, and Water Tunnel Tests of Such a Propeller
E. E. Larrabee, Massachusetts Institute of Technology