Recently, illustrations have appeared in the aviation press of a number of different aircraft with small, nearly vertical, surfaces mounted at the tips of the wings (fig. 1). These surfaces significantly decrease the drag or air resistance of the airplanes which allows reductions of engine power and fuel consumption. These improvements provide increases in the range or payload of the airplanes. Since the shape and basic aerodynamic action of these surfaces are similar to those of wings they are called winglets.

The lift or upward force on a wing is produced by air pressures which are less than atmospheric above the upper surface and greater than atmospheric below the lower surface. At the wing tip the reduced pressures above the wing draw the air inward while the increased pressures below the wing force the air outward (fig. 2). These crossflows persist behind the wing where these effects, together with a downflow behind the wing and an upflow beyond the wing tip, combine to cause a vortex or swirling flow behind each wing tip. These vortices are similar to small tornadoes. Substantial drag, called "induced" drag, is associated with these vortices; at the usual airplane cruise flight conditions it is about 40 to 50 percent of the total airplane drag. It has been recognized for many years that vertical surfaces at the wing tips should decrease the crossflows at the tips, lessen the strength of the

Mailed 6-13-78.
resulting vortices, and thus reduce the drag. As early as 1897 a patent was obtained by Lanchester for vertical surfaces at the wing tips. During the period from about 1925 to 1955 a number of wind tunnel experiments were conducted on various such surfaces, called end plates. However all of these experiments indicated very little or no reduction in drag at airplane cruise conditions.

Research on winglets was initiated at the Langley Research Center of the National Aeronautics and Space Administration in 1974. In contrast to the simple flat end plates tested earlier, winglets are designed with the same attention to detail as is used in designing wings. In particular, as for wings, the surfaces have specially designed airfoil shapes. (Airfoils are the cross sections of the wing or winglet parallel with the flight direction and perpendicular to the span or length of the surface.) For wings the airfoils are "cambered," that is the curvature of the upper surface is greater than that of the lower side. With such a shape lift is produced more effectively. For winglets mounted above the wing tips (fig. 1) the airfoils are cambered such that the inner sides have more curvature than the outer sides as shown in figure 3. Further, as for wings, the winglets usually have relatively high aspect-ratios, that is, the ratios of the length or span dimensions to streamwise or chord dimensions.
(See fig. 1.) Further details of the design of winglets are presented in reference 1.

The action of the winglets is illustrated in figure 3. Because of the camber of the winglet airfoil the winglet produces a significant side force directed inward. This inward force results in an outward redirection of the air flow behind the winglet in the same manner that the upward force on a wing causes a downward flow behind the wing. This redirection of the flow reduces the inflow behind the tip with a resulting decrease of the strength of the associated vortex downstream of the tip. As a consequence the drag is reduced. Theoretical analyses and experiments indicate that the effectiveness of winglets in reducing the vortex or induced drag is approximately proportional to the heights of the surfaces. However, increasing the height increases the aerodynamic loads imposed on the winglets and wing which then requires stronger, heavier structures to withstand these added loads. Analyses have indicated a winglet height approximately equal to the tip chord provides the most satisfactory compromise between the favorable aerodynamic effect and the adverse structural problem.

For a given winglet height a winglet extending downward from the tip is almost as effective as the upward extending version shown in figure 1. (For such an arrangement the winglet airfoil is cambered with
the greatest curvature on the outer surface since the winglet in this position must reduce outflow behind the wing (fig. 2). However, for an airplane with the wing mounted in a low position with respect to the fuselage a lower winglet of the desired length would impact the ground during landing and take off. Therefore, for such airplanes the primary winglet must extend upward. For a wing mounted high on the fuselage a downward extending winglet is practical. Also, a winglet combination incorporating a rearward located upper winglet and forwardly placed lower winglet may reduce the drag by a somewhat greater amount than a single upper or lower winglet. However the aerodynamic gain may not justify the added cost and structural weight.

At the high subsonic flight conditions of jet transports and business jets local regions of supersonic flow develop on the upper surface of the wing and the inner side of winglets mounted above the wing. When these regions are superimposed, a local shock wave develops at the juncture of the two surfaces which may cause a significant drag increase. To reduce or eliminate this problem the upper winglets on such airplanes are placed rearward on the wing tip as shown in figure 1. Also, this problem is reduced by inclining the winglets outward from the vertical slightly and providing fairings at the junctures of the wing and winglets, as shown in figure 1.
Extensive wind tunnel investigations of winglets on a number of different airplane configurations have indicated that these surfaces reduce the vortex or induced drag by between 10 and 20 percent depending on the specific design of the airplane wing and the flight conditions. These improvements result in reductions of total airplane drag at cruise of between 4 and 8 percent. Further, these wind tunnel tests have indicated no adverse airplane stability or control problems associated with adding winglets. (See ref. 2, for example.) Winglets are now incorporated in the Rutan Varieze, the Israeli Aircraft Industries cargo aircraft, and the Gates Learjet model 28. They are part of the design of the forthcoming Grumman Gulfstream III. Also, winglets will be tested in flight on the Air Force KC-135 in 1979. If the flight tests confirm the wind tunnel results (ref. 2) these surfaces will be retrofitted to most of the Air Force fleet of these aircraft. Further, wind tunnel tests of winglets on several commercial and military jet transport airplane configurations are continuing.
REFERENCES:


Figure 1.- Winglets on Gates Learjet model 28.

Source
Gates Learjet Corporation
Wichita, KS
Figure 2 - Vortex formation behind a wing tip.

Figure 3 - Effect of upper surface winglet on cross flow at wing tip.