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USES FOR ANGLE OF ATTACK
AS A
FLIGHT CONTROL INSTRUMENT

THESIS

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by

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Preface

This thesis is concerned with determining the state of the art of angle of attack sensor and display techniques and resultant uses that can be made of this aerodynamic parameter during flight.

The controversial subject of angle of attack has been debated for years in the military services, and in all probability it will continue to receive much attention and concern. I have, therefore, attempted to state in this paper both negative and positive criticisms, with perhaps a personal leaning toward a favorable acceptance of angle of attack.

I wish to thank Professor H. C. Larsen for his expeditious review of the rough draft of this thesis, and for his suggestions and aid throughout this project. I also wish to thank Mssr. J. H. Kearns, S. Knemeyer, and G. H. Purcell of WADD Flight Control Laboratory for their encouraging advice and assistance. Others whose assistance I deeply appreciate include Mr. Robert Stanton for much of the layout work and illustrations; my wife, Ruth, for editing; and my sister-in-law, Miss Mildred Bentley, for her efficient typing of the preliminary draft.

Willard E. Wilvert

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List of Symbols and Abbreviations

Symbol or Abbreviation	Meaning
a	Speed of Sound
AFFTC	Air Force Flight Test Center
AFIT	Air Force Institute of Technology
ARDC	Air Research and Development Command
CAA	Civil Aeronautical Authority
CADC	Central air data computer
C_D	Drag coefficient
C_{Do}	Zero lift drag coefficient
C_{D_P}	Parasite drag coefficient
C_L	Lift coefficient
$C_{L_{max}}$	Maximum lift coefficient
$C_{L_{max\ end.}}$	Lift coefficient for maximum endurance
$C_{L_{BC}}$	Lift coefficient for best climb
CRT	Cathode-ray tube
Comp.	Compressibility
D	Drag in pounds
$\frac{dC_L}{d\alpha}$	Lift curve slope, C_{L_α} or a
FY	Fiscal Year
g	Acceleration of gravity
GCA	Ground controlled approach
GPA	Ground plane accelerometer
H	Horizontal stabilizer force

List of Symbols and Abbreviations

Symbol or Abbreviation	Meaning
ILS	Instrument landing system
incomp.	Incompressible
K	Constant, K_1, K_2
L	Lift
LABS	Low altitude bombing system
L/D	Lift to drag ratio
$(L/D)_{max}$	Maximum lift to drag ratio
LOS	Line of sight
LSO	Landing signal officer
Max-Min	Maximum-Minimum
M	Mach Number
NADC	U. S. Naval Air Development Center
NATC	U. S. Naval Air Test Center
nW	Apparent weight
n	Load factor
psf	Pounds per square foot
q	Dynamic pressure, $1/2 \rho V^2$
R_{max}	Maximum range
R/S	Rate of sink
S	Area of lifting surface
SAC	Strategic Air Command
SAE	Society of Automotive Engineers
SCAT	Speed control after take-off

List of Symbols and Abbreviations

Symbol or Abbreviation	Meaning
T	Thrust
TAC	Tactical Air Command
TN	Technical note
TR	Technical report
u	X-component of longitudinal velocity vector V
V	Velocity
v	Y-component of longitudinal velocity vector V
V_T	True velocity
V_S	Stall velocity
V_V	Vertical velocity
VFR	Visual flight rules
W	Weight
WADC	Wright Air Development Center
WADD	Wright Air Development Division
α	Angle of attack measured from reference line (chord or zero lift direction) and the free stream velocity V_∞
α_L	Local angle of attack at location of sensing element
α_T	True angle of attack or local angle of attack corrected for position and Mach number errors
α_{L_0}	Angle of attack for zero lift
β	Angle of sideslip between the plane of symmetry and V_∞
Δ_α	Change in angle of attack
δ_F	Deflection angle of flaps

List of Symbols and Abbreviations

Symbol or Abbreviation	Meaning
θ	Pitch angle
α	Flight path angle
Ψ	Yaw angle
ρ	Air density
ρ_0	Air density at sea level
σ	Air density ratio ρ/ρ_0
Γ	Circulation
γ	Flight path inclination angle

Abstract

Since the advent of modern aircraft, numerous sensing and display techniques have been devised for use of angle of attack information within the weapon system. This report reviews some of the literature on the angle of attack sensor and display development. It emphasizes uses for angle of attack information in various phases with today's and probable future weapon systems.

It also traces progress made in attempts to improve the sensor and display of angle of attack information. Early studies tended to substantiate estimated potential of angle of attack information. Subsequent in-flight evaluations confirm that it is a useful parameter in certain modes of flight--take-off, climb, cruise, approach, and landing. Some of the proposed systems were quite satisfactory on static or limited dynamic testing, but had certain defects in actual in-flight use. The report points out a need for objective evaluations of displays in static, dynamic, and in-flight testing situations. Also pointed out are certain problem areas that require further investigation of sensitivity, damping, reliability, display design, human engineering input, scale factors, and calibration methods.

With regard to mechanization and sensing, the report traces the progress made in the various techniques used. It shows that an assessment of the present status of sensing techniques reveals that the differential pressure and vane sensing techniques remain the most adequate for subsonic and transonic flight.

Particular emphasis is placed upon present functional angle of attack devices in use, as well as those which are to be evaluated experimentally for possible use on advanced aerospace vehicles.

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USES FOR ANGLE OF ATTACK
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I. Introduction

A requirement for the sensing and displaying of angle of attack information exists in many present day operational aircraft, as well as with weapon systems of the future which include boost glide and re-entry vehicles. Though much progress has been made in mechanization, sensing methods, and display design, certain basic problems remain unsolved and grow more critical as the requirements placed on angle of attack are increased.

A review of available technical literature reveals few objective, well controlled studies on the display of angle of attack information. Nor does it reveal any systematic attempt to evaluate a particular system that uses a thorough program of static, dynamic (flight simulator), and flight test methods of evaluation.

Frequently, recommendation of a certain display type has been based only on the results of early static readability tests. Flight tests of practically all angle of attack systems have been made, but objective measures of pilot performance are lacking. The recommendations made in these flight tests, in nearly all cases, have been based solely upon subjective pilot opinion--an opinion resulting from viewing cockpit instrumentation. This, as can readily be seen, is an inadequate means for formulating an opinion as regards the total angle of attack system. In earlier attempts display was not a separately considered item, although it should have been. No simulator studies have been made which have sought an objective measure of pilot performance on the display type being evaluated, resulting perhaps in the fact that literature on dynamic evaluation of displays is scant.

There is a need recognized herein for a more objective and systematic approach to the problems associated with the display of angle of attack information. A complete program would include a survey of the literature; an assessment of operational requirements and applications for angle of attack in different classes of systems and modes of flight; evaluation of mechanizations, sensor, and calibration techniques; studies on evaluation methodology and evaluation criteria; a thorough and systematic screening of display types; design of new types of angle of attack systems based upon past experience and new requirements and a thorough and systematic evaluation of these systems (using static, dynamic, and flight test methods of evaluation); and finally, a development of the application or techniques of using angle of attack information under any given condition.

This report seeks to provide some additional background for this ambitious program and to define specific problem areas which require further investigation. It attempts to review available literature on all phases for use of angle of attack and to point out the more useful information so that additional work may not be required.

It places emphasis on the display and human engineering aspects of angle of attack as a visual display, as well as on the engineering methods of mechanization and sensing. If the complete system meets the approval of the engineer, the human factors specialists, and the flight test pilot; only then should the system be put into production.

The aerodynamic aspects of angle of attack are discussed in Section II, which emphasizes the theoretical aspects of angle of attack and its uses during various phases of flight, including take-off, climb, cruise (maximum range and endurance), approach, landing, and stall. An adequate review of these theoretical aspects is required prior to discussion of the display and mechanization-sensing areas.

In Section III the practical considerations are discussed concerning the operational requirements and the uses for the angle of attack parameter in today's first line military and civilian aircraft. Resulting from this section there evolves a definite awareness of the need for developing applications and techniques for using angle of attack when displayed in the pilot's cockpit. This need is taken into consideration as the thesis progresses.

Section IV is a chronological review of past evaluations conducted on various angle of attack systems. This review includes some of the more significant simulation, wind-tunnel, laboratory, and flight test evaluations conducted on the various devices; the evaluations being divided into three major periods: Pre-1940, 1940-1950, and 1951-1960. In reviewing past experiences, programs, and reports available, it is shown that considerable effort has been expended. Illustrations of many display configurations and sensing techniques revealed from this review are depicted in this section.

Section V has a brief description of functional angle of attack devices currently in operational or experimental use. It also names the types of information that are available to the pilot from the various displays. The latter part of this section presents devices, techniques, and displays which have been proposed for use on subsonic, transonic, and supersonic aircraft.

Section VI outlines possible future requirements for angle of attack information for advanced aerospace vehicles, including the X-15 aircraft and recoverable manned lifting re-entry vehicles.

In this report are offered two methods of description. A historical approach is offered in Section IV in which the angle of attack devices are described in the approximate chronological order in which they were developed and evaluated. In Section V the specific devices which are now in use are described in terms of sensors, indicators, and mechanisms. This two-way method of description adds value to this report.

Further, this report attempts to define desirable characteristics, limitations, and display factors in the use of the angle of attack parameter in aircraft. Angle of attack sensors are available for today's aircraft; the output from those sensors to be used either separately or in conjunction with other flight data. It has been shown by various tests and historical data that the display of this information can be a valuable aid for safe and accurate flight.

II. Theoretical Considerations

Aerodynamic Angle of Attack in General

At the onset, a brief review of basic aerodynamic theory to determine what angle of attack is and how it can be measured, should be considered. The airfoil section of an aircraft wing is inclined at some angle with respect to a reference line, such as the top fuselage line or the longitudinal axis of the aircraft. This angle is called "angle of incidence" and should not be confused with "angle of attack," which defines the attitude of the airfoil's chord line with respect to the relative wind. The term, "relative wind," refers to the airflow past the airfoil, and is equal and opposite to the actual velocity of movement of the airfoil section. The lift and drag components are shown in Figure 1. They are defined as acting perpendicular and parallel to the relative wind, through the center of pressure of the airfoil. Lift is essentially a function of angle of attack and angle of incidence is essentially a design constant for a given aircraft (Ref 12:78).

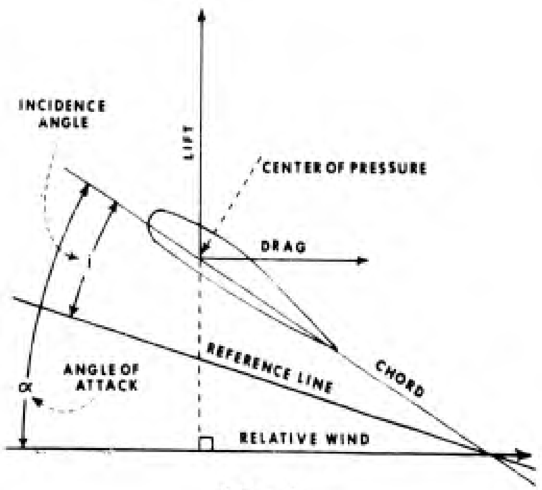

Fig 1.
Aerodynamic Airfoil Characteristics

The straight line relationship between lift, or coefficient of lift, and angle of attack is characteristic of rigid airfoils at subsonic speeds until just prior to the stall, when the lift coefficient drops off rapidly due to turbulent airflow around the airfoil. This straight line relationship will not hold for many of today's flexible wing aircraft. The equation defining this relationship is known as Glauert's equation of the lift curve:

$$C_L = \frac{dC_L}{d\alpha}(\alpha + \alpha_{L_0} + \delta_f)$$

Where $\frac{dC_L}{d\alpha}$ is the slope of the lift curve, α is the angle of attack, α_{L_0} is the angle of attack at zero lift and is constant, and δ_f is the displacement of the lift curve due to wing flap deflection. For many of the present day high speed aircraft the airfoil sections are symmetrical and therefore α_{L_0} is equal to zero.

Glauert's equation implies that the slope of the lift curve is not altered with flap deflection. This means that the curve is shifted upward when flaps are deflected, remains parallel to the original curve, and increases the value of the maximum lift coefficient. Similar curves are usually available with Mach number the parameter, showing that the slope of the linear section and the intercept with the axis vary as functions of Mach number. The effect of wing flaps, wing slots, and ground effect is shown in Figure 2.

The lift equation is defined as $L = C_L \frac{1}{2}\rho V_T^2 S$, where C_L is the lift coefficient, ρ the air density, V_T the true velocity, and S the wing area. The speed at which an airplane can maintain level flight at a given angle of attack or lift coefficient is dependent on weight, wing area, and the air density in the lower subsonic flight regime. Lift varies directly as the square of airspeed for any given practical angle of attack. Below, the critical Mach number and Reynolds number for lift variations with angle of attack are limited to the range between the zero-lift and the stalling angle of attack values. Since the lift force required for aircraft flight must be provided, and angle of attack is governed by horizontal control surface position, the stable aircraft must automatically adjust its steady state flight path inclination angle, γ , to obtain the airspeed required to balance the aerodynamic lift equation. Accordingly, the horizontal tail surfaces, in regulating the angle of attack value, also fix the airspeed-weight ratio for unaccelerated flight. Many high performance jet aircraft are capable of flight with unusually high positive angle of attack values as shown by the force vector diagrams in Figure 3 (Ref 62:1-3). The lift component of thrust during slow speed flight of such aircraft becomes an appreciable part of the lift requirement; consequently the use of angle of attack as a flight parameter is degraded by becoming thrust sensitive.

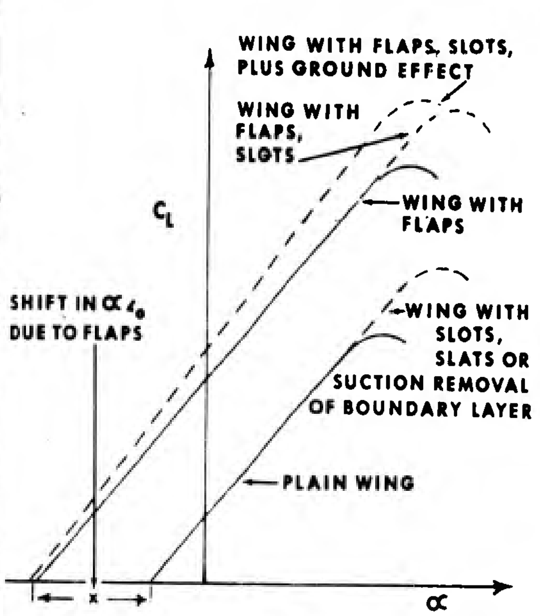

Fig. 2
The Effects of High Lift Devices on the Lift Curve

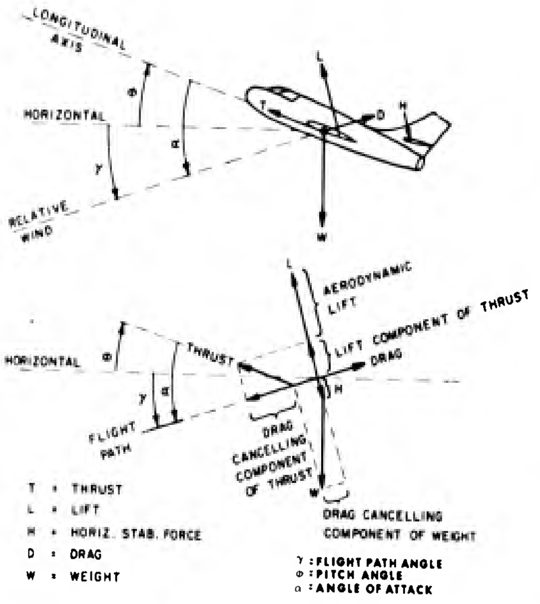

Fig. 3
Forces on Aircraft in Flight
(From Ref 18:8)

Sensitivity of Angle of Attack Relative to Airspeed

Aside from the theoretical usefulness of angle of attack information, there are several practical considerations which affect the sensitivity of this parameter, such as the dynamics of the vehicle, signal to noise ratio of the system, air turbulence, and controllability of the aircraft for desired accuracy. The sensitivity of any angle of attack device must be accurate if it is to have significant advantage over the use of airspeed for a given phase of flight. From the basic lift equation:

$$W = C_L \sigma \frac{\rho_0 S}{2} V^2 = a_0 (\alpha - \alpha_{L_0}) \frac{\rho_0 S}{2} \sigma V^2$$

it can be shown that the change of velocity with respect to angle of attack is:

$$\frac{dV}{d\alpha} = - \frac{V}{(\alpha - \alpha_{L_0})}$$

therefore any error in velocity due to an error in angle of attack is:

$$dV = - \frac{V}{(\alpha - \alpha_{L_0})} d\alpha$$

Similarly it can be shown that the error in equivalent airspeed is the same:

$$dV_e = - \frac{V_e}{(\alpha - \alpha_{L_0})} d\alpha$$

Since $M = \frac{V}{a}$ then $dM = - \frac{M}{(\alpha - \alpha_{L_0})} d\alpha$

but $$V = \left[\frac{W}{\sigma \frac{\rho_0 S}{2} C_L} \right]^{\frac{1}{2}} = \left[\frac{W/S}{\sigma \frac{\rho_0}{2} a \ (\alpha - \alpha_{L_0})} \right]^{\frac{1}{2}}$$

therefore the error in velocity due to error in angle of attack can be re-written as:

$$dV = \left[\frac{W/S}{\frac{\sigma \rho_0}{2} a \ (\alpha - \alpha_{L_0})^3} \right]^{\frac{1}{2}} d\alpha$$

Making the assumption that a given angle of attack device is capable of measurement within 0.10 degree accuracy, and substituting normal values for the KC-135 (or DC-8 such as $W/S = 100$, $a = 0.075/$ o with $A = 8$), it can be shown that a 0.10 degree change angle of attack would be equivalent to approximately a 1 knot change in airspeed during landing and take-off; 6 knots during cruise; and 60 knots during high speed flight.

Applications of Angle of Attack

Indications of true angle of attack and/or true angle of sideslip are useful to:

1. Computers controlling the firing of rockets or ballistic missiles
2. Autopilots
3. Gust alleviators
4. Stall warning
5. Flight instrument compensators
6. Devices which adjust cruising speed so that $\alpha = \alpha$ for L/D max (cruise controllers)
7. Approach controllers
8. Take-off controllers
9. Recovery from pitchup attitudes
10. Climbout
11. Maximum glide
12. Performance behind the power curve

Methods of Measuring Angle of Attack

Many methods have been proposed for measuring true angle of attack. (True angle of attack is the local flow direction, as measured by the sensor, corrected for position error). In some, the direction of the local flow is measured, then related to the true angle by a flight calibration. In others, the true angle of attack is measured directly (Ref 4:5-7, 5:1-3, 6:4-7). This paper will endeavor to cover numerous devices in the first category as well as those devices being used currently in operational military aircraft, which take these forms:

(a) A cylinder is placed with its axis normal to the stream. Two ports are placed at equal angles from the centerline. The pressures sensed at these points are used to rotate the cylinder either directly or through a pneumatic or electrical servo system to a position where the pressures are equal on the two ports. The cylinder position with respect to an arbitrary reference can then be measured.

(b) An aerodynamically stable surface is attached to a freely turning shaft. Since the stable surface always aligns itself with the flow, local flow direction can be detected by measuring the shaft position.

(c) An aerodynamic surface with a linear lift curve is attached to a constrained shaft. Since the force on the shaft is directly proportional to the angle the surface makes with the flow at any given indicated airspeed, it can be measured by strain gages or other methods and related to the flow angle.

(d) Pressures are measured on or near the surface of a body. The pressure distribution on a body varies according to the acceleration history of the flow over the surface. For a given point on the surface of a body, the pressure coefficients will change as the inclination of the body to the flow changes because the acceleration history is then different. By use of a body of suitable shape, substantial change in pressure coefficient with change in inclination angle can be made. Pressure coefficients measured on such a device may then be related to the inclination angle by calibration.

Devices or proposals which employ the principle of measuring true angle of attack directly have to date taken one of two forms: either they are a mechanization of the lift equation of the aircraft,

$$\Delta\alpha = \frac{\text{Aircraft mass x Acceleration normal to XY flight path plane}}{\text{Lift curve slope x wing area x } 1/2 \text{ x air density x } (V_T)^2}$$

or they determine the motion of air particles relative to the aircraft. The latter form has not progressed beyond the proposal stage because of the almost insurmountable problems associated with measuring the position of the same air particle at times sufficiently displaced so as to detect the direction of the aircraft's motion.

Lift equation mechanization has many desirable features. It requires no external moving parts, exposure to environmental or human impairment is at a minimum, it introduces no additional drag, and it can be made to give good results provided the lift curve can be determined accurately in flight. It can, however, require a complex computer since the lift curve of an aircraft is non-linear and changes with Mach number.

Null seeking vanes and pressure probes, while widely used because of their simplicity and the ease with which an angle indication can be obtained, have the disadvantage of requiring external moving parts. This makes them highly subject to environmental and handling damage. Most of the present day operational vane and probe type sensors will be described in detail later in this paper.

Pressure systems, if fixed, can be combined readily with a pitot-static probe. They can be built to measure α and β . They are comparatively rugged, and depending upon the accuracy to which the pressure can be measured, they can be quite accurate. Their chief disadvantage lies in the complexity of the function relating α and β to measured pressures. This can be overcome somewhat by using dual sensors or dual sets of pressure sources. These can be made so that no calibration is required. However, whether the complexity of an additional set of pressure measurements and corresponding increase in the sensor's physical size are worth the reduced computer complexity or not, is a matter for further study.

The currently available angle of attack sensors and indicators are described in the following sections. In addition, some of the proposed techniques for sensing angle of attack, cockpit displays, and future uses of the parameter are discussed (Ref 50:5-7).

Use of Angle of Attack During Various Phases of Flight

The following analysis briefly examines the uses and in some cases the limitations of angle of attack information by flight phases. It also indicates some of the general relationships between angle of attack and other flight parameters. In most present day high-performance aircraft, airspeed is still the only indication of flight condition pertaining to lift and drag. This is not a direct indication however, since any consideration of the relation of airspeed to optimum drag-lift ratio or stalling velocity must include gross weight information. The angle of attack parameter can furnish similar information to that of airspeed, independent of gross weight changes. Proper use of this information may result in not only more economical operation of aircraft (Ref 48:16-17), but also safer operation of aircraft in situations where this information becomes critical.

The use of angle of attack is discussed for each of several representative flight phases in the following paragraphs.

Take-off

During the take-off run on level ground, while the wheels are in contact with the runway, the pitch angle, θ, and angle of attack, α, are substantially equivalent. An angle of attack indication provides somewhat redundant information to that of the attitude instrument. Normally, with certain high speed aircraft, a positive angle of attack must be maintained in order to break ground with the nose wheel. The attitude indicator can provide adequate pitch information for the take-off phase; however, in some of the heavier jet aircraft, such as the KC-135, it has been found during heavy-weight take-offs and initial climbouts that the attitude indicator and its associated gyroscope system develop a precession error, due to longitudinal acceleration during the take-off ground roll. With angle of attack it is possible to accelerate to the calculated rotation speed and rotate to the desired angle of attack for take-off and initial climbout. It is possible to encounter a type of phugoid oscillation during take-off utilizing a constant angle of attack. After elevator control becomes effective and after reaching an established minimum rotation speed, with certain highspeed aircraft it is necessary to maintain a specific angle of attack for optimum take-off run. Angle of attack data can be used to provide optimum performance during take-off and climbout of modern high performance aircraft. In addition, this parameter is suitable for automatic or semi-automatic speed control during landing and other phases of flight. Take-off procedures in use today are essentially as follows: (1) Prior to take-off, an optimum rotation airspeed, lift-off airspeed, minimum controllable airspeed, and best climb airspeed for 50'' clearance are all precomputed from applicable performance tables based on runway temperature, runway slope, aircraft weight, wind direction and velocity, and pressure altitude: (2) The take-off is with full rated thrust or combat rated thrust with afterburner; (3) When the precomputed rotation speed is reached, the pilot rotates the aircraft to a prescribed nose high attitude for lift-off; (4) The pilot then climbs the aircraft at a precomputed safe speed for landing gear and flap retraction. Present runway and field restrictions, especially for the heavier weight tanker, passenger, and bomber type aircraft, indicate a need for better control of the rotation, lift-off, and climbout phases of take-off. A system which uses angle of attack as the principle reference is considered superior to any system based on air speed or pitch angle as the principle reference, since it represents one of the most fundamental factors for keeping an aircraft airborne. Experience in both flight test and simulation testing have shown that angle of attack, used as the only pitch reference for controlling the aircraft, is unsatisfactory since it tends to induce relatively long period oscillations which follow the aircraft's normal phugoid period. As a matter of interest, Capts. W. G. Moretti and C. A. Neuendorf of AFIT class CGC61, are preparing a thesis entitled: "Design and Longitudinal Analysis of a Take-Off Indicator for a Critically Loaded KC-135 Aircraft," in which they are investigating the use of angle of attack to resolve primarily the KC-135 take-off problem as referenced in WADD Flight Test Report WWF NR 60-28 (Ref 58:1-2).

Since an increase in angle of attack also causes an increase of aerodynamic drag, there is a reduction of forward acceleration. (A by-product of angle of attack is induced drag). Because of extremely thin and highly swept wings (low aspect wings), a pilot must depend on high angle of attack operation to supply the necessary lift at low airspeeds. As increased speed gives increased lift at any angle of attack, the angle required for level flight reduces constantly with speed increase; the lift increases with the square power of the speed increase.

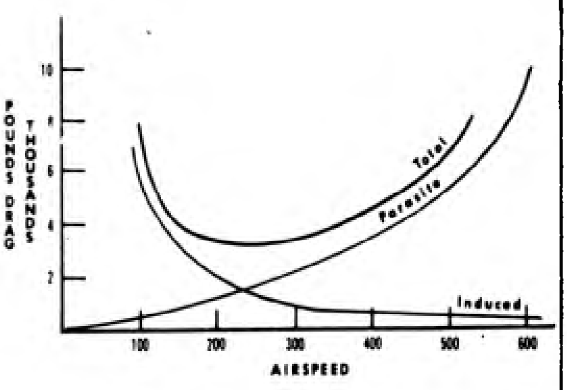

Fig 4.
Thrust Required Curve

As total drag is the combination of induced and parasite drag, induced drag increases as the square of the angle of attack, whereas parasite drag is viscous and pressure drag, or frontal surface type drag (gear, flaps, tanks and dive boards)(Fig. 4).

The power curve, as shown in Figure 5, shows that in order to maintain level flight one pound of thrust must be applied for each pound of drag, provided the speed is sufficient to supply lift. The minimum point on the curve is the point of least drag, and identifies the speed for maximum gliding distance. When the aircraft is operated at any speed below this mid-point, it is on the

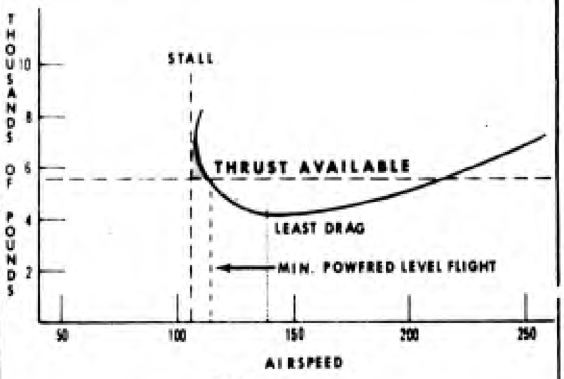

Fig 5.
Drag Curve

"back side of the drag curve." The shaded area sometimes referred to as "coffin corner" is the point at which 100% thrust will not support sustained level flight. At this angle of attack there is more drag holding the aircraft back than there is thrust available. The curve is almost identical for take-off and landing phases of flight, since partial or full flaps are used on most of our late model aircraft.

Induced drag is perhaps less critical on take-off as there is full thrust, often with afterburner. In this case, the excess thrust gives a favorable situation. If the aircraft does not perform according to the predetermined take-off conditions as computed from the applicable aircraft performance handbook, at least one of three things may be wrong: the engines are grossly short of thrust, the performance section of the aircraft handbook is in error, or there is poor pilot technique. The pilot must keep the aircraft in the most favorable attitude for proper acceleration, raising the nose wheel off the runway prior to shimmy speed, which, if done too soon will cause reduction in the proper acceleration schedule. The initial attitude angle should be only as high as is necessary to lift the nose wheel, as each inch above that induces more drag, robs acceleration, wastes thrust, and lengthens the take-off roll. As this problem is handled by pilot technique, it appears that angle of attack is a useful parameter in the take-off phase of flight, perhaps not as direct angle of attack, per se, but as a valuable tool for obtaining optimum performance in a high performance fixed wing aircraft.

Climb

During the climb, when angle of attack and pitch angle are no longer equivalent, the former may be used as a stall warning device to determine the minimum safe climbing speed. Changes in lift coefficient with changes in angle of attack are proportional in the lower subsonic region where initial climb occurs (See Figure 2). The objective of the climb phase is to change the total energy with side conditions at a maximum rate, at maximum economy, at as steep an angle as possible; or a variation of these requirements. The rate of change of specific energy of an aircraft, at a fixed gross weight, is a function only of altitude and velocity (Ref. 43:188). Since rate of climb is the vertical component of the aircraft velocity, it is a function of true airspeed (V_T), flight path angle (γ), weight (W), thrust (T), and density (ρ). The flight path angle is defined as the angle between the relative wind (relative velocity) and the local horizontal reference line (See Figure 3). The flight path angle (γ) is the difference between the angle of attack (α) and the pitch angle (θ). The procedure normally followed for establishing the desired climb condition is to set the thrust with the throttle on a predetermined performance chart value and establish the best climbing speed by elevator control action. (For jet aircraft it is usually Military Rated Thrust or Combat Rated Thrust). It should be noted that angle of attack cannot be substituted directly for airspeed in this instance, unless a correction is made for decreasing aircraft gross weight and Mach number for the higher flight levels. Angle of attack is related to vertical speed (rate of climb), assuming that the thrust line is essentially parallel to the flight path.

For an aircraft in equilibrium, in constant weight, and not accelerating, static equilibrium equations may be written along and perpendicular to the flight path (See Figure 3). The equations are as follows:

$$L - W\cos\gamma + T\sin\alpha = 0$$

$$T\cos\alpha - W\sin\gamma - D = 0$$

These equilibrium equations for unaccelerated flight may be used to describe both climbing and level flight (Ref 12:229, 249). In the climbing case, if it is assumed that the angle of attack from the flight path is small and that the flight path angle γ from the horizontal is less than 15°, then the product $T \sin \alpha$ will be small in comparison to the other terms and may be dropped; furthermore, $\cos\alpha$ and $\cos\gamma$ may be assumed equal to 1. Thus the above equations become:

$$L = W$$

$$T - D = W\sin\gamma$$

If both sides of the second equation are multiplied by V (the flight path speed) and divided by W, there is obtained:

$$\frac{(T-D)V}{W} = V\sin\gamma$$

But $V \sin \gamma$ is the vertical speed, or rate of climb, and $T-D$ is the excess thrust, therefore:

$$V_v = \frac{(T-D)V}{W}$$

substituting $C_D = C_{D_0} + \frac{C_L^2}{\pi\rho A}$ and $C_L = K(\alpha - \alpha L_0)$

into $D = \frac{1}{2}\rho V^2 C_D S$

$$V_v = \left[\frac{2(T - W\sin\gamma)}{\rho S\left(C_{D_0} + \frac{K^2(\alpha-\alpha_{L_0})^2}{\pi\rho A}\right)}\right]^{\frac{1}{2}} \mathrm{SIN}\,\gamma$$

since $C_{D_0} = K_1,\ \frac{K^2}{\pi\rho A} = K_2,\ \frac{2}{\rho S} = K_3,\ \alpha_{L_0} = 0$

then $V_v = \left[K_3\,\frac{T - W\sin\alpha}{K_1 + K_2\,\alpha^2}\right]^{\frac{1}{2}} \mathrm{SIN}\,\gamma$

This formula establishes the relation of vertical speed, the flight path elevation angle, and the angle of attack. The procedure implied in this method is that of choosing the proper angle of attack and flight path angle that will result in the desired V_v, and maintaining this constant relation between the two angles (Ref 36:3-5).

Angle of attack information is useful to indicate incipient stall and high drag in a climb or turn. This information is particularly useful when it becomes necessary to make steep turns after take-off or to gain altitude rapidly after take-off when thrust for acceleration may be limited. In higher performance aircraft there is usually large excess thrust, particularly with afterburner, and unless stall is incipient, flight is still possible though control action may be lost.

In the case of high speed jet aircraft the maximum rate of climb is a function of both L/D ratio and airspeed. Angle of attack information, therefore, would not be solely sufficient to control a specific climb. By making use of an additional parameter (the flight path elevation angle, for example), and by maintaining the proper relationship between both parameters, there may be found a solution (Ref 6:4).

Recent flight test data has confirmed that the attitude indicator and its associated gyroscope system can produce a detrimental precession error, due to the longitudinal acceleration on take-off. Phugoid oscillations can be encountered using standard flight manual technique take-offs as well as those attempting to use a constant angle of attack. A constant airspeed climb can result in angle of attack continually decreasing, while a constant angle of attack can result in an airspeed phugoid.

Subsequent test equipment utilizing a gyro stabilized ground plane accelerometer provided the necessary anticipatory characteristics to decrease the phugoid oscillations (Ref 58:8-15). During transition from take-off to climb, the aircraft experienced a normal acceleration slightly greater than 1 g and the angle of attack was higher than that for a 1 g at level flight. In the period of time between the transition to climb and this point, the aircraft attained a quasi steady-state condition where the acceleration being experienced was close to 1 g. If the pilot had been trading forward velocity for vertical velocity too rapidly for the initial climb speed, there resulted an above-normal bleed-off of airspeed. Having been completely isolated from his airspeed indicator, the pilot noted this airspeed bleed-off and started correction by rotating the nose of the aircraft down. As soon as he did so, there was an almost immediate effect on the angle of attack due to the decrease in g's being imposed upon the airframe. This lesser g force coupled with ground effect caused a lower angle of attack than was experienced under previous g conditions, which was counteracted by an increase in angle of attack from a progressive decrease in airspeed (which continued to be experienced until the climb path was flattened sufficiently to preclude further airspeed bleed-off). The pilot, observing this (the approximately steady angle of attack resulting from the two opposing effects with a continuing decrease in airspeed), reacted by rotating the nose of the aircraft down still further. This caused a further decrease in g which tended to yield a lower value of angle of attack than was expected. This accumulative condition continued until the aircraft had leveled, or was in a shallow dive, permitting the airspeed and the g force to increase. It should be noted that ground effect has a significant effect on the slope of the lift curve, particularly at height of less than one wing span of the aircraft.

This condition probably was created because of ground effect and because the pilot was unable to read accurately the angle of attack indicators, and too, it likely was aggravated by the pilot inadvertently monitoring the airspeed while flying angle of attack reference. A correction was started, based on an airspeed trend, but completed on the basis of angle of attack information. From the theoretical considerations and flight test data available, the use of angle of attack for climb reference seems to hold no advantage over the use of Mach number (**Ref** 55:19-20 and Ref 40:257).

Level Flight (Maximum Range or Endurance)

The technical requirements for an angle of attack display is limited primarily to the maximum range or maximum endurance phases of flight. These may or may not be in the level flight configuration as a cruise climb schedule can be used for a maximum range problem. For reciprocating-engine and jet aircraft cruising in the low subsonic range, both of the corresponding aerodynamic functions are uniquely defined in terms of angle of attack. With an angle of attack indicator it is theoretically possible to continuously change power to maintain the desired angle for maximum range or maximum endurance by keeping the pointer fixed on a prescribed mark indicating the required angle. From the analysis of the range problem with special techniques in the operation of gas turbine propelled aircraft (Ref 27:8-9), and from using Oswald's parabolic drag polar, the following expression can be derived:

$$\frac{C_D}{C_L^{\frac{1-n}{2}}} = \left[\frac{C_D + C_L^2/\pi A e}{C_L^{1-\frac{n}{2}}}\right] = \left[\frac{C_{D_p}}{C_L^{1-\frac{n}{2}}}\right] + \left[\frac{C_L^{1+\frac{n}{2}}}{\pi A e}\right]$$

The only variable in this expression is the lift coefficient, as C_{D_P} is a constant for any one airplane for incompressible flow. Differentiating this expression with respect to C_L, and equating to zero, one obtains:

$$\frac{C_L^2}{\pi A e} = \frac{1-\frac{n}{2}}{1+\frac{n}{2}} C_{D_p}$$

The exponent n describes the variation of thrust horsepower specific fuel consumption with true airspeed. Since n is a positive number, one concludes that for maximum range the parasite drag will be greater than the induced drag. Thus one must fly at a speed greater than the velocity for maximum lift to drag ratio, where the induced drag equals the parasite. Solving the equation above for the lift coefficient, and using the subscript BC to designate "best cruising", one obtains the expression for the "best cruising lift coefficient" as: $(C_L)_{BC} = \left[\left(\frac{1-\frac{n}{2}}{1+\frac{n}{2}}\right) C_{D_p} \pi A e\right]^{\frac{1}{2}}$

Similarly, the expression for "maximum endurance" would be:

$$(C_L)\,\text{max. end.} = \left[\left(\frac{3-n}{1+n}\right) C_{D_p} \pi A e\right]^{\frac{1}{2}}$$

knowing that $C_L = \frac{dC_L}{d\alpha}(\alpha - \alpha_{L_0})$ and substituting above, the "best cruising angle of attack", is:

$$\alpha_{bc} = \frac{C_{L_{bc}}}{\left(\frac{dC_L}{d\alpha}\right)} + \alpha_{L_0}$$

and "maximum endurance" angle of attack is: $\alpha_{\text{max. end}} = \frac{(C_L)_{\text{max. end}}}{\left(\frac{dC_L}{d\alpha}\right)} + \alpha_{L_0}$

One observes that this is constant so that flight is always at the same angle of attack independent of altitude and weight, keeping in mind that this is limited to aircraft which attain maximum range and maximum endurance in the subsonic region where C_L vs α is not affected by compressibility effects.

The equations are also applicable to aircraft which operate at maximum range and maximum endurance in the higher subsonic region (Ref 35:9-13), where $\frac{dC_L}{d\alpha}$ is a function of Mach number, when the variation of $\frac{dC_L}{d\alpha}$ affects the slope of the $\frac{C_L^{1/2}}{C_D}$ vs α curve, and the value of α at which $\frac{d\left(\frac{C_L^{1/2}}{C_D}\right)}{d\alpha} = 0$. This is a special case where the thrust horsepower specific fuel consumption is constant. At constant altitude, with constant fuel load and fuel consumption rate, the range is represented by the equation:

$$R_{MAX} = K\left(\frac{C_L^{1/2}}{C_D}\right)_{MAX}$$

Since the optimum maximum range flight is a cruise-climb condition, this constant altitude assumption is valid, especially above the tropopause as long as the rate of climb in cruise climb is small. Since 10 - 20,000 feet gain in altitude occurs for maximum range it is usually small and can be neglected. For maximum range in a jet aircraft it requires that the pilot maintain $\frac{d\left(\frac{C_L^{1/2}}{C_D}\right)}{d\alpha} = 0$.

In most cases the pilot observes the airspeed indicator and the altimeter and controls these to achieve a maximum range condition. If airspeed is one of the controlled parameters, the pilot must know the gross weight at discreet intervals during the flight in order to determine the best airspeed at a specific altitude. In the range problem as in the stall problem, the aircraft weight is not a direct consideration in establishing the flight configuration when an angle of attack display is used properly.

Likewise, for the maximum endurance problem the variation of $\frac{dC_L}{d\alpha}$ with Mach number changes the value of α at which $\frac{d(\frac{C_L}{C_D})}{d\alpha}=0$. The condition for maximum endurance occurs when $\frac{C_L}{C_D}$ has its maximum value. The specific fuel consumption, the initial aircraft weight, and the change in weight caused by fuel expenditure must be known if the pilot wishes to determine actual time in the air. Where maximum endurance rather than quantitative time aloft is the criterion, the pilot will have only to maintain $\left(\frac{C_L}{C_D}\right)_{MAX}$. This information is readily available to the pilot and corresponds to the angle of attack at which $\frac{d(\frac{C_L}{C_D})}{d\alpha}=0$. Since this occurs at a single value for each airplane, an angle of attack display appears to have merit as a maximum endurance as well as a maximum range instrument. However, as previously shown, any angle of attack device with a 0.10 degree sensitivity may not be as efficient as the airspeed or Mach number system during these phases of flight (Ref 36:9-13 and Ref 27:16).

Stall

Present stall warnings are usually provided by indicated airspeed instruments, and aircraft buffeting. The stalling indicated airspeed, for a particular airplane at a fixed configuration, is a function of the aircraft gross weight:

$$V_I = \left[\frac{2W}{\rho C_{L_{MAX}}} \; S \right]^{\frac{1}{2}}$$

When the stall buffeting occurs, the time available for corrective action may be dangerously short. An angle of attack display is not subject to this limitation. The effectiveness of this display as a stall warning device, however, is a function of Mach number. In the lower subsonic region, compressibility effects are negligible. There exists in this region a linear relationship between C_L and α , until the stall vicinity is entered (See Figure 2). In the higher subsonic region the effect of compressibility on the pressure coefficient must be considered. The effects of airspeed and temperature cannot be neglected in determining C_L. The effect of compressibility on the lift coefficient in this region can be approximated by Glauert's formula:

$$C_L\,(\text{Comp}) = \frac{C_L\,(\text{Incomp})}{(1-M^2)^{\frac{1}{2}}}$$

The effect of increasing Mach number is to increase the slope of the lift curve and to shift the point at which $\frac{dC_L}{d\alpha} = 0$ to a lower corresponding value of angle of attack. Stall angle of attack, therefore, is not uniquely defined in this region. A stall condition could only be reached in this region by attaining an extremely high wing loading such as occurs in a high-g pull-out, a condition sometimes referred to as a high speed stall. If a maneuver imposes an acceleration on the airplane n times that of gravity, the apparent weight is nW, thence:

$$V_s = \left[\frac{2nw}{\rho C_{L_{MAX}} S}\right]^{\frac{1}{2}} \quad (or) \quad V_s = K\left(\frac{w}{\alpha}\right)^{\frac{1}{2}}$$

It can be seen from the preceding equation that it is possible to use an angle of attack instrument as a speed control device for flight in the vicinity of maximum lift coefficient or minimum speed. Changes in altitude and temperature will cause a change in the density and therefore will affect the stalling airspeed. Angle of attack with respect to the stall condition in the subsonic case is independent of altitude, temperature, and weight.

The wing lift is of critical importance in the transonic speed region since loss of wing lift results in a loss of downwash over the tail which, in turn, results in a nose heavy tendency. This may cause the nose to drop, the aircraft to accelerate (resulting in a further loss of lift), and it may become locked in a dive. In the transonic region, C_L drops as Mach number increases toward M = 1, the rate of decrease being related to the value of angle of attack. This sudden decrease in C_L at a constant α is sometimes called the "shock stall". An aircraft entering the transonic region with an angle of attack of approximately 2° or greater may experience a severe buffet. An indication of angle of attack may enable the pilot to avoid this undesirable condition. This parameter may also be useful as an indication when entering the pitch-up boundary at transonic speeds with certain present-day high performance fighter type aircraft.

According to Ackert, C_L vs α may be represented in the supersonic region by the relationship $C_L = 4\alpha (M^2 - 1)^{-1/2}$. As the Mach number increases, at a fixed angle of attack, the lift coefficient decreases, thereby invalidating the use of angle of attack information to define stall in this region. Also, shock detachment limits the usefulness of Ackert's theory. It may be concluded that since $C_{L_{max}}$ determines stall conditions, and since relationships between C_L and α vary in different sonic regions, isolated angle of attack information is normally not sufficient to define stall (Ref 36:8-9).

Descent Approach and Landing

The relationships between angle of attack and other related flight parameters during the descent substantially conform with those established for the climbout phase. The landing phase of flight is conducted in the proximate vicinity of the stall. Safety considerations therefore dictate that the parameters affecting stall be accurately monitored. Since landings are accomplished in the lower subsonic flight regime, the material covered above under "Stalls" will apply. If the pilot maintains angle of attack at a value corresponding to .9 $C_{L_{max}}$, the indicated airspeed of the aircraft during the approach will remain at a safe increment above the stall. The advantage of using this method for maintaining a safe airspeed during the landing phase is that angle of attack information is not dependent upon aircraft weight. Another advantage is the favorable sensitivity attainable by the angle of attack indicator when employed as a stall warning device. For a typical airfoil, the change in angle of attack corresponding to a change in lift coefficient from $C_{L_{max}}$ to

.9 $C_{L_{max}}$ is greater than one degree. This provides a wide margin above minimum instrument readability for the pilot, as compared to the margin provided by conventional airspeed indicators. The stall angle of attack varies with airplane configuration, and in most cases, flaps, slots, and ground effect tend to increase the value of $C_{L_{max}}$ and thus the stall angle of attack (See Figure 2).

In Figure 3, γ is the flight path approach angle of the aircraft; α is the aircraft's wing's angle of attack. Utilizing the equations of equilibrium as used in the climbout phase, it can be shown that the rate-of-sink becomes:

$$\frac{R}{S} = \frac{V}{W} \, (D - T)$$

Making similar substitutions as with the rate of climb phase, it can be shown that the rate-of-sink is a function of angle of attack:

$$\frac{R}{S} = \left[K_3 \, \frac{W \sin\gamma - T}{K_1 + K_2 \alpha^2} \right]^{\frac{1}{2}} \sin\gamma$$

For any given flight condition the weight of the aircraft will essentially be constant for the approach phase; the approach flight path angle will vary because of the difference between thrust and drag. The best approach angle of attack will fix the best approach speed for any given landing gross weight. (An aircraft may fly a predetermined fixed glide-path or approach angle, such as in a GCA, ILS, or pre-computed approach glide-slope to the landing runway). Deviation from the best approach glide path may be corrected by increasing or decreasing the thrust, while correction for angle of attack for the best approach angle may be made by pitch control of the aircraft.

Position Error

Because of the distorted flow field induced by a body, the flow over the body is not in the same direction as the free stream velocity vector (relative wind). The difference between the local flow angle and the free stream direction is defined as position error, which generally speaking is experienced at all points on a body throughout the Mach number, altitude, and flight attitude ranges. Whenever possible, fuselage or wing-mounted flight data sensing devices are mounted at a point where the position error is small and will not vary much throughout the flight envelope. Position error can be predicted analytically or determined empirically with accuracy for a particular aircraft.

It is difficult to determine the position error of an individual aircraft so closely that a system accuracy of 0.10 degree may be obtained, as the error contribution of uncertainty of local flow conditions must then be reduced to a small portion of 0.10 degree. The problem becomes more acute for production aircraft because of variations among individual vehicles.

From position error considerations, the most suitable location for an external sensing device is forward of the aircraft, perhaps on a boom mounted on the fuselage nose. This fact can be verified from classical fluid mechanics where it can be shown that the slope of a streamline at a fixed point from the bound vortex is of the form:

$$\frac{dY}{dX} = \tan^{-1}\frac{v}{u} = \frac{a + b\Gamma}{c}$$

but

$$\Gamma = \frac{2VS\,C_L}{\pi b} = dC_L = d\left[\frac{dC_L}{d\alpha}(\alpha - \alpha_{L_0})\right] \quad \text{and} \quad d = \left[\frac{2VS}{\pi b}\right]$$

From the Kutta-Joukowski theorem it can be shown that the slope of the streamline is:

$$\frac{dY}{dx} = \frac{a + b\,d\left[\frac{dc_L}{d\alpha}(\alpha - \alpha_{L_0})\right]}{c} = \frac{K_1 + K_2\,\alpha}{K_3}$$

where a and c are constants which express the effect of the thickness of the body (Ref 13:11 and Ref 25:65, 100).

III. Operational Applications for Angle of Attack

In this section an endeavor is made to outline the practical considerations concerning the operational uses for the angle of attack parameter in today's first line aircraft. Angle of attack sensor and/or indicator systems are currently being tested or used on operational military or civil aircraft to provide:

(1) Input to computers controlling the fire control systems for releasing rockets or missiles

(2) Input to automatic pilot to aid airspeed control for final approach phase

(3) Input for stall warning devices (including horn, light, stick, and/or rudder control shaker signals)

(4) Input for the final landing approach phase in conjunction with a controlled glide-path system (i.e. GCA, ILS, Navy Mirror Landing System)

(5) Input for take-off controller

(6) Input for automatic pitch-up control.

Navy

Angle of attack information has been available for years. Naval aviation has been using angle of attack devices for approximately twelve years, and since 1958 all USN first line aircraft (which require carrier landing capability) have had a standard angle of attack system. (The system must operate properly prior to the aircraft's being considered operationally ready). The Navy systems are being used primarily in its aircraft as aids in the landing phase, or as input to the fire-control systems. The Navy emphasizes use of angle of attack display information while making land or carrier base approaches utilizing the standard

Navy Mirror Landing System. It is also presently using angle of attack instrumentation during training and pilot checkout phases of operation in aircraft such as the F-9F. The Specialties type of angle of attack system is installed in the Navy F-9F-8, T-2J, FJ-3, F-8U, and A-4D type aircraft. Angle of attack sensor inputs are used in the fire-control systems on the F-3H and F-4D aircraft (Ref 9:1-9).

The standard Navy angle of attack system includes a sensor (vane or probe), cockpit indicator, visual approach indexer, and a set of three external color-coded approach lights (Ref 54:1-5). (This system is discussed more in detail in Sections IV and V of this paper). Of the military services, the Navy, to date, has had the most operational experience in the use of displayed angle of attack information in the cockpit. This has been due primarily to a firm requirement for the use of this parameter as an aid during critical carrier landing operation when the aircraft tailhook must engage with the arresting wires on the approach end of the aircraft carrier deck. During carrier suitability trials for new high performance aircraft utilizing mirror and standard LSO (Landing Signal Officer) approaches, precise speed control was found to be a stringent requirement. Therefore it was determined that there was a firm requirement for an angle of attack system in these current aircraft in order to achieve the flight precision necessary.

Information received from the angle of attack system has been recognized as vitally important and particularly necessary in the newer high performance aircraft during carrier approaches where it affords better information than airspeed. The Navy, over a period of years, has sold the use of the angle of attack parameter to its operational pilots, and during this time, over nine thousand (9,000) Specialties angle of attack systems have been bought by the Navy.

In the initial years pilots did not use angle of attack because of lack of confidence in the instrumentation, poor readability, and to some degree, ignorance of its usability. The problem areas of poor instrument reliability, improper calibration techniques, and inadequate instrument sensitivity have apparently been corrected in today's Navy operational angle of attack systems. As a result, the angle of attack indicator is being used quite extensively by Navy pilots as a primary instrument in the landing approach. The Navy has stated that a good angle of attack installation in any aircraft could be useful when considering the following:

(1) Crucial moments immediately following take-off under critical conditions (Maximum Lift)

(2) Acceleration from loiter to climb speed (Minimum Drag)

(3) Maximum endurance conditions (Maximum Lift/Drag)

(4) Maneuvering limits

(5) Landing approach and stall warning (The effect of flaps or other external configuration variables should be accurately calibrated and published).

With the advent of high speed jet aircraft and associated increases in approach and landing speeds, the problem of speed controllability in the landing configuration has become critical, especially during carrier approach. It has been determined that the optimum parameter for speed control during an approach is angle of attack. The presentation to the pilot and the integral parts of the angle of attack system have been standardized and are being installed during production and/or by aircraft service change. The Naval Bureau of Aeronautics has provided adequate information for pilots and maintenance personnel on already installed angle of attack systems in appropriate Flight Handbooks. In addition, Naval Operations has prepared a "sense pamphlet", outlining the use of angle of attack.

Operational uses of angle of attack parameter displays are:

(1) Optimum power approach. Use of the angle of attack indication is of prime importance when setting up mirror approach conditions at the 180° position in the landing pattern. At this point, with angle of attack at its optimum approach, or 3 o'clock position on the indicator, and with gear and flaps down, a quick reference to the airspeed indicator will tell the pilot at what speed his approach will be made without reference to gross weight or temperature calculations. From this point on through touchdown his entire attention may be focused outside the cockpit. The angle of attack can be maintained in the turn to glide slope by reference to the cockpit approach indexer in the pilot's periferal field of vision (Ref 52:1). Arrival at the glide slope should be under straight and level conditions where a proper reduction in power will initiate the correct rate of descent. Correlation of the "meatball" of the mirror system and the bullseye of the approach indexer can be achieved through the use of both stick and throttle with the proper glide slope maintained to touchdown. Speed will increase slightly after transition from level flight to descent and should be anticipated by the throttle adjustment.

(2) Stall Warning. Angle of attack is the only consistent means of indicating an approach to a stall condition under all phases of flight.

(3) Approach Without Flaps. This flight configuration can be safely

accomplished with ease if the correct angle of attack indication is followed to touchdown.

(4) Catapult Take-off. A known angle of attack value which can be achieved immediately after a catapult take-off is insurance against over or under rotation after a launch.

(5) Flame-out Conditions. If a flame-out should occur, judicious use of the proper angle of attack indication will give the best glide slope possible for maximum distance and at the same time allow the pilot to concentrate on a re-start or emergency procedure with the greatest safety.

(6) Climb. Optimum climb performance can be duplicated under varying conditions with the same angle of attack.

(7) In-flight Refueling. Holding angle of attack constant while taking on additional weight during in-flight refueling can be of great assistance.

(8) Maximum endurance. Coupled with power setting, the same indication will always result in the aircraft's best performance, regardless of wing loading or altitude.

(9) Optimum Cruise. With current instrumentation, the scale may be considered too coarse for fine cruise. However, angle of attack can be of assistance in establishing duplicate conditions.

The Navy Chance-Vought F-8U has the Specialties angle of attack system with the Servomechanisms vane type sensor, which is used for the aircraft's fire-control system. The A4D-2H aircraft has a Bendix indicator, a Specialties indexer, and a Daystrom vane type angle of attack sensor, the latter being used in conjunction with the fire-control system (Ref 9:1-9). The A4D-1 and the A4D-2 aircraft have the Specialties probe type sensor in accordance with Navy specifications MIL-T-7785 or MIL-T-19229A. Two A3D aircraft squadrons will be conducting carrier qualification tests during 1961. One squadron will be equipped with the newest type Specialties angle of attack system which includes the modified indexer with the meter dial giving trend information (Ref 51:1-3). The second squadron will be equipped with the Safe Flight Corporation angle of attack system (Ref 44:1-4).

According to Naval Aviation News (September 1959), Naval aviation in FY 1959 reported an accident rate of only 2.6 per 10,000 flying hours. Installation of speed control and angle of attack devices doubtlessly contributed to the lessening of landing accidents.

Army

The Army recently indicated that it also has a requirement for angle of attack information for use in the cockpits of its operational support type aircraft. Specifically, recent flight test qualifications for the DeHavilland CARIBOU revealed a need for the angle of attack approach device for its tactical short field landings. The CARIBOU has the Safe Flight angle of attack system which utilizes the stick-shaker mechanism to pre-warn the pilot of the stall buffet or best approach angle of attack (Ref 44:1-4). To date, the Army has not indicated a requirement for angle of attack information other than in the landing approach phase of flight.

Air Force

During the past thirteen years the Air Force with concurrent efforts of the Navy has conducted numerous theoretical studies, has developed and tested new mechanical devices and different types of displays, and has completed a great deal of flight testing of several experimental angle of attack systems. These systems have been known by several different names--"lift indicator", "angle of attack indicator", "stall warning indicator", "max-min indicator", "safe speed indicator", and "SCAT indicator" (Ref 47:14). Primary emphasis has been placed on devices providing closer control in the approach-for-landing phase of flight, and for input to applicable fire-control systems of today's modern weapon systems. The need for angle of attack information to be displayed in the cockpit has been pointed out by the increasing number of landing approach accidents. Providing the pilot with angle of attack information is considered to be a direct approach toward alleviating landing accident problems.

The vane type angle of attack sensors are currently installed and are being used as input to the fire-control systems on several operational weapon systems. These vane type sensors are manufactured by Servomechanisms, Giannini, U. S. Science, Daystrom, and other companies for use on aircraft such as the B-52H, F-101, F-102, F-104, F-105 and F-106. Angle of attack information is used on the B-52 aircraft in computing the flight path vector of the aircraft in a relatively limited flight regime. For accurate calculation of the fire-control problem, the rocket-fire ballistics computer requires continuous data of the angle between the aircraft armament datum line and the relative wind direction. Since the true angle of attack of the aircraft armament datum line at the time of rocket firing determines the angle at which the rockets are launched, a measurement of the angle of attack of the interceptor permits a correction to be made for the weather-cocking of the rockets (Ref 7:5).

Another operational use of angle of attack after correction for Mach number effects is to warn the pilot, when at high speeds, that a pitch-up condition may occur resulting from flight maneuvers, such as break-away from attack. Incorporated in the fire-control system is a command signal limiter based on angle of attack which prevents the pilot from getting into a critical pitch-up situation, and which limits the inputs to obtain an optimum break-away path from the attack phase. The indication to the pilot may be in the form of an angle of attack indicator in the cockpit, pitch control system warning horn, and/or control stick shaker or stick pusher warning system. The F-101 and F-104 aircraft have automatic pitch-up warning control systems.

During the last few years renewed interest in the parameter angle of attack has been expressed by various using agencies within the AF. Basically this interest stemmed from take-off or landing accident problems associated with the F-102, F-100, KC-135, and B-58 aircraft. The problem of the B-58 is a combination of high approach speed, high sink rate, and marginal pilot visibility caused by the high angle of attack required on the final approach. To help prevent hard, short, long, or fast landings, it is required that the pilot attain an optimum approach speed, which necessitates precise attitude information. (Night and adverse weather conditions intensify the situation). A pilot uses the airspeed indicator as an instrument for attitude control during the final approach as he must compute his final approach speed and flare speed, which are based on the gross landing weight of the aircraft. The airspeed is controlled by changes in aircraft attitude, by rate of sink, and by changes in engine thrust. The power-off approach angle of attack for any aircraft remains constant regardless of gross weight. During the take-off phase of flight, the aircraft, if rotated to an angle of attack greater than the optimum for liftoff, shows marked increase of the take-off roll. With the aid of ground effect it is possible for the aircraft to be lifted off at an angle of attack greater than the optimum for take-off. After climbing above the ground effect, it is still possible for the aircraft to settle again on the ground. Because of a recognized need for operational requirements for angle of attack, several aircraft now in the Air Force inventory have some form of stall-warning devices such as is found on the C-123, C-133B, T-37, and other type aircraft.

Attitude control of guided missiles is generally necessary during the propelled phase of their flight in order to enforce a flight path leading toward the prescribed target. The guidance system, which requires precise angle of attack control for beneficial effect upon control deflections in response to the wind, will define a required attitude for the missile (Ref 15:25-26).

Myers of Convair Aviation has recommended repeatedly that an angle of attack indicator be installed in operational F-102A and F-106A aircraft as a landing aid. These aircraft are equipped with the vane type (relative wind transmitter) angle of attack sensor which feeds information to the Hughes fire-control system. There is no angle of attack displayed in the early models of these aircraft, but in the later F-105 and F-106 production aircraft (equipped with the new Advanced Air Force Integrated Flight Instruments), there is the angle of attack tape instrument. These are the only operational Air Force aircraft presently in use equipped with angle of attack continuously displayed in the cockpit as an integral part of the flight instrument panel. The Directorate of Flight Safety and Missile Research has recommended continued research and development in the improvement of landing aids, such as angle of attack presentation coupled with a means of conveying flight path information to the pilot during ILS, GCA, and mirror landing approaches. In addition to the landing and fire-control phases of flight, angle of attack may also indicate:

(1) Optimum control of indicated air speed to obtain maximum range from high altitude to a high key position during an engine flame-out pattern

(2) An approaching stall during a go-around

(3) An optimum angle for take-off (However, with most fighter type aircraft, more than adequate thrust is available.)

(4) A calculated cruise angle

(5) A desirable angle for loiter type missions in order to provide maximum endurance.

Numerous articles have been published in recent years emphasizing the need for angle of attack devices, primarily to aid the pilot during the approach phase of landing in the higher performance aircraft. It has been estimated that at least 30% of all fighter aircraft accidents in the Air Force and Navy have occurred during the landing phase of flight. These accidents usually fall into one of the following categories: (1) Undershooting (collision with the ground); (2) Hard landing (late attempt to flare or too fast a flare resulting in a ballooning effect and possible stall from five to ten feet above the runway); (3) Stalling during the approach (steep turn because of too close a downwind leg resulting in overshooting the crosswind leg or an incorrect airspeed/gross weight relationship); (4) High sinking rate (traffic pattern so tight that there is insufficient time for reasonable glide slope and pilot is forced to perform a power-off tight turn to final); (5) Overshooting on approach (running off the far end of runway, too high and too fast over the fence, or excessive holdoff).

The pilot, to be aware of how near the airplane is to a stall, must have either a plot of stall airspeed versus gross weight or a cockpit presentation of angle of attack. The plot, to be complete, would have to be stall speed versus gross weight per angle of bank, whereas the angle of attack at which stall occurs is the same regardless of the bank angle. A set of thrust required versus thrust available curves for a typical jet fighter are presented in Figure 6. Curve AE represents the thrust required at the minimum gross weight, while the curve A' E' is a similar curve for the maximum gross weight. (The dash lines represent constant angle of attack). Examination of the curves reveals the following facts: Less thrust is required to maintain level flight at B (170 knots) than at A (240 knots); to maintain level flight at D (118 knots) requires more thrust than to fly at either points A or B;

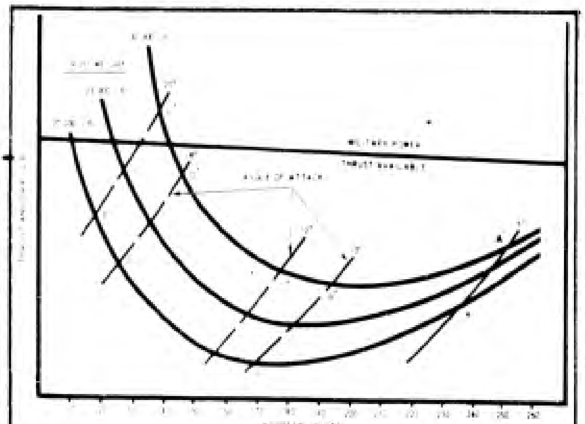

Fig 6.
Thrust Required and Thrust Available for a Typical Fighter Aircraft (Ref 34:25)

the margin of thrust available for acceleration is represented by the vertical distance between any point and the thrust available curve (this margin decreases with an increase in gross weight and/or angle of attack); the optimum approach speed varies with gross weight from 157 knots (light) to 177 knots (heavy), whereas the angle of attack is constant.

Flying at angles of attack to the left of B B' has become commonly referred to as flying on "the back side of the power curve". Most approaches are made slightly on "the back side of the power curve", but further to the left than is represented by C C'. Such an approach permits the pilot to cross the fence at a minimum speed consistent with safety and yet allows plenty of margin for acceleration, should it be required for a go-around. A stall warning device, if installed, should be set to react when the angle of attack reaches the line D D'. Basically there are two categories of approaches: (1) Power approach with a glide slope of between 2 and 4 degrees, with rates of descent between 500 and 1000 fpm; (2) Idle power approach with a glide slope of between 7 and 10 degrees, with rates of descent between 2500 and 3500 fpm. The first approach should be flown at the best airspeed for corresponding gross weight; the second should be flown at 20 to 30 knots above the optimum speed to allow for the flare. When performing a power approach at a 3 degree glide slope, a high performance fighter may have an attitude of between 8 to 10 degrees nose high. This thrust contributes to the total lift vector and allows the pilot to fly the airplane approximately 3 knots slower than would be possible during the steeper idle-approach.

Other variables which the pilot must consider when determining the airspeed for a particular approach are the various devices employed to increase lift during low-speed flight. (They include flaps, spoilers, slats, boundary layer control, and combinations of these). In determining the optimum approach speed for a particular configuration, the following parameters are considered: stability, controllability, stall characteristics, power available vs power required, forward visibility, desire to land as slow as possible, and sufficient speed to allow for flare.

To use angle of attack for an approach during the turn from downwind to base leg, the pilot slows the aircraft by reducing power and maintaining altitude until the approach angle of attack is reached. During the descending turn from base to final, power is adjusted to maintain the approach angle of attack. In doing so, the airspeed which results will be the optimum airspeed for the current gross weight, bank angle, and normal accelerations. This same angle of attack will dictate the optimum airspeed during the final approach. Experience has proven that the safest landing approach during visual flight conditions is the same as the approach which is flown under instrument conditions. This approach is characterized by a 2.5 to a 3 degree glide slope with sufficient power to maintain the correct approach airspeed. Corrections should be made to the flight path with elevator control and power changed to maintain the airspeed within limits of plus or minus five knots of target speed. This same technique is used to maintain the desired angle of attack, with the limits being plus or minus 1/2 degree (Ref 34:23-27).

Civilian

Mr. M. G. Beard of American Airlines and Mr. Scott Flower, Pan American Airlines, representing the SAE-S7 Committee during an Aircrew Station Standardization Panel meeting held at Ft. Rucker, Alabama, on 6-7 December 1960, stated that commercial airlines operating the Boeing 707 and the Douglas DC-8 aircraft were interested in a possible angle of attack system primarily for the take-off phase of flight. Several commercially available angle of attack devices are currently being evaluated for possible use on the larger jet transport type aircraft. A number of recent accidents involving commercial jet aircraft during take-off would indicate that angle of attack could contribute to simpler and safer flying.

Many civilian light aircraft are presently equipped with a stall-warning system which includes a tab-type lift transducer (mounted on the lower leading edge of the wing), and a warning device (which blows horn, flashes light, or shakes control column). The requirement for stall-warning on light aircraft was initiated by CAA in the 1940's, as outlined in Section IV of this report.

IV. Review of Angle of Attack Sensor and Display Evaluations

Angle of attack and other lift instrumentation have been examined and considered for use as flight instruments during the past 20 years or more. Interest in the application of angle of attack information as a primary flight instrument has waxed and waned, but in general there has been a strong antipathy to any thought of such application. In fact, it has been within the past five years that strong feelings against any possible advantages which would accrue through utilization of angle of attack as a cockpit displayed parameter have been removed from all levels of the Navy and Air Force. Angle of attack instrumentation is not a revolutionary item; many engineers and pilots who read this paper have themselves conducted evaluations of various systems during the past 13 years. The results of the evaluations were not gratifying. However, most of the personnel associated with these evaluations are in agreement as to the potential of angle of attack, recognizing that objections to the systems have been related to response, accuracy, reliability, flyability, and display. Although angle of attack is a basic aerodynamic parameter used extensively by aircraft designers, its use in flight has not been fully accepted by pilots as a basic aircraft flight instrument. There are several things to be considered in choosing an angle of attack system, some of which are:

(a) application
(b) display
(c) complexity
(d) performance
(e) reliability
(f) supply
(g) relative cost
(h) installation
(i) maintenance
(j) environmental condition

Many of these factors cannot be determined properly on the basis of subjective pilot "opinion type" evaluation; to consider past experience, programs, and reports that are available adds to the validity of such evaluation.

Pre-1940

The display and sensing of angle of attack information dates back as far as 1903 when an angle of incidence indicator apparently was used on the earliest power driven, heavier-than-air machine of Wilbur and Orville Wright. In their earlier glider flights they demonstrated that they could control sidewise balance by presenting the right and left wings at different angles to the wind. From subsequent wind tunnel tests they compiled the first reliable tables of air pressures on cruved surfaces. By using these tables it was possible for them to design a machine that would fly. Their angle-of-incidence indicator consisted of a weather-vane type sensor mounted on a semi-circular scale, which increased counter-clockwise. (Reference 37:8). Army specifications called at that time for a dead beat operation, free from effect of gravitation. The device was attached in advance of the wings on a tractor biplane, clear of the propeller or fuselage influence; yet it had to be legible to the pilot.

About this same time Samuel P. Langley, pioneer in aeronautics, being interested in aerodynamics and theory of flight, was also utilizing some form of angle of attack information to balance out the pitching moment witn thrust on his early heavier-than-air flying machines. Later years saw even more interest in speed than in lift efficiency, hence the development of the airspeed indicator and system.

In 1923, Lavender developed a claw type instrument which consisted of four bent tubes, two symmetrically placed in each principle meridian plane of a 90 degree cone, with a total-pressure orifice at its apex. The accuracy of this instrument at low speeds was about 1/10 degree for large ranges of incidence.

In 1929, B. G. Van der Hegge-Zijnen developed a pressure head which consisted of five surface orifices in a sphere, four located symmetrically at 45 degrees from the central fifth. It contributed the simultaneous determination of direction and speed by calibration (Ref 50:43).

The display and sensing requirement for angle of attack information is as old as manned flight itself, as it was obviously an informational requirement in the earliest attempts at flight. Further, angle of attack is a direct function of the most important force acting on an aircraft in flight--namely, lift.

Constantin, a French aeronautical engineer, was responsible for the invention of the slotted wing and floating aileron. In the early 1920's he developed a vane-type angle of attack indicator as a primary flight control instrument. Later he proposed to stabilize the flight of aircraft and to alleviate the effects of gusts by feeding in angle of attack information to an autopilot. His concepts became actualities and were successfully test flown before World War II on various biplane trainer and heavy bomber type aircraft (Ref 64:1).

The CAA became concerned with the high incidence of accidents due to stalls, and started investigating ways and means of providing stall warning as early as 1918.

Xhignesse (Ref 66:1-11) compiled a list of 176 references concerning lift information, 19 of which were dated prior to 1940. The majority of these references were NACA Technical notes or memorandum which reported on wind tunnel and flight test evaluations of angle of attack devices for recording flight data. (NACA itself had developed and tested a stall warning device as early as 1938). A review of available literature revealed that angle of attack devices prior to 1940 had been relegated to NACA for wind tunnel and flight testing. It is noteworthy, also that both German and French aerodynamists published technical papers relative to the subject of angle of attack during this period of time.

1940-1950

During this period the Air Force, through the Engineering Division of AMC, began to show an active interest in angle of attack devices--an interest primarily in input signals to airborne rocket launching, although consideration was given to its possible use as a stall warning device. (Vane type sensors had been developed and in use for many years, mostly for use of collecting flight test data). Initial efforts were expended on the procurement of sample angle of attack items and on performing wind tunnel investigations.

The CAA had already begun an independent investigation of various ways and means of providing stall warning to the pilot, and they agreed when, upon request from the NACA in 1941 to continue with this work, to coincide their wind tunnel and flight test investigations. In their review, CAA determined that the stall was essentially dependent on angle of attack of the wing and not on airspeed. They also noted various characteristics of air flow about the wing that resulted from changing angle of attack. One of the criteria stated was that stall warning indication must be independent of airspeed, since stall is a direct function of angle of attack. Considered stall warning devices included: a leading edge vane type instrument devised by Dr. Leonard Greene; a diaphram switch actuated by pressure reversal at an orifice in the wing's leading edge devised by Mr. Ralph Upson; an instrument triggered by initial change in airflow characteristics on the upper surface of the wing's airfoil developed by United Airlines; and various differential pressure operating techniques.

In 1944 the CAA performed flight tests on a Westinghouse angle of attack device installed on a Boeing 247-D aircraft (Ref 66:130). The resulting report, compared with previous test results obtained by United Airlines, confirmed the interesting fact that airspeed varied at stall points, dependent on flight configuration, while angle of attack remained relatively constant.

AMC started flight tests on various angle of attack devices in 1946. Initial tests were conducted on an F-80 aircraft utilizing the technique of differential pressures from numerous orifices on upper and lower surfaces of the wing. Too, various commercial manufacturers became interested in developing angle of attack devices during 1946, including Butler, Maxson, and Specialties. It was during this year that one of the first AMC reports was published, entitled: "Wind Tunnel Tests at Wright Field of Specialties Quantitative and Qualitative Side Slip Detectors" (Ref 66:122). A device utilizing the null seeking differential pressure principle was tested, showing that the system had an accuracy of plus or minus 1/2 degree.

During November of 1948 the All Weather Flying Division of AMC (then based at Clinton County Army Air Field, Wilmington, Ohio) became interested in angle of attack devices for use in all-weather testing in the following areas: (1) in lieu of airspeed indicator; (2) as a gross load or high efficiency fuel consumption indicator; (3) as a stall warning indicator; (4) in recovery from a stall; (5) in flying turbulent air; (6) in overriding the autopilot in turbulent air; (7) in constant attitude automatic landings; (8) as an effective icing meter; (9) in determining effect of flaps on angle of attack; (10) in presentation of angle of attack; (11) in installation of angle of attack indicators; (12) in calibration methods; and (13) in flight test methods. Through AMC contacts with the Navy it was found that they were mainly interested in angle of attack devices in order to determine their usefulness as: a fundamental instrument of flight, an aid to flying constant attitudes during automatic landings, an aid for high efficiency (fuel consumption) flights, and as an aid in dive bombing. The Navy at that time had active programs with Bendix for angle of attack indicators and with Minneapolis-Honeywell for an automatic landing system, which made use of an electronic autopilot in conjunction with the angle of attack indicator, that fed signals to the throttle controls. The All-Weather Flying Division, from its investigation, concluded that there are a large number of theoretical applications of angle of attack indicators in flight. These theories when flight-tested and proven practical, will do much toward facilitating and increasing safety and efficiency of flight. Subject theories have however, long been the source of much discussion and controversy.

One of the most important applications of the angle of attack indicator is its use in flying turbulence, stall warning, automatic flight and landing. About this time Mr. Robert N. Buck of TWA proposed the integration of angle of attack with the artificial horizon display for use in recovery from stalls and in flying turbulent air. His suggestion was based on facts obtained during flights through thunderstorms when constant angle of attack indications were utilized (Ref 3:1-4).

The angle of attack for stall is influenced by Reynolds number, surface roughness, small scale turbulence, planform, high lift devices and Mach number. Above a given Reynolds number for a specific airfoil and planform the stall for roughness is at an almost constant angle of attack. Surface use from dents and nicks can cause premature stalls. Subsonically the angle of attack decreases with Mach number, and above the critical decreases rapidly (Ref 17:1-3).

In April 1947, a group of representatives from the All-Weather Division and Aircraft Laboratory of AMC convened to discuss utilization of angle of attack indicators as an aid in all-weather flying. The group's major concern was with the safest manner of flying through turbulent and gusty air encountered during thunder storm penetrations. Their consideration of angle of attack as a possible application to this problem was one of the earliest indications of its application to gust alleviation. Conclusions of this meeting were: that if a satisfactory instrument was developed that angle of attack could be controlled through the aircraft's automatic pilot; and that such an angle of attack instrument should be the differential pressure type similar to that developed by the Engineering Division of AMC.

AMC (Kollsman Vane)

The Equipment Laboratory of AMC in 1948 reported results of laboratory and wind tunnel tests conducted on the Kollsman vane type angle of attack sensor (Ref 33:1-3). These tests showed that the sensor had an accuracy throughout its range of ± 1.0° with a repeatability of 0.1°, and that it was suitable for use in measuring angles of attack or sideslip. This represented the current status of the commercial manufacturer development so the Kollsman Transmitter and Indicator were recommended as standard for those applications where accuracy requirements for angle of attack did not exceed ± 1.0° (See Figures 7 and 8).

Fig 7
Kollsman Angle of Attack Transmitter (From Ref 33:3)

Fig 8
Kollsman Angle of Attack Indicator (From Ref 33:3)

APGC (Safe Flight Tab)

The Air Proving Ground Command issued a report in 1949 on a device tested that consisted of a small tab-vane mounted in the wing's leading edge, which operated a micro-switch as the stagnation pressure point passed the vane during a stall. It was found that installation was impractical on some aircraft depending upon the configuration and that the device was unsatisfactory during asymmetrical power conditions on multi-engine aircraft. Most pilots questioned felt that a stall warning indicator would not help to prevent stalls, and that the horn-light warning presentation was unsatisfactory (See Figure 9).

In the meantime CAA had been progressing in work on stalls. Research had determined that accuracy of recognition of incipient stall even among experienced pilots was not high. An investigation was conducted at Ohio State University under the direction of Dockeray and Bakan, to examine the effectiveness of training on stall recognition (Ref 66:51). The experiment pointed out that accuracy of stall perception could be improved by special training using an indication of approach to the stall angle; that performance was safer and considerably improved through the use of lift instrumentation.

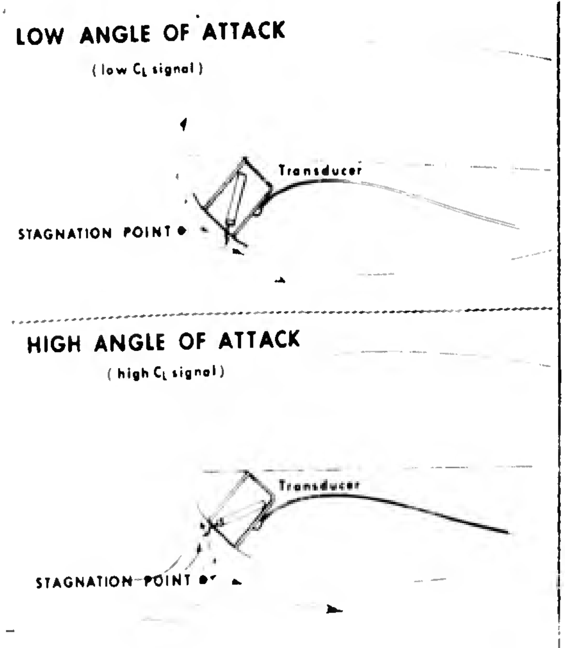

Fig 9
Illustration of Safe Flight Lift Transducer Operation

An investigation of serious and fatal accident records during 1939 and 1940 was conducted by Raymond Fransen and Dean R. Brinhell under the auspices of the National Research Council Committee on Aviation Psychology. Their report revealed a high incidence of stalls, particularly from turns, immediately preceding the crash. Some 65% of private

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plane accidents resulting in fatalities involved a stall, and more than half of them followed improper execution of a turn at low altitude. Examination of current aircraft accident statistics for the Air Force do not reflect a great improvement over this status of 20 years ago, as the majority of aircraft accidents still occur during landing or take-off phases of flight.

Further research was conducted at the Educational Research Corporation, Cambridge, Massachusetts, again under the auspices of the National Research Council. This was a more exhaustive analysis than was the previous research, in that particular attention was paid to the pilot's age and experience, flight conditions, and relationship between accuracy of stall recognition in different maneuvers under various flight conditions. An important conclusion that came out of this research was that stall recognition is specific to the flight condition in which it is attempted. Pilots who were good at recognizing incipient stalls in one maneuver or flight condition were not necessarily good at recognizing the same in some other maneuver or flight condition--an important point as recognizing incipient stalls is not a natural reaction. Regardless of methods or clues used, they were of little help when transferred to an unfamiliar aircraft. Whatever neural mechanism the pilot may have used in avoiding stalls was fallible, as he could have been misled by such items as engine sound and vibration, the feeling of G-forces, and the misinterpretation of the nearness with which a preceding flight condition approached the stall. Pilots who performed best in normal flight in the familiar airplane were among those who departed most dangerously from normal flight in the unfamiliar airplane. As a result it was recommended that aircraft be equipped with devices for stall warning. (Again in May of 1949 it was recommended by CAA that regulations be issued requiring the installation of some form of lift, stall, or angle of attack indicator in every licensed private plane). The results of this study helped lay the foundation for the requirement that exists today--that most private light aircraft have a stall warning horn or light system (Ref 66:54).

During this period the Equipment Laboratory at AMC considered that angle of attack had an application in an automatic cruise control system and requested that its potentialities be investigated. Autopilot manufacturers began considering the use of angle of attack for stall prevention, safe flying at minimum air speeds, cruise control, gunnery, and for automatic landing at low airspeed--among them: Cook Research, Kollsman, General Electric, Specialties, Minneapolis-Honeywell, Curtis Wright, and Seaboard Electric.

AMC (Young Probe)

Primary effort within the Air Force at this time was in evaluating various methods and techniques in the development of suitable angle of attack systems. AMC reported a test that was conducted to determine accuracy and suitability of a null-pressure type instrument, invented by D. W. Young, of the Aircraft Laboratory, for measuring angles of attack and yaw (See Figure 10). This work showed that the principle of utilizing a pressure differential as a signal for servo alignment of the sensor with the airflow was a suitable one on which to base the design of a flight instrument. Although the dynamic characteristics and

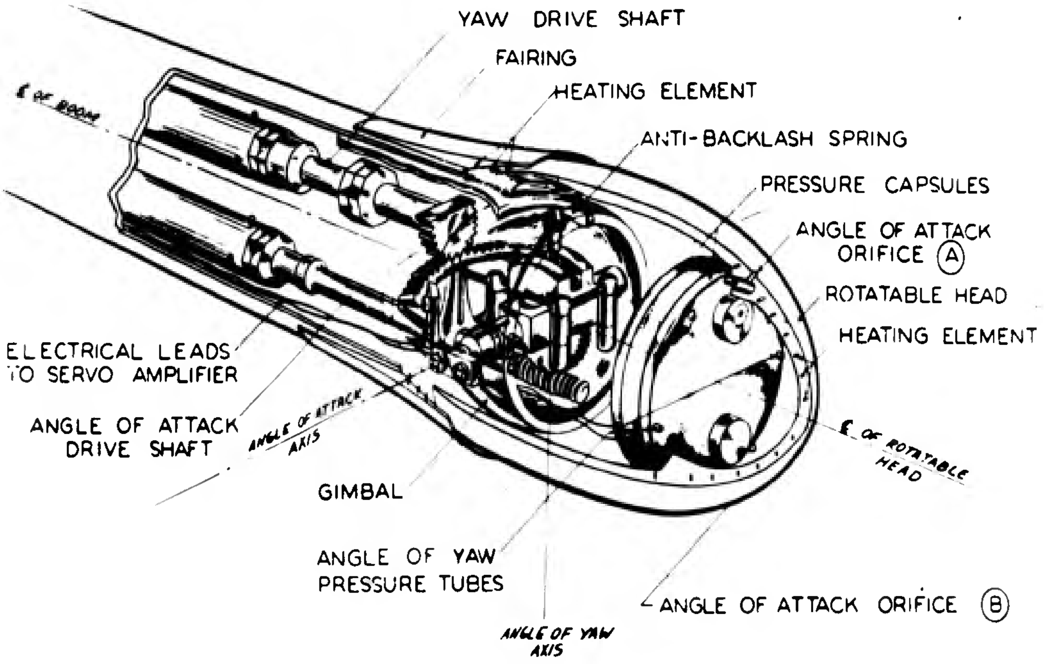

Fig 10
Cut-away Drawing of D. W. Young's Null Differential Pressure Sensor (From Ref 62:16)

accuracy of the instrument tested on a B-29 type aircraft were unsatisfactory, it was felt that these mechanical discrepancies could be corrected. Conclusions from flight tests were: that the principle of design was sound, that the instrument did not provide the desired accuracy of 0. 1 degree in angle of attack in level unaccelerated flight, that there was appreciable wear in the drive system, that the instrument had a proportional position error, that there were objectional oscillations in yaw, that the dynamic characteristics of the instrument were not satisfactory, that the boom mounted device was satisfactory for large type aircraft, and that the thermostatically controlled heated head was satisfactory during icing and precipitation conditions (Ref 10:1-9 and Ref 62:15-17).

AMC (Kollsman Vane, Seaboard Probe, Specialties Probe)

AMC flight testing of the Kollsman vane type and Seaboard Electric differential pressure type angle of attack sensors was begun in 1950 on a B-26 type aircraft. A 4-foot boom of the Seaboard Electric Sensor was mounted on the wing tip with the axis of rotation sensing head located on one chord length ahead of the wing's leading edge (See Figure 11).

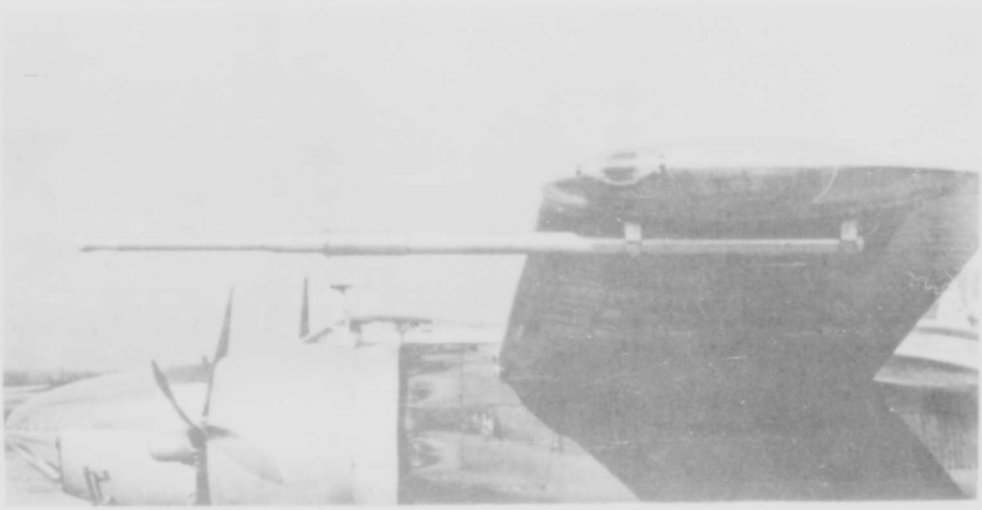

Fig 11
Boom Mounted Seaboard Electric Null Pressure Type Sensor
(From Ref 62:12)

This instrument's sensing mechanism consisted of a rotatable spherical shaped head mounted in the end, housing two orifices that were joined by flexible tubing, connected to a differential pressure transducer located in the base of the boom housing (See Figure 12).

Wind tunnel tests conducted on this instrument showed that it had an average error of 0.1° during calibration runs. The sensitivity adjustment of the servo amplifier was found to be critical, and during

Fig 12
Close-up View of Seaboard Electric Null-Pressure Type Sensor
(From Ref 62:8)

several test runs the sensing head rotated to one extreme stop position. In laboratory tests it was found the servo amplifier was sensitive to frequency of voltage changes. During flights in turbulent air the indications of angle of attack varied as much as plus or minus 3 degrees, which was primarily due to the heaviness of the instrument mounted on the end of the boom and the flexible wing tip.

The Kollsman wind director transmitter and indicator also flown during this flight test are depicted in Figure 13; Figure 14 shows the angle of attack sensors that WADC Flight Test Division developed (Ref 62:28).

NATC (Specialties Probe)

Published about this time was an NATC report based on test work done to determine the practicability of using an angle of attack indicator as an aid during landing, for showing proximity to stall, for operation of approach lights during night operation, and as an aid for cruise control. The device used was a cylindrical probe type sensor (See Figure 15).

During the test it was determined that the instrument did not have the required range for full operation, therefore the sensor was set to operate primarily at and near the stall range of operation. It was observed that in the landing configuration, the stall angle was always the same below 20,000 feet, regardless of wing loading, but that there were no other indications of specific altitudes checked below or above this level. For the clean configuration it was observed that the angle of attack was constant for stall below an altitude of 10,000 feet regardless of wing loading, but that it gradually decreased up to 35,000 feet. (This was a variance because of Mach number and should have been expected). In additional comments on the landing approach, reference was made to changing of indicators, implying change was made in the damping factor of the indicator due to excessive fluctuations in flight. With the damped instrument pilots were able to hold the aircraft within 2° angle of attack (the smallest increment on the dial). The pilots were actually holding the aircraft within 1°, as the indicated angle of attack was approximately twice that of true angle of attack (Ref 66:95).

Fig 13
Kollsman Vane Type Transmitter and Angle of Attack Indicator
(From Ref 62:28)

Fig 14
WADC Flight Test Vane Type Angle of Attack Sensor
(From Ref 62:28)

1951-1960

During this period the Air Force continued flight testing of various angle of attack sensors that had been tested previously in the wind tunnels at WADC. The devices were flight tested in B-17, B-26, and B-29 type aircraft, including the Young differential pressure probe, Kollsman vanes, and Safe Flight stall warning tab. Thus, the automatic flight control people were obviously becoming interested in the parameters of angle of attack and side-slip for use in rocket fire-control, automatic approach systems, and optimum cruise procedures (Ref 62:6-31).

Fig 15
Specialties Probe Differential Pressure Type Angle of Attack Sensor
(From Ref 62:19)

NATC (Specialties Probe)

In the meantime a tuft study by NATC was made on an F9F-2 aircraft to relocate the position of the sensor. The recalibration produced a linear curve of indicated angle of attack versus lift coefficient for the aircraft in the landing configuration. Much of this test was devoted to various phases of carrier landing approaches, the external lighting color sequence for signaling the landing signal officer (LSO) being one of the major considerations. Primary criticisms of the angle of attack display were: (1) the indication fluctuated in gusty air, (2) the indicator moved clockwise as airspeed moved counterclockwise, (3) the indicator readings were not representative of true angle of attack, and (4) the dial moved through a greater angle than the actual angle change of the aircraft.

These comments made by pilots gave evidence that they did not understand how to use the parameter of angle of attack.

The utilization of angle of attack for maximum range flight was also considered in this particular flight test program. When a pilot flew the angle of attack indicator one index in error (or two degrees) his specific range was reduced, whereas when he flew airspeed one index in error (or 10 knots) his specific range was less reduced. This pointed out that angle of attack had to be flown accurately for maximum range and that an indicator having an increased scale factor for the range problem could possibly be unusable in the landing phase of flight.

The report also stated that angle of attack would remain constant for maximum range or endurance problem only if Mach and Reynolds number effects were neglected. However, there was variation due to Mach number, consequently it was deemed impractical to investigate cruise control by using angle of attack (Ref 29:6).

AMC (Safe Flight Tab)

During 1952 an AMC publication outlined a flight test program conducted on the Safe Flight stall warning device--the detector, which was installed in the lower side of the leading edge of the left wing's airfoil. The test data indicated that this system used as a means of controlling the landing approach was inaccurate and unsuitable (Ref 1:1-3).

WADC (Young Probe, Kollsman Vane, Specialties Probe, Seaboard Probe)

A USAFIT student, the author, in 1952, reported on several types of angle of attack devices, which included: the Seaboard Electric differential pressure, D. W. Young null-pressure angle of attack and angle of yaw, Specialties null-pressure seeking probe, Kollsman, General Electric, WADC Vane type, and the Safe Flight type stall warning device. (See Figure 9 and Figure 15). These devices were tested by WADC and these conclusions drawn: (1) a constant reading instrument rather than an "on-off" type indicator was desirable, especially when used as an aid during landing approaches; (2) the differential pressure type angle of attack instruments had greater accuracy (0. 1-0. 2 of a degree) than the vane types (0. 2-0. 5 of a degree); (3) the use of boom mounted angle of attack sensors, especially on flexible wings, was not desirable; (4) the fuselage mounted vane or probe type sensors withstood severe operational usage better than more complicated differential pressure servo-driven types; and (5) the sensitivity of the angle of attack system would have to be reduced for high angles (low airspeeds) and increased for low angles (high airspeeds).

The report also outlined other possible uses for the parameter of angle of attack, such as cruise control, automatic landing approaches, gust alleviation, bombing, rocket firing, and automatic pilot systems. There was no mention of particular displays used during testing nor suggestions as how to fly the angle of attack parameter during other modes of flight (Ref 62:6-31).

WADC (Specialties Probe, Safe Flight Tab)

As a result of flight testing to determine the possibility of using Specialties angle of attack or Safe Flight devices for approach and landing of B-47 aircraft in lieu of airspeed, WADC published these conclusions: (1) the Safe Flight stall warning indicator, as a means of controlling the B-47 landing approach, did not allow the aircraft to be flown safer nor more easily, nor did it offer better control; (2) the Specialties indicator, while not a necessity on B-47 aircraft, would be desirable and (3) both type indicators were considered to be susceptible to ice accumulation which could make them inoperative or erroneous under icing conditions.

Comments made regarding the test were varied. It appeared that at least an attempt had been initiated to determine the usefulness of angle of attack or stall warning indication for the final landing approach phase of flight. The use of lights in supplying proper angle of attack approach had been taken from the Navy LSO system. The calibration method of doing a tuft study on the airplane was found to be time consuming and complex in determining the proper location for the sensor. It was pointed out that on-off type light indications were not as satisfactory as trend information provided from continuous indication on the angle of attack dial instrument. The requirements for trend information and angle of attack sensors to incorporate de-icing capability were mentioned. It was also noted that fuel readings obtained from standard fuel gages, the normal procedure for computing gross weights, were not accurate; thus pointing out the variable of human error in computing best approach and landing speeds (Ref 24:1-5).

WADC (Specialties Probe, Kollsman Vane)

During 1954 there were four significant flight test programs conducted on Specialties, Kollsman, and Safe Flight angle of attack devices. Brandenburg in reporting on the Specialties and Kollsman angle of attack air stream direction detectors made on a T-33 jet trainer aircraft, wrote on determining the practicability of these instruments during the landing approach and in cruise control. (Both systems were tested simultaneously, one in the rear cockpit and one in the front). He showed that the Specialties indicator had good repeatability during normal flight conditions, but that in turbulent air the time of response of the sensing head to changes in local air stream was so brief that the indicator fluctuated rapidly. This made control of angle of attack by reference to the indicator alone difficult during climb, cruise, and final approach. He concluded that the Kollsman vane type sensor and indicator had fair repeatability, were greatly affected by turbulent air, and in general, were considered unsatisfactory.

Pilots objected to both angle of attack presentations for the following reasons: (1) the indications of angle of attack fluctuated rapidly in gusty air, (2) the sensitivity of indicators increased with decreasing airspeed, thus making flying at constant angle difficult, (3) the indicator did not read true angle of attack, and (4) the pointer on the Specialties indicator moved clockwise while the airspeed indicator decreased counterclockwise. (See Figure 16 and Figure 17).

It should be noted that evaluation of the entire angle of attack system was based on final display given to the pilot in the cockpit, and that due to poor scale factor, erroneous pointer movement, poor repeatability, and sensitivity, the complete system was rejected--based on pilot opinion (Ref 6:8).

SAC (Specialties Probe, Safe Flight Tab)

Tests were conducted by SAC involving two B-47's, using the Specialties angle of attack and Safe Flight landing speed systems, tested simultaneously. Results of the test included: (1) a definite requirement for lift instrumentation in the B-47 a/c; (2) a safer, more uniform, and easier B-47 landing approach by use of direct sensing lift instrumentation; (3) superiority of both systems over the use of airspeed; (4) superiority of presentation of the landing speed indicator to the angle of attack dial indicator; and (5) indication that the landing speed indicator was constant regardless of flap setting for a given pre-stall condition, whereas the angle of attack indicator gives a different reading for each wing flap position.

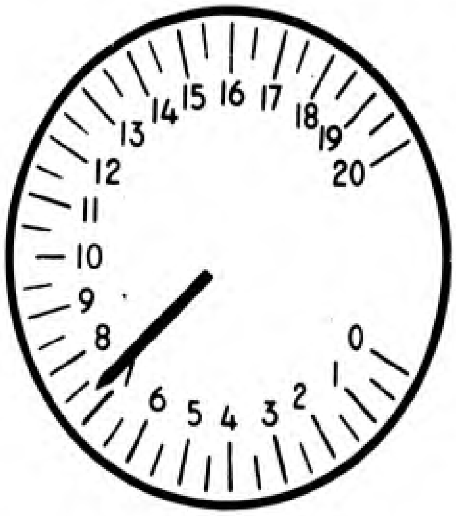

Fig 16
Specialties Angle of Attack Indicator (From Ref 6:App)

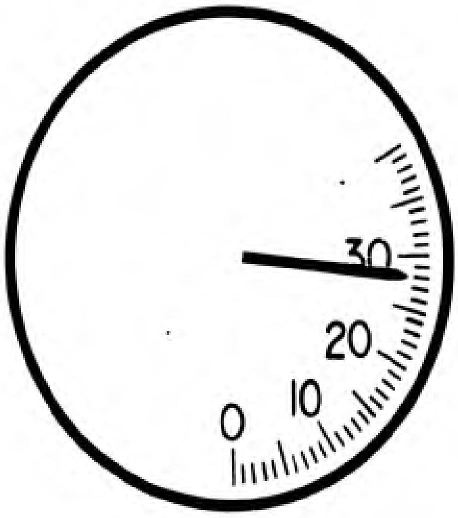

Fig 17
Kollsman Angle of Attack Indicator (From Ref 6:App)

The display used during the test was considered to be unsatisfactory for control of the approach. Pilots' reactions and comments concerning the equipment tested ranged from simple disbelief to mild skepticism at first but after a demonstration of the applications and capabilities of these instruments, some pilots saw the advantage of completely relying on the landing speed indicator during approach. Consequently, it was recommended that all B-47 aircraft be equipped with lift instrumentation--either the landing speed indicator (Safe Flight) or the angle of attack indicator (Specialties). It was realized that either system could be modified to do the job completely and effectively, but combination of the two systems was advantageous since one could be used as a primary approach instrument and the other could be used as a stand-by, as well as a primary reference for other flight conditions (Ref 4:1-4).

SWISSAIR (Specialties Probe)

A SWISSAIR Report in 1954 gave a thorough investigation of uses for angle of attack indication for commercial piston DC-6B type aircraft, The report went into considerable theoretical and factual background on the DC-6B aircraft during various phases of flight, including take-off, climb, cruise, approach and landing. It emphasized the use of angle of attack in the cruise mode of flight, as commercial carriers are primarily interested in economical and safety factors of operation. Commercial air-carriers are currently using one of the following methods for improving the economic factor during the cruise phase of flight: constant power, constant speed, performance for maximum range, and constant angle of attack. The use of angle of attack greatly simplifies requirements for changing airspeed, power, and possibly altitude as required in the case of maximum range. The Specialties system was used on a SWISSAIR DC-6B for over a year with no mechanical difficulty and was flight tested during various modes of flight operation.

Knowing the proper angle of attack for lift-off speed was relatively unimportant to the pilot. He was interested in continually being informed of his acceleration down the runway on take-off, and found it difficult to give attention to an instrument other than the airspeed indicator. During the climb it was determined theoretically that the optimum rate of climb was reached, at all heights and for every wing loading, with a constant angle of attack. Therefore, climbing according to a constant angle of attack did simplify work of the pilot, and contributed appreciably to shortening climb time. (Figure 18 depicts the Specialties angle of attack indicator).

The conclusions of the tests were: (1) the Specialties system as installed in a SWISSAIR DC-6B for approximately one year operated properly without any required maintenance; (2) accuracy of the instrument made it acceptable as a safety instrument; (3) for use in the cruise range of flight it was recommended that the scale factor on the indicator be increased either mechanically or electrically; (4) the indicator was stable under normal flight conditions; however, under gusty air conditions the indicator should be damped; (5) the angle of attack indicator had other potential uses as a safety device during engine failure, approach and landing, overload landings on short runways, and holding

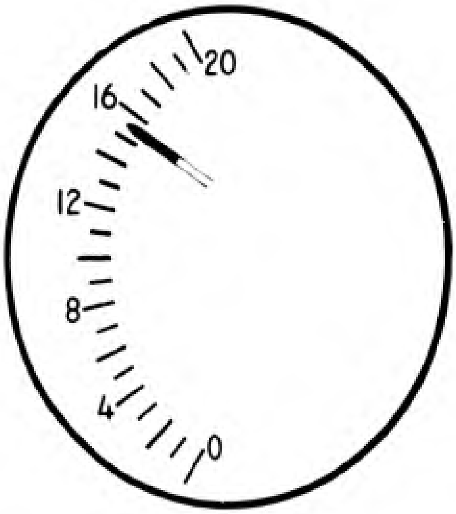

Fig 18
Specialties Angle of Attack Indicator Used in SWISSAIR DC-6B
(From Ref 48:19)

with minimum engine power; (6) the indicator should be located as close as possible to the airspeed indicator (a visual or audio warning system was recommended for stall warning); (7) for climbing and cruising the angle of attack indicator showed promise for controlling the aircraft efficiency during flight; and (8) an additional possible application was that of measuring the angle of yaw which could increase the efficiency of operation (Ref 48:5, 9, 12-17). This report was one of the first to indicate uses of angle of attack information during the take-off, climb, cruise, approach and landing, and stall phases of flight.

NATC (Specialties Probe, Safe Flight Tab)

The fourth report of significance during this year was by NATC on the Specialties angle of attack system which was installed in an F7FU-3 aircraft and evaluated on a comparative basis with the Safe Flight Instrument landing speed indicator system, installed in the same aircraft. The Specialties system functioned satisfactorily during normal and field carrier landings, field take-offs, and field catapult shots, and it provided a means of actuating the approach lights. However, the pilot's indicator presentation was unsatisfactory as it required excessive familiarization with the system in order for him to gain confidence in it. The results of the tests were: (1) the Specialties system had limited effectiveness as a general low attitude stall warning device due to changing the landing configuration or sideslipping the aircraft; (2) during normal field take-offs the system gave a "flyable" indication, but the pilots were primarily interested in attaining an increase in airspeed and altitude rather than maintaining a constant angle of attack; (3) on field catapult take-offs the system presented a "flyable" indication as to attitude of the aircraft; (4) after pilots familiarized themselves with the system, they completely ignored the airspeed indicator and used the angle of attack indicator as the sole source of approach speed information; (5) the approach lights functioned perfectly and provided the landing signal officer with excellent approach speed information; (6) the direction detector probe sensor was subject to ground handling damage and therefore had to be readily accessible for ease of replacement; (7) the system had no "fail safe" feature; (8) the indicator presentation was unsatisfactory and subject to considerable improvement as it did not present the pilot with a complete picture at a glance (he was not concerned with numerical values of angle of attack, but with an indication of his angle of attack relative to that which had been decided to be an optimum); (9) the unsatisfactory indicator presentation needed to be modified to provide an expanded scale and increased pointer travel during slow speed flight (though this would limit its use during other modes of flight); and finally; (10) the presentation of the Safe Flight system was considered to be superior to the Specialties type as it required a minimum of pilot familiarization and provided more precise speed control.

It was in this report, too, that it was pointed out that the Navy required some means of providing lift information for the pilot so that he might fly the airplane more accurately at its optimum angle of attack during carrier approach and/or catapult take-off. A contradiction appeared in the report, however--recommendation called for an expanded scale and increased pointer travel on the Specialties indicator, while another called for utilization of an easy-to-interpret indicator such as the ILS (ID-249) or Safe Flight null-type of presentation.

Some of the first indications of human engineering and control display input appeared in this report, with recommendation that a small indicator be installed above the glare shield on the left side of the cockpit of carrier type airplanes. (It should be noted that the recommendation for improvement of display apparently was the establishment of the requirement for the present day standard "Indexer" which Specialties produces for the Navy) (Ref 11:1-7).

NATC (Specialties Probe)

Lanham published for NATC in 1956 a report that covered tests that were conducted to determine if the location of the Specialties angle of attack transmitter was satisfactory with and without the AN/ARN-25 "chin" radome installed on the F9F-5 aircraft. It was concluded that the location was satisfactory in either flight configuration, and recommendation for acceptance for service use was made (Ref 26:1-4).

NADC (Topps Probe)

The U. S. Naval Air Development Center in 1958 published a report authored by Canavo that gave laboratory results of an evaluation conducted on the Topp Industries compensated angle of attack and angle of yaw system. The system consisted of an angle of attack transducer, an angle of yaw transducer, an electro-mechanical computer, and an angle of attack indicator, designed to provide true angle of attack and yaw for use by the fire control system. Angle of attack transmitter (Navy Specification MIL-T-7785A) and angle of attack indicator (Navy Specification MIL-I-7783A) were used as guides for laboratory tests and evaluation.

Test conclusions were that the angle of attack and yaw transmitters gave sufficient accuracy and repeatability to operate the pilot's indicator and to provide true angle of attack to an armament system through the Mach number compensator. The indicator was useful only with a synchro input such as could be furnished by the Topp Mach Compensator (not interchangeable with indicators presently in use, i. e. Specialties). (Ref 8:1-2).

WADC (AF Vertical Tape)

In 1958, WADC published a report that summarized, correlated, and analyzed knowledge obtained from total flight experience on the Air Force Integrated Instrument Panel. Two separate flight test evaluations were covered--one by Flight Test Directorate of WADC, the other by the Air Proving Ground Center, with added informal evaluations and flight demonstrations by key Air Force personnel; representative pilots of using commands; Army, Navy, Royal Air Force, airframe and equipment industry test pilots. This advanced flight instrument panel was developed by the Flight Control Laboratory under the Control Display Integration Program established in 1955--the first time in history that a flight instrument panel was integrated, with definite weapon systems in mind. Figures 19 and 20 depict two preliminary WADC designed dial type indicators, integrating angle of attack with other flight parameters (Ref 65:9).

This paper will discuss only those portions from that report which pertain specifically to the angle of attack tape type display, recalling

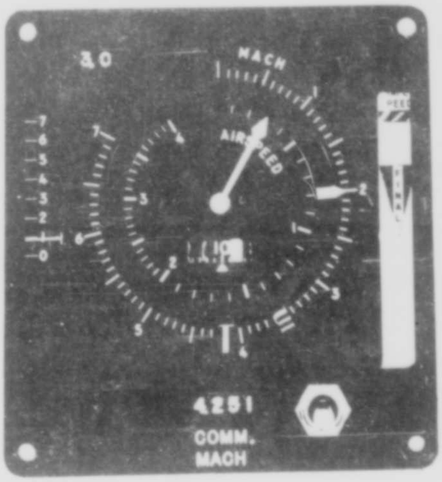

Fig 19
Model of WADC Dial Type Angle of Attack-Mach-Airspeed Indicator

that the primary objective of this development was not to improve present standard displays for parameters, but to find a suitable method to convey both command information and actual performance to the pilot in a readily interpretable manner. The fact that standard round dial presentations prevented realization of this objective was the basis for development of vertical tape instruments currently in use in F-105 and F-106 type aircraft. Figures 21, 22 and 23 depict the display evolution that took place during development of the final angle of attack tape instrument as shown in Figure 24.

Fig 20
WADC Designed Angle of Attack and Pitch Angle Indicator

The indicator was located left of the attitude director and included from left to right: Mach, airspeed, and "maneuverability scale" tapes.. The maneuverability indication comprised an angle of attack tape and a load index; its location immediately adjacent to the attitude indicator permitted the pilot to monitor easily his aircraft performance against defined structural and aerodynamic limits. To achieve the desired uniform control display interaction, the angle of attack tape and load index were made to move down with increasing values. Only well defined and useful regimes such as final approach, maximum cruise and stall were shown (Ref 63:47).

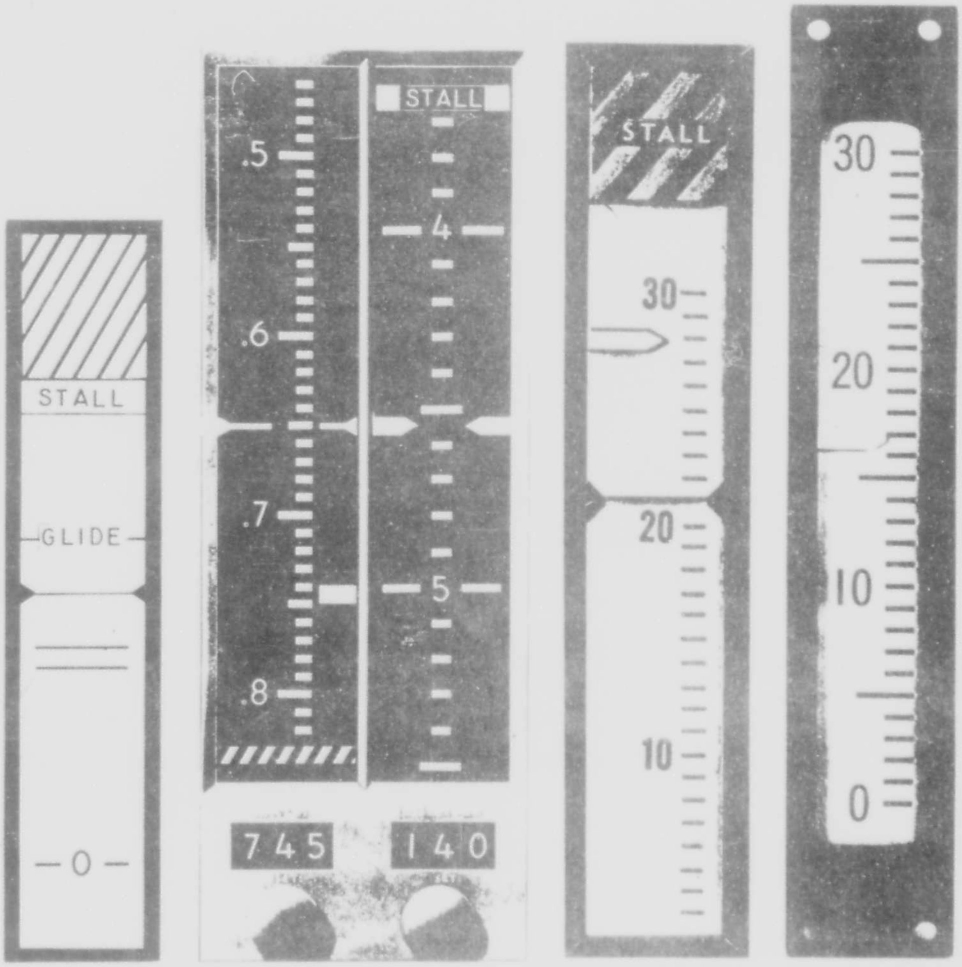

Fig 21
WADC Preliminary Vertical Tape Displays for Angle of Attack

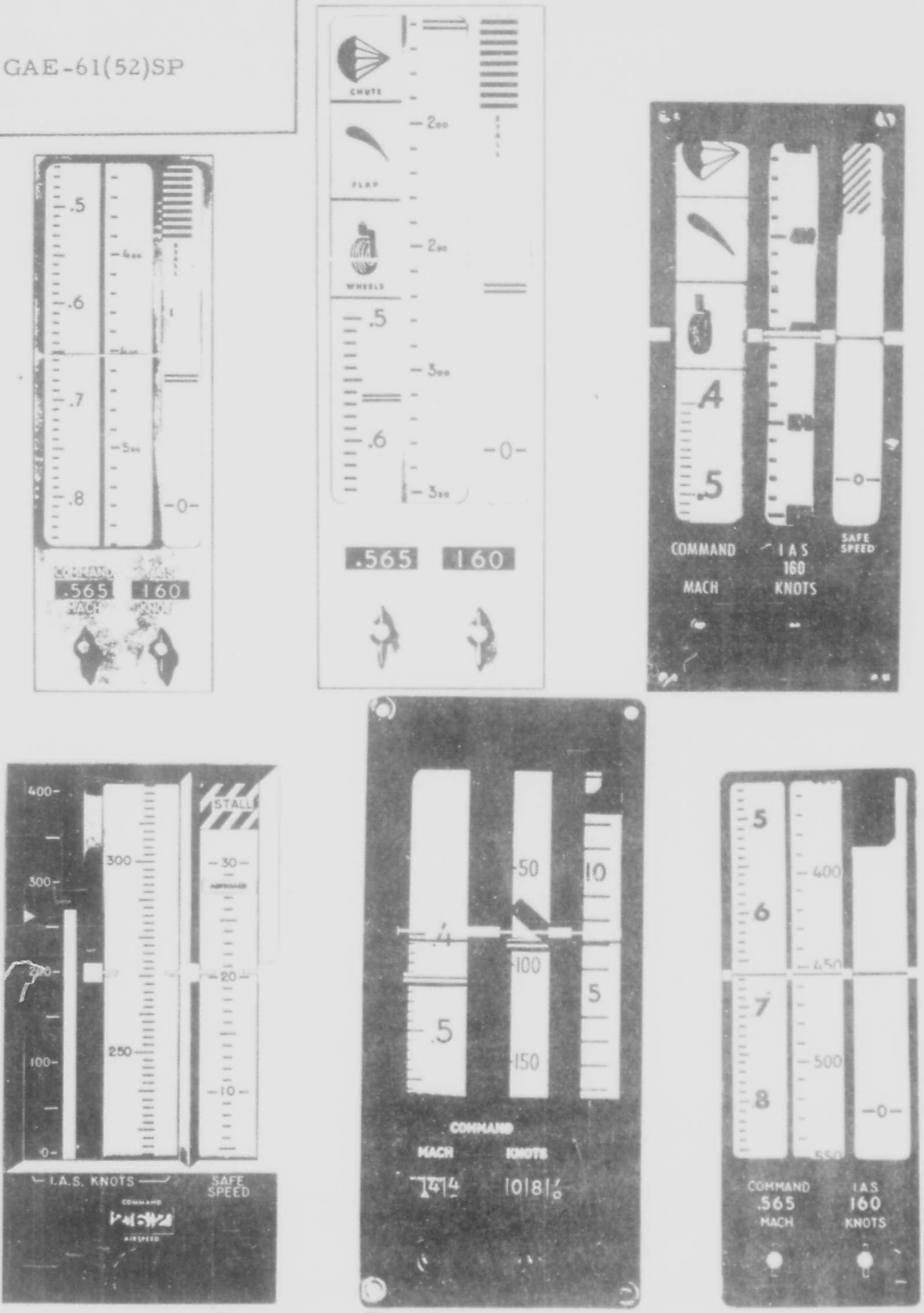

Fig 22
WADC Preliminary Vertical Tape Displays for Angle of Attack

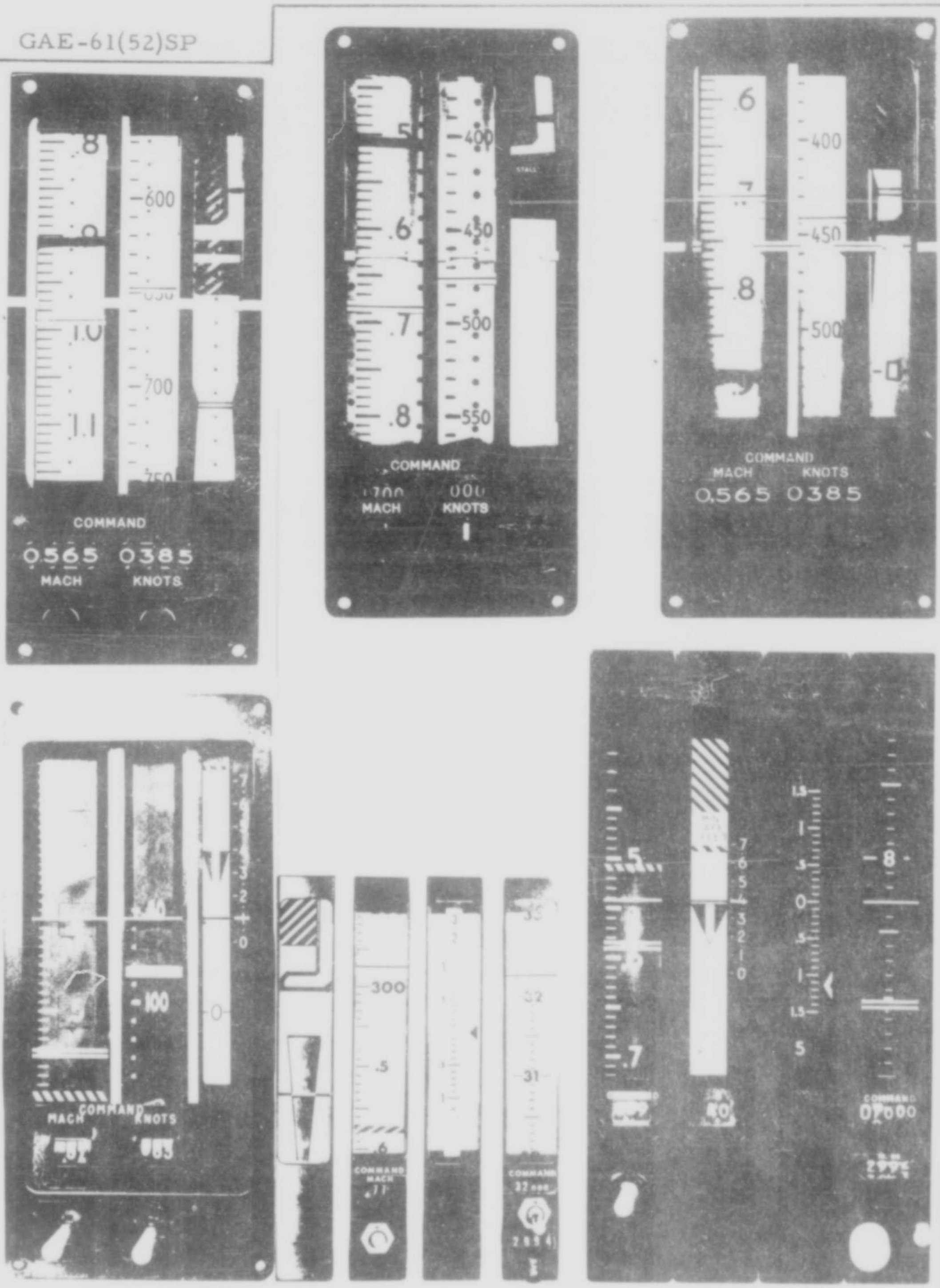

Fig 23
WADC Preliminary Vertical Tape Displays for Angle of Attack

The angle of attack display was the recipient of considerable criticism during flight tests conducted in the T-33 and TF-102 aircraft about this time. Two factors contributed to pilot comment: angle of attack was an entirely new control parameter to the Air Force pilot and its significance and potential uses were not well known to him; the initial large scale factor utilized in the test article and the poor dynamic characteristics of the display, especially in turbulent air, prevented his developing suitable techniques for use of this parameter. Under these conditions, the inevitable result was that pilots attached much more importance to airspeed. It was, therefore, recommended early in the program that the entire maneuverability scale be shifted to the outside of the instrument, thus placing the airspeed next to the attitude director. (This change was incorporated in the production article as is shown in Figure 24). It was pointed out toward the end of the program that when the scale factor of angle of attack was reduced and its mechanization improved, some pilots having achieved a better understanding of the potential utilization of this parameter, no longer considered the move essential (Ref 59:38).

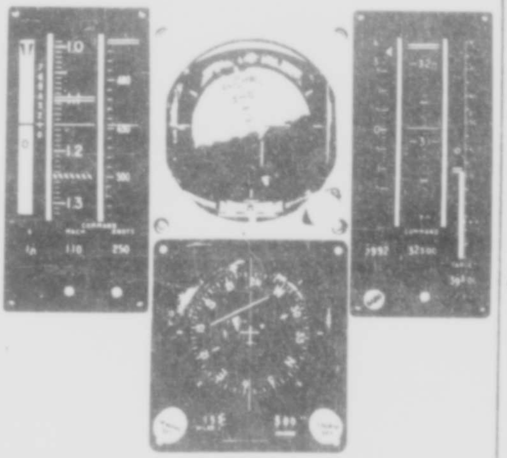

Fig 24
Air Force Advanced Integrated
Flight Instrument Panel
(From Ref 59:25)

There is an inherent paradox in the dynamics of angle of attack presentation which stems from the nature of the sensing of this parameter. When sensing of the angle of attack is done in outside air as through an angle of attack vane, the signal naturally picks up all external noise that is present in this medium. The inertia of the angle of attack vane and of the overall loop also contributes to the total noise level. The ensuing smoothing of the signal, as through damping, to eliminate the undesirable noise, inevitably results in a less responsive signal. In the initial test model (See Figure 21, 22, and Figure 23) the large scale factor utilized for the angle of attack tape further magnified these sensed and induced oscillations and rendered the indication unusable. In later models the scale factor was considerably reduced and general tightening of the loop and damping of the signal combined to provide a satisfactory presentation of angle of attack to the pilot. These improvements have been incorporated in the production article (See Figure 37, Section V).

The development of new flight instruments, possessive of improved and/or different functional capabilities, as in the case of angle of attack, often results in changes in instrument flying procedures. The impact of the integrated flight instrument panel on existing flying procedures has not yet been fully determined. Pilot procedures which would best exploit the information content presented by the panel in all different modes of flight need to be defined. It was recommended that the USAF Instrument Pilot Instructor School, James Connally AFB, Texas, investigate a flight program aimed at determining recommended procedures in the use of the AF Advanced Flight Instrument Panel in various modes of flight. Production versions of the F-105 and F-106 were in the AF inventory before this was accomplished; in fact, production versions of the F-106 aircraft were delivered with angle of attack tape instruments inoperative, due to a delay in the production of a three dimensional cam mechanization. It was not until October 1960 that the first F-106 operational squadron, 329th Fighter Interceptor Squadron, George AFB, Calif., received the first production aircraft with angle of attack tapes working as they should. To date, F-105, and F-106 Flight Manuals do not explain the use of this still relatively new flight parameter to the pilot; this should be the responsibility of the Training Research and Development group (located at the USAF Instrument Pilot Instructor School) in coordination with the using commands (Ref 59:38, 43, 67, 69).

WADC (Specialties Probe)

WADC in 1959 reported on the Specialties airstream direction detector device of the null-pressure seeking type, which consisted of two major components: a sensor and an indicator-relay unit; but which also included a cockpit light assembly that operated in conjunction with the indicator-relay unit. Two different sensors were used during the flight tests, a type L-30 with 30 degree angular movement and a type L-50 with 50 degrees of angular movement. Essentially the two sensors were identical except for probe rotation and magnitude of potentiometers. The system incorporated the standard components previously tested and currently being used by the Navy as described in Section V (See Figure 34 and 35).

The primary purpose of the tests was to consider the potential of available equipment for a standard for measuring angle of attack on high performance aircraft and to investigate uses of this parameter. The test installation included indicators in the cockpit as well as a photo panel which recorded applicable parameters during flight. The tests included flying various maneuvers, using standard procedures, to determine if angle of attack information could be satisfactorily substituted for airspeed as the primary flight reference. This is one of the first flight test programs which considered each possible mode of flight and recorded specific data to correlate with final results when using angle of attack as a flight instrument. The flight test was conducted on an F-100C aircraft with these conclusions: (1) presentation of indicated angle of attack by the test system was generally inadequate and failure to obtain conclusive results in some areas of the investigation was attributable to this inadequacy; (2) sensitivity of the indicator was in most cases not enough and a system with variable sensitivity would be required to obtain desired sensitivity for use over any but a small range of flight conditions; (3) angle of attack indication did not provide the solution for all flight reference inadequacies, nor did it lessen the importance of the airspeed indicator (these two indications should be closely allied, each supplementing the other); (4) satisfactory use of angle of attack as a flight reference will require a considerable amount of pilot training and indoctrination flying to eliminate reluctance to use a basic flight reference other than some form of indicated airspeed; (5) use of angle of attack during swoop or energy schedule climbs demonstrated no significant improvement over use of Mach number; (6) use of angle of attack as a low speed stall warning device was effective; its use as a stall warning for high speed stalls was possible except for extreme areas (seldom encountered in normal flying); (7) angle of attack was demonstrated to be as effective a cruise climb parameter as Mach number; (8) use of angle of attack during approach to landing, particularly GCA and ILS approaches, as well as the final leg of VFR approaches, was valuable and presented needed information which was not given by airspeed; and (9) use of cockpit signal lights during final approach was unsatisfactory.

It was recommended that presentation of angle of attack indication be developed to a standard necessary for its use in flying high performance aircraft and that this and airspeed indication be displayed in close proximity to each other. It was also recommended that angle of attack displays incorporate variable sensitivity and that variable damping also be incorporated (Ref 55:19-20).

AFFTC (Specialties Probe, Kollsman Max-Min)

A preliminary report was published by AFFTC in 1959, the specific objectives of which were to determine qualitatively: (1) oomparison and relative advantages of the Specialties and Kollsman angle of attack systems; (2) capabilities of both systems; (3) benefits of such equipment in providing optimum approach and landing information for F-106 and F-102 aircraft; and (4) recommended procedures for use of the systems. The Kollsman, which presented angle of attack indirectly, was considered adequate. The Specialties system tested was the standard type used during previous flight test programs with a direct indication of angle of attack in "units".

Its indicator provided the same indices for various flight conditions, excluding the loiter phase, and were considered unsatisfactory with the exception of the stall position because the small blocks of various shapes representing the angle of attack indices did not readily identify their functions. Results of the evaluation showed that for take-off the use of the Specialties indicator approach indice was feasible for military power take-offs, with some limitations. Use of the Specialties gage for maximum power take-off was determined to be impractical as it was extremely difficult to attain proper angle of attack in the limited time period between nose wheel lift-off speed and take-off speed. The Kollsman gage was used during take-off but its response rate was too slow to provide take-off capability at either maximum or military power. The Kollsman indicator had an advantage over the Specialties in that its presentation was integrated with the airspeed indicator. The Specialties instrument had an advantage in that the indices could be calibrated independently, while the Kollsman indices were premanently fixed in relation to each other. Neither of the two systems presented stall proximity in a readily usable form.

Pilots considered the approach speeds too low in the F-106 when the glide slope exceed 5 to 6 degrees. Use of either system was difficult in gusty air. The Kollsman angle of attack system was relatively insensitive to turbulence, and very little movement of the approach index was encountered; the dynamic response of the Specialties system resulted in large fluctuations of indicated angle of attack. Opinions recorded in this report were: (1) angle of attack indication was unnecessary for use on approach since it provided proper airspeed only for a specific glide slope; (2) angle of attack was usable during go-arounds, but was considered to be unnecessary and undesirable in the F-106; and (4) the method of calibration of the Specialties system was considered superior to the Kollsman technique (Ref 61:16).

WADC's report covering work done under an AF contract by Rosemount Aeronautical Laboratories in 1959 at the University of Minnesota had to do with experimental and analytical investigation of the effects of dimensional variations on the reproducibility of angle of attack measurements with null-seeking differential-pressure and vane sensors. The conclusions reached after wind tunnel tests and investigation with variations in physical geometry were: (1) that null-seeking differential-pressure sensors were extremely sensitive to variations in slot geometry, and to assure reproducibility of angle of attack measurements within 0.1 degree at all flight conditions (up to Mach 2.54), stringent tolerances were necessary for some dimensions--slot width, edge radius, and edge elevation (with respect to nominal probe diameter); and (2) that null-seeking vane sensors were relatively insensitive to dimensional variations and 0.1 degree reproducibility could be assured with easily met manufacturing tolerances (Ref 60:1, 15, 20).

In late 1959 a flight test report was published on how to obtain local angle of attack values for take-off rotation, initial climb, cruise, slow speed flight, downwind leg, final approach and landing flare for F-102 type aircraft. Local angle of attack values obtained were considered accurate as determined by available instrumentation. All maneuvers were made at recommended airspeeds and configurations as outlined in the Pilot's Flight Manual (Ref 32:1-2).

NATC (SMI Vane, Specialties Probe)

In Nov 1959, NATC reported on the SMI angle of attack system with viscous damped transmitter wind vane which was flight tested on a Chance-Vought F8U-1 aircraft during landing and shipboard operations. It was determined that the system was suitable for take-off and carrier approaches with minor modifications although results under high speed operation were not determined as the test transducer was not compatible with the MK 16 aircraft fire control system, and the system did not incorporate a position error compensator. (Figure 25 depicts vane operation in flight). It was concluded that the SMI vane type system was interchangeable with the Specialties probe type angle of attack system with minor modifications. Conclusions of the tests stated that: (1) all new equipment be satisfactorily demonstrated in the laboratory prior to flight tests, (2) viscous damping be incorporated in future vane type transmitters, and (3) a simple method of checking the boresight retention be promulgated for service use on vane type angle of attack transmitters (Ref 39:1-3).

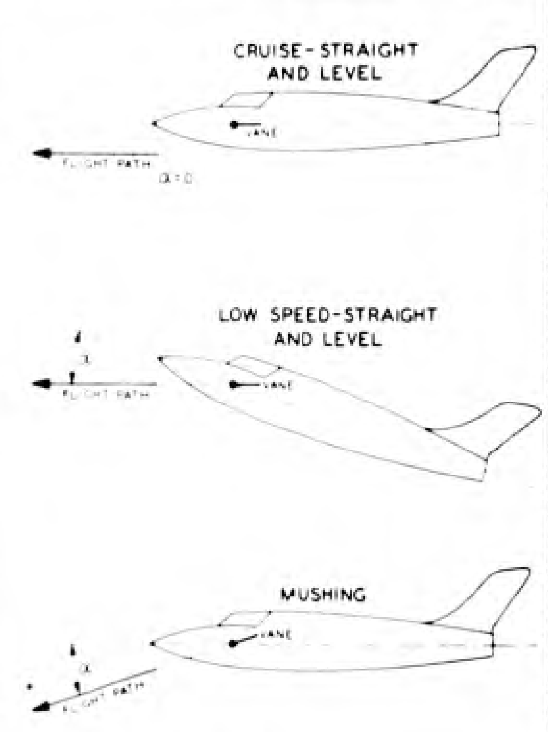

Fig. 25
Operation of Vane Type Angle of Attack Sensor in Flight

Andresen of Kollsman published in January 1960 report results which were based on 14 take-offs with the KC-135 aircraft. It was never established definitely that values of angle of attack used during these take-offs with the Max-Min Airspeed System were optimum for the particular aircraft used. When a climbout angle of attack was attained during rotation of the aircraft prior to lift-off and held constant, airspeed continued to increase at a rate dependent on the take-off gross weight of the aircraft. The lesser rate of airspeed increase was due to increasing induced drag caused by angle of attack. After approximately 8-12 seconds after start of rotation, indicated airspeed began to drop and the airspeed trained pilots lowered the nose of the aircraft to gain airspeed with angle of attack decreasing. (Figure 26 shows the Kollsman line of sight (LOS) indicator installed in the KC-135.) This problem might have been caused by: extra thrust after rotation due to the efflux on the ground, attitude gyro precession, ground effect, pitot-static system error, or combination of these causes. When pilots attempted to hold airspeed after rotation, angle of attack would decrease. Conversely when angle of attack was held constant the airspeed phugoid developed.

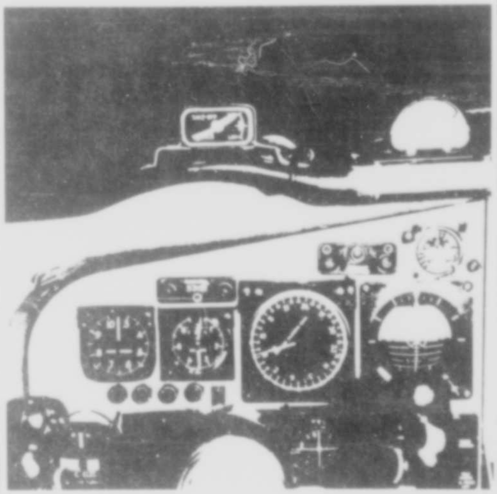

Fig. 26
Kollsman Line of Sight (LOS)
Indicator Installed in KC-135
(From Ref 58:Appendix)

When the SCAT system, which was installed on the same aircraft, was flown and held constant, the angle of attack indication was also constant.

However, when constant angle of attack was maintained, the airspeed and SCAT system both varied. The pilots tended to climb more conservatively (low angle of attack) at light gross weights and less conservatively (high angle of attack) at heavier loads. This was probably due to reluctance on the part of the pilots to pitch the aircraft up to the high angles required for optimum take-off at these loads; or it could have been due to a physical limitation of dragging the tail boom (Ref 2: 1-5).

AFFTC (AF Vertical Tape)

During USAF evaluation of the production F-106 vertical instrument presentations at the Air Force Flight Test Center, Edwards AFB, Calif., a significant error in calibration of the angle of attack index was noted. It was subsequently recommended that the angle of attack system be redesigned to provide accurate approach and flare information. An approach index modification to the air data compensator was made by Hughes Aircraft for test purposes. Although the test unit was modified only for the initial approach condition, it was desired that this unit be calibrated by flight testing in order to provide quantitative substantiation of the approach modification incorporated, as well as to provide information necessary to modify the compensator over the entire range of operation. Qualitative results of the tests indicated that approach and flare indices were conditionally acceptable. The ARDC minimum safe speed-Mach number-airspeed vertical instrument (Type AVU-1A) displayed a composite load factor, calibrated airspeed, true Mach number and a minimum safe speed-approach-flare (angle of attack) index on one instrument (See Figure 24).

Each of the above functions is presented on a vertical tape which moves up or down behind a reference lubber line fixed on the instrument facing plate. The tapes are driven by synchro motors which in turn receive their driving signals from the air data compensator of the air data computer. The approach-flare index is a triangle with the apex at the bottom (See Figure 37, Section V). The tape should function such that when the apex is coincidental to the lubber line during ILS approaches, the proper approach airspeed is established for the particular aircraft landing weight. During flare, the triangle moves down (angle of attack increases) with decreasing speed until "over-the-fence" speed is indicated when the base falls on the lubber line (Ref 59:15).

Convair and Hughes initially had difficulty with the F-106 weapon system in getting the right calibrated air data compensator to correspond correctly with the angle of attack display. (A vane type angle of attack sensor is presently used with the F-106 which furnishes the local angle of attack data to the compensator. The compensator corrects the computer input signals for static position error by means of a 3-dimensional cam and furnishes true angle of attack information to the vertical tape instrument. The Central Air Data Computer (CADC) group senses, corrects, manifolds, organizes, and distributes the information to the systems and subsystems of the aircraft needing the information). Maj. R. R. Luedeka, Operations Officer, 329th Fighter Interceptor Squadron, George AFB, Calif., stated in October 1960 that the first F-106 aircraft equipped with properly operating angle of attack vertical tapes were in use by his squadron. This particular squadron had a U. S. Marine exchange pilot who had been thoroughly indoctrinated in the use of angle of attack, and who was in turn indoctrinating AF pilots in the use of this new parameter (Ref 31:1-7).

WADD (Projection System)

WADD's flight test report in July 1960 covered the qualitative evaluation that was made to obtain pilot opinion of a new technique of optically presenting an angle of attack instrument display on an F-101A type aircraft. The optical display device contained a cathode ray tube (CRT) which was used to project an angle of attack signal onto the combining glass; a light source projected a stationary reference (or a fixed scale) onto the combining glass. In this angle of attack display, climb, cruise, approach and stall indices were projected (See Figure 27). The angle of attack signal was supplied to the test equipment by a yaw and pitch sensor mounted on a nose boom on the F-101. (See Figure 28).

Fig 27
Projection Display of Angle of Attack of the F-101
(From Ref 23:Appendix)

The test concluded that the technique of windscreen projection was unacceptable for weather flying because of the possibility of inducing vertigo. It also concluded that this type of presentation was convenient during several phases of VFR flight but was considered to be of little value. The windscreen projection system, as tested, was unsatisfactory for the following reasons: (1) distracting and annoying reflections on the combining glass; (2) insufficient light intensity for bright backgrounds; (3) the large scale which made it impossible to see both upper and lower indices without considerable head movement; and (4) sensitivity and damping inadequacies in the angle of attack sensing system. The value of angle of attack presented in a windscreen projection display was not determined due to varied opinions obtained and deficiencies of the test system (Ref 23:1-3).

Fig 28
Boom Mounted Vane Type Angle of Attack and Angle of Yaw Sensors (From Ref 23:Appendix)

NATC (Specialties Probe, Topps Probe, Daystrom Vane, SMI Vane)

In July 1960 NATC published a flight test report which had been done to determine those phases of flight for which angle of attack was an appropriate information parameter for representative Navy fleet and training aircraft, such as the A3D-2, A4D-2N, F4D-1, F9F-8T, F11F-1, F3H-2, FJ-4B, F8U-1, and -2, T2J-1, and T2V-1 type aircraft. Various systems tested included: cockpit indicator (Specialties type B-2 or 1A1-A2 Bendix); approach index light (Specialties or Grimes type); and airstream direction detector (either Specialties or Topps probe, or the Daystrom or Servomechanisms vane). The Specialties B-2 and B-3 (as well as a similar instrument of Bendix) indicator pointer moved counterclockwise with increasing values of angle of attack. This was against normal aircraft instrument convention, but was in consonance with movement of the airspeed pointer and aircraft pitch attitude control movement as stall was approached. The fixed index at the 3 o'clock position was used to make the optimum approach angle of attack setting which was adjustable for the particular aircraft. The other indices were used for other modes of flight such as stall, cruise, and climb (See Figure 34).

Primary objective of the tests was to determine if angle of attack was a useful parameter as a primary attitude instrument during catapult take-off, bolter climbout (Navy terminology for carrier touch-and-go landings), normal take-off, climb, cruise, tactical turn, best glide, jet penetration, and landing approach phases of flight. Qualitative comparisons were made on such performance factors as time to climb, specific fuel consumption, and simulated power-off glide distance when using angle of attack as compared to the normal parameter of airspeed or Mach number. It was determined that angle of attack was not useful prior to liftoff, but was useful immediately after take-off when steep turns or gain in altitudes were required. However, for those aircraft with excessive amounts of thrust available, such as with the F8U aircraft, angle of attack information was of no practical use, in fact it could lead into a severe longitudinal overcontrol situation.

Angle of attack for best climb varied with altitude and its usefulness was of no particular advantage over standard airspeed-Mach number climb techniques, nor in cruise flight was there a marked difference between preference for the angle of attack method over the standard airspeed Mach number methods. It was determined that angle of attack information for the maximum endurance phase of flight was useful, as the slower speed provided ample time to establish a desired angle of attack.

Tactical turns made using angle of attack as the primary instrument did not prove to be practical except in the specific instance of a minimum radius turn. The higher performance aircraft had to maintain a high Mach number during maximum rate turns where compressibility effects on the Specialties type probe sensor during transonic flight affected the reading accuracy. During VFR jet penetrations the use of angle of attack was useful.

During GCA approaches the utility of angle of attack was especially useful when landing weights were excessive. The best approach index located at the 3 o'clock position on the indicator was found to be very helpful during approach patterns. During normal landings pilots felt that the angle of attack system provided invaluable information in smooth air. However, during turbulent air the approach indexer display changed too rapidly for proper interpretation and the pilot reverted to airspeed for control.

Usefulness of angle of attack indications for estimating post catapult pitch attitude was limited because of the transitory nature of the maneuver. The pilots tended to overcontrol during pitch attitude corrections when using angle of attack as a primary instrument. The use of maximum angle of attack following a maximum allowable speed catapult launch resulted in excessive rates of climb and climb angles.

For carrier landings, all angle of attack systems furnished useful information for all aircraft tested. The report pointed out that the standard angle of attack indicators were not useful for all types of aircraft due to scale factor, length of scale, and displayed indices. It also pointed out various complicated techniques of checking angle of attack systems prior to flight as outlined in existing maintenance handbooks (References 7, 53, and 54). In addition, the determination of optimum angle of attack for each possible combination of altitude, speed, and weight for each type aircraft required an exhaustive test program.

Conclusions of the test program were: (1) utilization of angle of attack systems tested was greatest in constant speed maneuvers at relatively high angles of attack; (2) angle of attack had less resolution for pitch attitude control at low angle of attack than airspeed and Mach number; (3) pilots had difficulty using angle of attack because of the transient change in angle of attack in response to stick movement; (4) ground check time was consuming and inadequate to assure proper system operation in flight; (5) angle of attack was used as a standby instrument source of pitch attitude information for high speed maneuvers; and (6) angle of attack was used primarily for pitch attitude control information for carrier approaches, GCA, stall warning, and normal field landings (Ref 9:1-9).

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WADD (Kollsman Max-Min, Safe Flight SCAT)

In August 1960, WADD published a report on a flight test evaluation of airspeed-maximum-minimum allowable (Max-Min) and speed control-after-take-off (SCAT) systems tested on the KC-135 aircraft. The primary objective of this test was to determine whether angle of attack would be a suitable and feasible parameter for use in the KC-135 as a stable reference for take-off and initial climbout. Secondary considerations were given to various other phases of flight, such as stall, approach, and cruise, to determine the optimum amount of damping required in the Max-Min system and to the procedures to be used for both the Max-Min and SCAT systems. The gryoscope systems precession error caused by longitudinal acceleration on take-off coupled with pitot-static system errors during rotation of the aircraft during the take-off run was the cause for looking toward one of the two proposed systems for correction of the problem. The Kollsman Instrument Corporation supplied the Airspeed-Maximum-Minimum-Allowable system which used the Me-6 type airspeed indicator with angle of attack information incorporated on the outer ring of the scale (See Figure 42, Section V), and a Line of Sight (LOS) indicator (See Figure 26 and Figure 29). Previous flight tests conducted on the B-47 type aircraft with this system were unsatisfactory. (Figure 30 shows the vane type angle of attack sensor location).

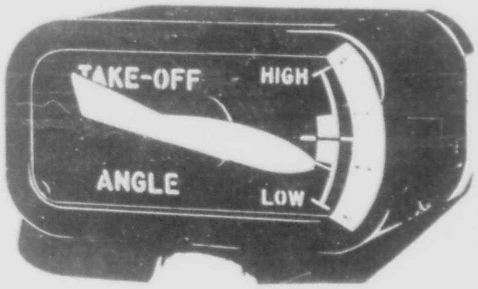

Fig 29
Close-up of the Kollsman Line of Sight (LOS) Indicator
(From Ref 58: Appendix)

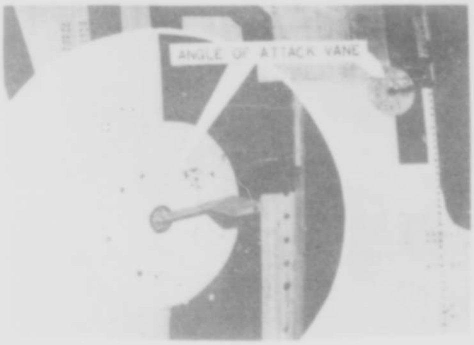

Fig 30
Vane Type Angle of Attack Sensor
Mounted on the KC-135 Fuselage
(From Ref 58: Appendix)

The LOS indicator was added to the basic Max-Min system to provide a VFR take-off capability and was located on the pilot's glare shield. Safe Flight Instrument Corporation proposed that the use of its SCAT system was better than pure angle of attack as used in the Kollsman system.

Conclusions of tests made on the two individual systems stated in regard to the Max-Min system that: (1) it was not acceptable due to backlash error, presentation, and parameter measured; (2) angle of attack was not a suitable parameter for use during rotation, take-off, and initial climbout; (3) the display on the indicator with a moving index and moving pointer was too difficult to fly; (4) using the LOS indicator and slowly bleeding off angle of attack after take-off was acceptable; (5) the LOS indication was too small for sensitive corrections; (6) two distinct damping and response rates were required for the Max-Min indicator, one for take-off and one for all other phases of flight; and (7) location of the vane type angle of attack transmitter near the cargo door (See Figure 30) was unsatisfactory due to possible damage.

Conclusions relative to the SCAT system were: (1) it provided a suitable signal that could be flown easily and safely during rotation, take-off, initial climb, and approach; (2) it showed enough promise to warrant further testing of a production model; (3) the gyro stabilized horizontal accelerometer installed in the system effectively dampened the pitching, phugoid; (4) use of the system for take-off resulted in aircraft performance which exceeded Flight Manual specifications; (5) a flap potentiometer was required to insure proper system indication as various wing flap settings; and finally (6) a second SCAT indicator should be added on the pilot's instrument panel to enhance the system.

A Servomechanisms, wedge-shaped, electrically heated vane type angle of attack transmitter was used in conjunction with the Kollsman Max-Min system. Reference is made to Figure 1, Appendix A, which shows the relationship between LOS units and Max-Min index numbers on the Me-6 type airspeed indicator.

Three different rotation speeds were used during take-off tests: (1) the normal rotation technique of beginning rotation of the aircraft at 6 knots before take-off speed; (2) the technique of early rotation, or rotating the aircraft at 16 knots below take-off speed; (3) the technique of late rotation, rotating 10 knots above take-off speed (16 knots above normal rotation speed). There are times when the late rotation technique is required due to minimum control speed being greater than normal rotation speed. The airspeed phugoid oscillations were encountered when using normal Flight Manual take-off and constant angle of take-off techniques. The two requirements, constant angle of attack and constant airspeed, could not be met simultaneously during the take-off situation. It was determined that the curise and take-off "bug" on the Kollsman Max-Min indicator were unusable during the tests. The use of the LOS on go-around procedures resulted in the airspeed phugoid

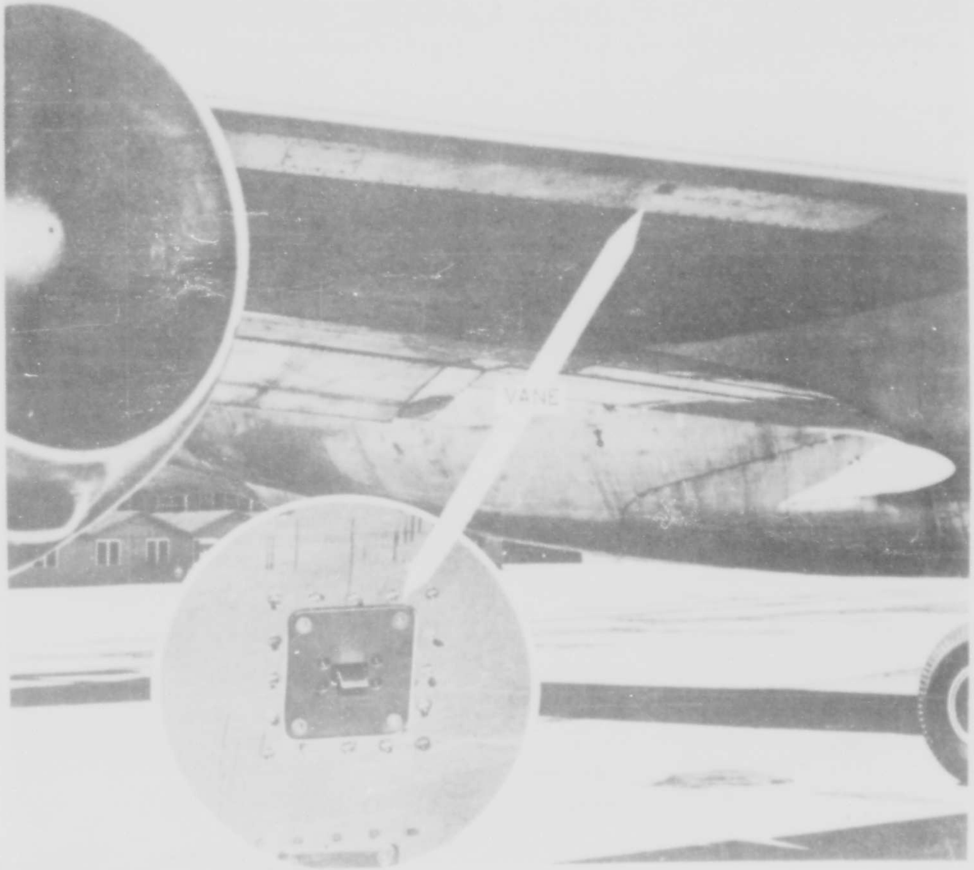

Fig 31
Safe Flight Lift Transducer Installed on KC-135
(From Ref 58:Appendix)

situation and was unacceptable.

The lift transducer for the SCAT system was installed on the underside of the right wing and perpendicular to the leading edge of the wing (See Figure 31). The signal developed by the transducer was a result

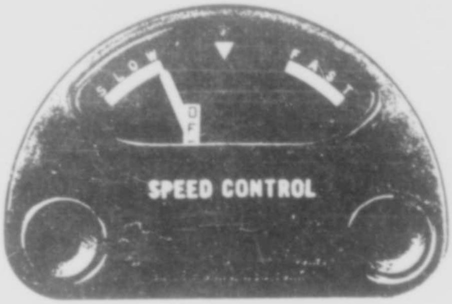

Fig 32
Safe Flight Speed Control Indicator
Used in the KC-135
(From Ref 58:Appendix)

of vane (tab) movement and was used to produce a signal proportional to $C_L/C_{L_{max}}$. The vane sensed the airflow pattern in the vicinity of the stagnation point, then produced a signal to cause the SCAT needle to move toward the "slow" bar (See Figure 32). The vane responded to wing loading, angle of attack and airspeed, and was actually measuring the pressure near the stagnation point. In addition to the lift transducer, the system consisted of a gyro stabilized accelerometer and combined with the pitch gimbal system of the vertical gyro provided a measure of the ground plane acceleration (GPA) of the aircraft. The lift computer combined the signals from the lift transducer and the gyro stabilized horizontal accelerometer into one signal which was sent to the SCAT indicator. A mode selector switch was provided to select various modes of flight such as speed control, standby, take-off, and landing. (This switching function is now done automatically in the production version). In all cases the rate of climb performance to the 500 feet altitude exceeded the performance predicted in the Flight Manual.

ATC (Kollsman Max-Min)

ATC tested and evaluated the Kollsman Maximum-Minimum Airspeed Angle of Attack indicator in the T-29 aircraft. The purpose of the test was to investigate uses of angle of attack information during instrument flight. The Kollsman type AVU-4/A combined airspeed and angle of attack indicator with a vane type sensor for use during this test program (See Figure 42, Section V). A typical simulated instrument flight included instrument take-off, climb to altitude, curising flight, holding, ILS approach, missed approach, and radar approach to a full stop landing.

The findings of this report described different instrument flight techniques that were required to utilize angle of attack information during instrument take-off, climb, holding, and precision approaches. This is one of the first flight test reports reviewed that outlined in detail flying procedures using angle of attack as a primary or secondary flight instrument. During the approach phase it was recommended that the method of control be such that rate of descent was determined by pitch control and angle of attack was maintained by use of power.

The conclusions of this flight test were: (1) there is an ideal angle of attack for each desired condition of flight such as climb, cruise, approach, and landing; (2) angle of attack information is of value and is desirable for use during instrument flight; (3) angle of attack information is of most value in performing the instrument approach; (4) angle of attack information should not be combined with the airspeed indicator or any other instrument (movement of the pointer and the angle of attack reference scale generally oppose one another, thus making the presentation difficult to interpret); (5) extension and retraction of the landing flap has a pronounced effect upon the angle of attack indication; (6) although a relationship exists between angle of attack and airspeed indications, angle of attack information cannot replace airspeed information during instrument flight; (7) fluctuation in angle of attack indication prohibits making angle of attack corrections solely by reference to this instrument; and finally (8) use of the angle of attack indicator should be relegated to that of supplemental information and the pilot should not make a control movement in direct response to its indications (Ref 30:1-5).

V. Types of Angle of Attack Sensors and Indicators

A brief outline of the present angle of attack systems, including the sensor and indicators, either currently being used or under development for operational military and civilian aircraft, will be covered in this section. It will include numerous sensing methods theoretically available, such as the pressure-sensitive, force-sensitive, thermodynamic, and air particle identification types described in References 13, 46, and 47. Herein is a detailed discussion of the systems which are presently available as research tools in the collection of wind tunnel and flight test aerodynamic data, and others which may become available for future aerospace vehicles. Some proposed future types of angle of attack sensors or indicators for which information was available are outlined--the descriptions present general information and are accompanied by figures. The reader is referred to the appropriate reference or individual manufacturer for additional information if required.

Types Now in Use

In general there are three sensing techniques employed in the angle of attack systems presently in use on today's aircraft; (1) the null-seeking differential pressure sensor; (2) the null-seeking vane sensor; and (3) the lift transducer sensor. The mechanization of the lift equation of the airplane utilizing inertial and pressure-sensing devices will not be included as one of the operational techniques. The type of sensor, type of indicator, description of the mechanization and operation, and types of aircraft presently using these systems, will be identified by the individual manufacturers where known.

Null-Seeking Differential Pressure Sensor

The null-seeking differential pressure sensor is usually from a 3 to 4 1/4 inch cylindrical probe, 3/8 to 5/8 of an inch in diameter, its bearing mounted with its axis normal to the direction of airflow to be measured. Two longitudinal slots, spaced approximately ninety degrees, sense local flow pressures. Separate air passages in the probe lead from each slot to separate compartments of the paddle chamber. When the slots are asymmetrical with respect to the local flow direction, a pressure differential causes the paddle, which is connected to the probe with pin and slot linkage, to rotate until the pressures are equalized in the compartments (Ref 57:1). Potentiometers, whose wipers rotate with the probe, provide the input signals to the correction computer or remote indicator. Figure 33 is a cut-away view of Type RL50 Airstream Direction Detector manufactured by Specialties, Inc., Syosset, L. I.,

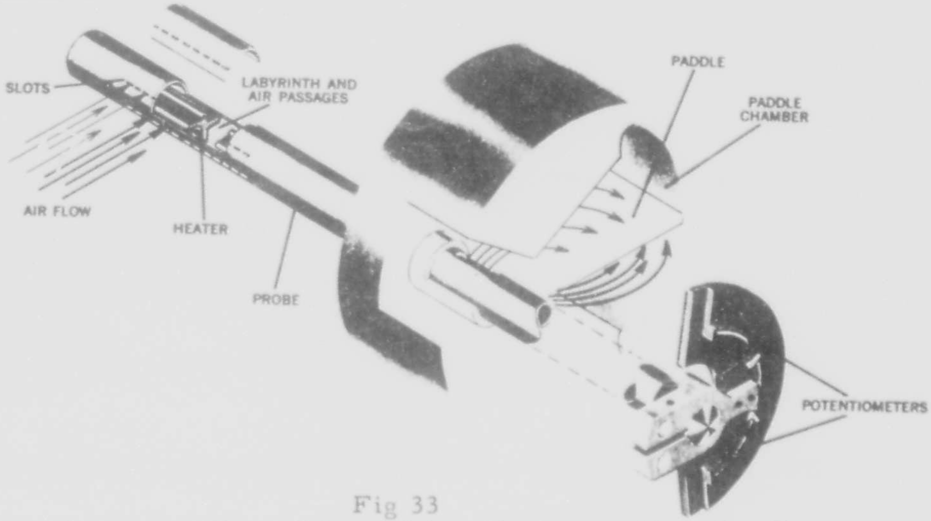

Fig 33
Cut-away View of Specialties Airstream Direction Detector
(From Ref 51:3)

N. Y. (Ref 53:3 and Ref 54:3). A similar type angle of attack (wind direction) transmitter is manufactured by U. S. Science Corp., (formerly Topp Industries, Inc.), Los Angeles, Calif. (Ref 7:3).

The probe type sensors have been used by the Air Force in the past on operational aircraft such as the F-89 and F-101. The Navy is the main military service presently using Specialties (or Topps) type sensors on the A3D-2, F4D-1, F9F-8T, F11F-1, F3H-2, FJ-4B, T2J-1 and T2V-1 aircraft. The angle of attack systems provide inputs to fire control systems as well as to a pilot's glare shield display above the instrument panel (See Figure 35). Operated as auxiliary equipment are approach lights mounted on the nose wheel strut to be viewed by the landing signal officer on carrier landings, and a stall warning indication which is available on some aircraft in the form of a control stick or rudder pedal shaker (Ref 49:1).

The Specialties angle of attack system also has a flap compensator as one of the component parts that functions to continuously sense and indicate to the pilot and the landing signal officer (in cases of aircraft carrier landings) angle of attack of the aircraft.

The indicator dial is graduated from 0 to 30 increments. A pointer sweeps from 0-30 as the

Fig 34
Specialties Type B-3 (or B-2)
Angle of Attack Indicator
(From Ref 54:4)

probe of the airstream direction detector is rotated from one limit to the other. The dial is adjustable in either direction, so that any dial reading between 12 and 26 units can be placed at the 3 o'clock fixed index. The auxiliary bugs on the outer scale of the dial are for climb, cruise, stall or other modes of flight.

The approach index is a three light device designed to give the pilot a visual indication of his angle of attack during normal and carrier approaches. The light is normally situated on or above the instrument panel in such a manner that angle of attack information is in the pilot's secondary field of vision during that portion of the landing approach when his vision is directed out of the cockpit and on to the landing area. With the index, GCA, ILS, and mirror landing approaches can be

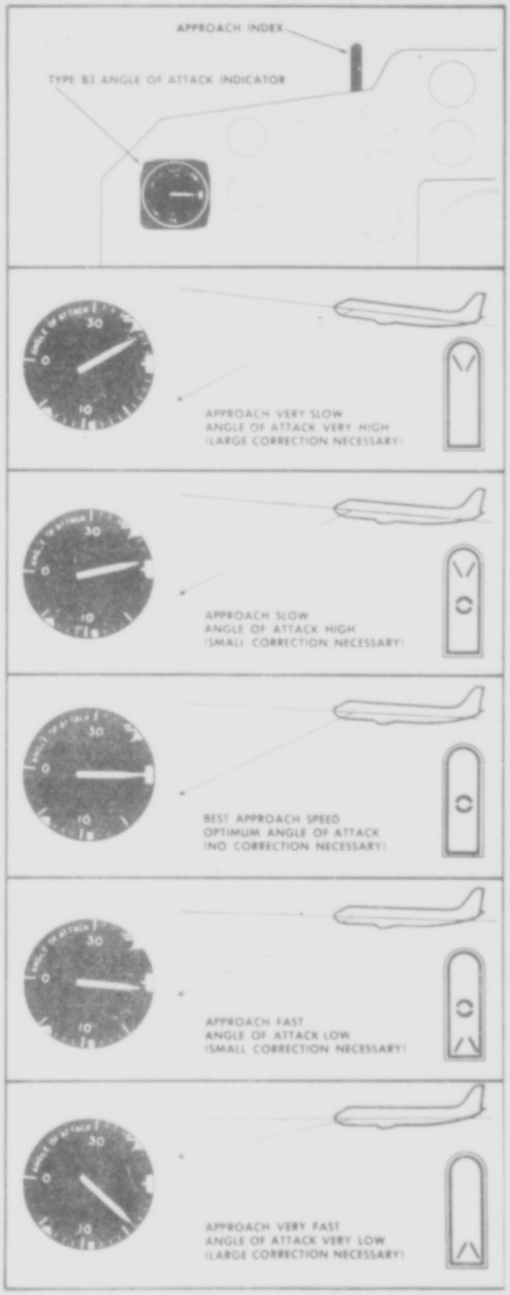

Fig 35
Specialties Angle of Attack
Indicator and Approach Index
(From Ref 52:1)

maintained at the optimum angle of attack after transition from instrument to visual flying conditions. Reference 49 and Figure 35 describe the operation of the Approach Index.

Null-Seeking Vane Sensor

Typical null-seeking vane sensors are shown in Figures 13, 28, and 36. The bearing mounted vane is free-floating and automatically aligns itself downstream from the axis of rotation. The supporting shaft is geared to the shafts of two synchro-transmitters which convert the angular position of the vane to electrical signals for input to synchro-receivers in remote indicators and/or correction computers. Damping to minimize oscillations and a counterbalance are provided internally. Both the vane and probe type sensors have been tested through a Mach number of 2. 54 and have been found to have a reproducibility of 0. 1 degree angle of attack measurement at all flight conditions (Ref 60:15, 20). Available sources for angle of attack transmitter units in accordance with MIL-T-25627 (USAF) or MIL-T-19229A (USN) specifications are Giannini Controls Corp., Pasadena, Calif.; Servomechanisms, Inc.; El Segundo, Calif.; U. S. Science Corp. (formerly Topps Industry), Los Angeles, Calif.; Daystrom, Inc.; and others. Figure 36 illustrates one of the typical vane type sensors.

The Giannini vane type angle of attack sensor is one of the units making up the stall warning system designed for the Douglas C-133B Cargomaster aircraft (Ref 19:1 and Ref 21:1). Other vane type sensors are presently being used on USAF F-101, F-102, F-104, F-105, F-106, B-52, and on USN A4D-2N and F8U type aircraft. These sensors are being used in conjunction with applicable fire control systems, indicators in the cockpit, and computer input for determining the flight path vector of the aircraft. Some typical displays that are used in conjunction with vane type sensors are depicted in the following figures.

Fig 36
Giannini Vane Type Angle of Attack Sensor (From Ref 19:1)

In addition to the fire control systems on some F-105 and F-106 aircraft the vane type sensor furnishes local angle of attack data to the compensator which in turn corrects the computer input signals for static position error by means of a three-dimensional cam, and furnishes true angle of attack information to the vertical tape instrument. (Figure 37 is of the AF angle of attack-Mach-airspeed vertical tape instrument from the advanced integrated flight instrument panel). The left tape indicates angle of attack and "g" normal acceleration. To achieve the desired uniform control display interaction, the angle of attack tape and the load index are made to move down with increasing values. The apex of the triangle depicts the best approach angle of attack, while the base of the triangle shows the best flare angle of attack. The cross hatched portion of the tape is the minimum safe speed, or "stall" range for the particular aircraft. This instrument is presently being manufactured by Eclipse Pioneer, Teterboro, N. J., for the AF. The reader is referred to Reference 30, 31, and 56 for more specific information relative to this instrument.

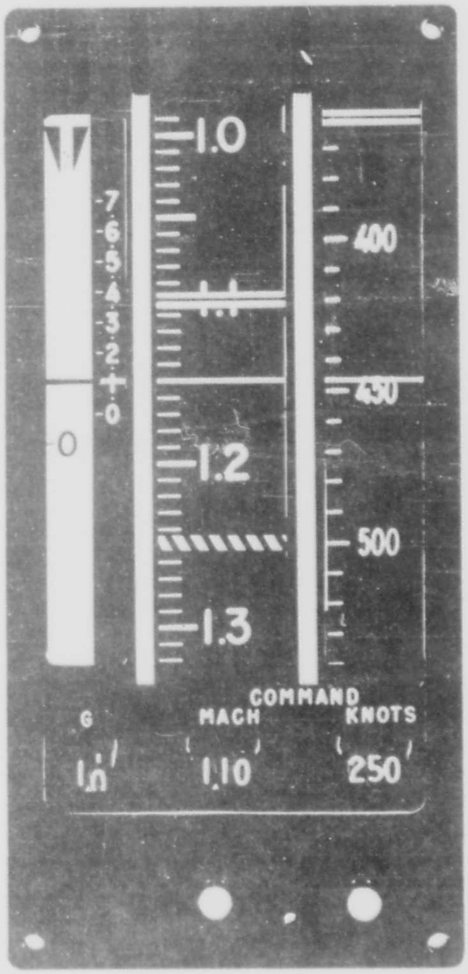

Fig 37
Air Force Angle of Attack-Mach-Airspeed Tape Instrument
(From Ref 59:14)

Other uses of vane type angle of attack sensors are as inputs to the computer systems installed in the F-101 and F-104 aircraft for automatic control of the pitch-up condition encountered primarily in the transonic region at relatively high angles of attack.

This system provides horn and pusher warning in that order, as the aircraft approaches the pitch-up boundary. The actuation of the pitch-up warning system is directly dependent upon the rate of aft stick movement and the aircraft's angle of attack. Low angles of attack will allow greater rates of aft stick movement than high angles of attack. Except during fast stabilizer rate of travel, air frame buffet will always precede the horn as angle of attack is increased at subsonic speeds. At supersonic speeds, no buffet precedes the horn or pusher. On the earlier model F-104 aircraft there was an equivalent angle of attack indicator on the instrument panel which gave a warning of impending pitch-up maneuvers. Angle of attack sensors are also used to supply signal to operate stick shaker or rudder shaker warning systems in some aircraft.

Lift Transducer Sensor

The principal input on which operation of the speed control system depends is obtained from the lift transducer which is mounted in the outer panel of the wing. Basically, this device consists of a small metal vane protruding from the under surface of the wing and a variable reluctance transformer with a movable core attached to the vane. The local airflow direction and dynamic pressure stemming from the stagnation point (the point at which the airflow divides to pass above or below the wing surface) moves the vane against a light spring pressure, causing a corresponding movement of the transformer core. Since the location of the stagnation point is determined by angle of attack, transducer vane position is principally a function of angle of attack. However, the true airspeed, to a lesser degree, affects the velocity of flow stemming from the stagnation point and consequently, the pressure exerted on the vane. (Reference is made to Figure 9 which illustrates the Safe Flight lift transducer operation in flight). When the angle of attack is such that the stagnation point is forward of the transducer vane, the dynamic pressure and direction of flow cause the vane to be deflected to the rear and a "low C_L" signal is transmitted to the computer. Conversely, when a high angle of attack shifts the stagnation point behind the vane, the vane is deflected forward and a "high C_L" signal is sent to the computer. The lowest local velocity of flow occurs near the stagnation point and increases away from the stagnation point. Thus, as the stagnation point approaches the vane from either fore or aft direction, the pressure on the vane diminishes; the vane is deflected less and less until the crossover point is reached, after which further movement of the stagnation point causes deflection of the vane in the opposite direction. For a given wing design and flap position, there exists a fixed relationship between the coefficient of lift and the data as sensed by the lift transducer. It is possible to obtain an accurate and continuous measurement of the lift coefficient which may be modified in the computer and displayed on the cockpit indicator as $C_L/C_{L_{max}}$. The Safe Flight speed control system as installed on the C-123 aircraft consists of the lift transducer, flap potentiometer, lift computer, speed control indicator, and stall warning shaker (See Figure 38).

Since the use of wing flaps will effectively increase the amount of lift available for a given angle of attack, and ultimately, the angle of attack at which the airplane will stall, flap position must be a continuous input to the computer. The

Fig 38
Safe Flight Speed Control Components for C-123 Aircraft

function of the lift computer is to modify the output of the lift transducer for the effects of flap position and power or thrust. Inasmuch as the lift transducer is installed outside the area affected by the propeller blast, the effect of power on the lift must be obtained from another source. Essentially, this information is obtained from a longitudinal accelerometer, contained in the computer, which senses accelerations and decelerations due to adjustments in power and the accompanying changes in airplane attitude. In comparing the output of the lift transducer and that of the longitudinal accelerometer, the computer determines the subsequent change in lift which accompanies any change in power. The output of the computer drives the speed control indicator and controls the operation of the control column shaker to provide pre-stall warning.

The speed control indicator provides a continuous indication of wing lift in terms of the ratio, $C_L/C_{L_{max}}$. When the speed control indicator needle is in the fast range, the momentary coefficient of lift as compared to the maximum available coefficient of lift (the point where the stall occurs) is small. As the coefficient of lift is increased because of an increase in the angle of attack (necessitated by a decrease in airspeed or a reduction in power), the needle moves toward or into the slow range. At a present high coefficient of lift, the needle reaches the slow band and the control column shaker is energized to provide warning that angle of attack, airspeed, flap position and power are of such values that the aircraft is very near a stall. The Safe Flight Speed Control indicator as used in the C-123 aircraft is shown in Figure 39 (Ref 14:1-6 and Ref 44:1-4).

Abbreviated versions of this system are being used on the Army CARIBOU type support aircraft as well as on enumerable light civilian and military type aircraft. The AF-T-37 jet trainer utilizes a transducer vane sensor to actuate the spoiler system in providing sufficient stall warning. The reader is referred to References 1, 4, 24, and 44 for more specific details regarding this system.

Fig 39
Safe Flight Speed Control Indicator for the C-123 Aircraft

The sensors and displays covered above have been tested either separately as a system or in some cases by intermixing the various available types of component units to serve a particular need for the Navy or Air Force. For example, the Specialties airstream direction detector was used in conjunction with a Sperry automatic flight control system utilizing control wheel steering, body axis stability augmentation sensors, isolation of short period stabilization motions from the manual controls, "g" limiting, and stall warning. One of the conclusions from Reference 56: Chap. II, p. 2 was that the stall prevention system operated satisfactorily by automatically correcting aircraft pitch attitude to the maximum safe angle of attack. On the C-131B test aircraft a gated stall signal was obtained from the local flow sensor and amplified to operate a stall detector relay. The gate was set to operate the detector at angles of attack between 10 and 20 degrees. If a manual pitch correction is not inserted the automatic stall prevention sequence operates. This sequence disengages all selected path references and engages the airspeed control mode with the airspeed reference continuously programmed as a function of the aircraft's excess angle of attack (Ref 56: Chap. IV, p. 10). Angle of attack information is also used in the coupling of data from the REGAL system to the AFCS and instrument system of an Air Force C-131B test aircraft, to provide automatic, manual, semi-automatic, and fully automatic landing. The throttle control configuration must provide control of thrust based on airspeed error, and the integral of angle of attack (angle of attack programmed as a function of range and glide path angle) (Ref 57: Chap. II, p. 2 and Chap. III, p. 6).

Future Types

There are several types of angle of attack devices that are presently being tested or evaluated by the military services. Within the scope of this paper only a few of these will be mentioned--the Kollsman (Max-Min) airspeed-angle of attack system, Specialties angle of attack system (Type J-2), and the Safe Flight stall or drag-rise warning system. Basically all of these systems use the identical angle of attack sensors as previously described. There is one new vane type sensor manufactured by U. S. Science Corp., Los Angeles, Calif., which is presently being evaluated by WADD, W-PAFB, Ohio. This vane sensor is designed with heat resistant materials to operate at ambient temperatures of 1300 degrees C, speeds of Mach 5, and altitudes of 150,000 feet. (Figure 40 shows the supersonic vane type angle of attack sensor.)

Fig 40
U. S. Science Supersonic
Vane Type Angle of Attack Sensor

Kollsman Max-Min Airspeed Angle of Attack System

The Kollsman airspeed (Max-Min) angle of attack system consists of the standard Type L-7 airspeed indicator to which a means of measuring local angle of attack has been added by electrical servo methods. The angle of attack reference markers or "bugs" are mounted on a single geared ring which rotates around the periphery of the airspeed indicator dial. The servo is so arranged that the angular position between the airspeed pointer and a "bug" is proportional to the deviation between desired and actual local angle of attack display as sensed by the vane. The gear ratio is such that angle of attack display is several times that of actual vane sensor movement. Basically, the two sections of the instrument function separately so that if the airspeed system malfunctions, angle of attack will still be displayed. Regardless of the airspeed pointer position, angle of attack is always measured relative to the airspeed pointer. An "Off" flag is also incorporated on the indicator to show when power is not available to the system. Figure 41 shows the Kollsman airspeed-angle of attack system consisting of the indicator, the line of sight (LOS) indicator, a control box, and a standard vane type angle of attack sensor.

The stall bug on the indicator shows the angle of attack corresponding to the minimum allowable airspeed; it is red with yellow cross hatched stripes and has "Stall" written on it. A yellow triangular shaped piece is added to the leading edge of the stall bug as a warning indicator. The take-off bug is green with a small point on the inner edge to indicate the desired angle of attack for take-off, with the letters " T O" written on it. The approach bug is rectangular with an "A" on it; the cruise bug is triangular with a "C" on it. All bugs are adjustable dependent on the particular aircraft being used (See Figure 42).

The LOS indicator covers angle of attack range of 20 degrees. The indicator can be adjusted to cover any 20 degree segment of the total degrees that the angle of attack vane traverses. The scale shown is not a part of the standard LOS indicator. (The indicator presents a "fly from" indication.)

Fig 41
Kollsman Max-Min Airspeed Angle of Attack Components
(From Ref 58:App)

Specialties Type J-2 Angle of Attack System

Essentially the new Specialties angle of attack system incorporates approximately the same component units with several modifications directed toward jet transport operation. The angle of attack system com-

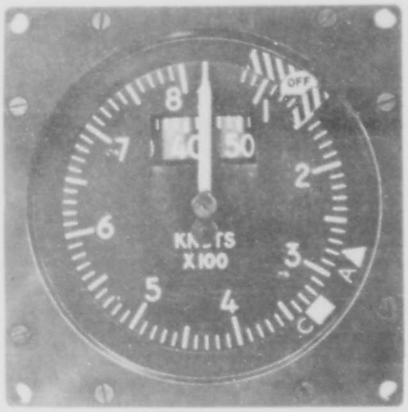

Fig 42
Kollsman Max-Min Airspeed Angle of Attack Indicator
(From Ref 2:5)

ponents consist of: the meter index, J-2 indicator (or B-2), trimming unit, flap position transmitter, and modified airstream direction detector (See Figure 43). The pilot's approach index instrument is optional and the principles of the system are compatible with other types of dial presentations, such as the Type B-2 or B-3.

Specialties angle of attack indicating system presents optimum angle of attack for all standard modes of flight at the 3 o'clock position on the indicator dial; the stalling angle of attack is indicated at the 9 o'clock position; and other specific flight modes are indicated by the intermediate positions. For example, for take-off, the engine power is always the maximum available and a given flap setting is always used; or for best cruise, the power is set to the maximun continuous rating and flaps are fully up. Even with the flaps set incorrectly, the system will indicate the best angle of attack for that particular configuration. The system always indicates best angle of attack in a simple manner without any requirement for setting a mode selector switch. The correct rotation to the angle of attack for best L/D ratio can be performed instantly with the system. Figure 43 also depicts the Type J-2 angle of attack indicator which presents the best angle of attack for all modes of the 3 o'clock position of the dial. The stall, nose rotation, and emergency modes are presented at clearly marked intermediate positions. The indicator shows the margin of reserve lift for all conditions of weight and flap position.

Specialties recommends that the angle of attack indicator be located near the airspeed indicator and be designated for use as an airspeed monitor. An incorrect angle of attack indication would mean: a faulty fuel gauge, an arithmetical error in computing the mode of operation, or incorrect use of the performance tables for the applicable aircraft. Specialties also points out that not all pilots are aware of the fundamental nature and use of angle of attack, and that they must be educated on the use of this new parameter in conjunction with or in place of the airspeed. They also state that accuracy and dependability of the new instrumentation must be demonstrated.

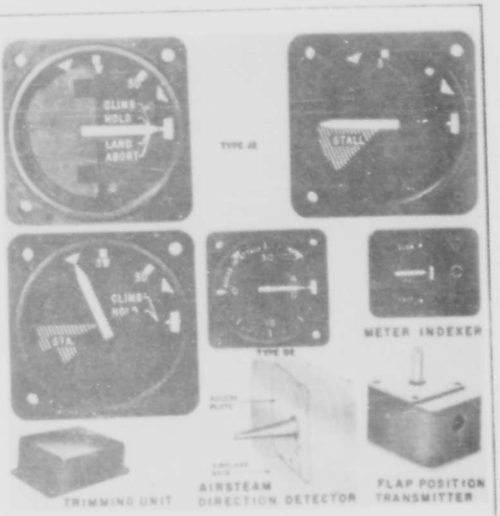

Fig 43
Specialties Angle of Attack System Components
(From Ref 51:2)

The approach index has been developed to provide angle of attack to the pilot during the final approach or go-around when he has transitioned from instrument to visual flight conditions. Figure 44 shows the operation of the approach index with the angle of attack indicator during the final approach phase of flight. The index is located on the glare shield of the pilot's instrument console, and the angle of attack indicator is located on the flight instrument panel. At the correct angle of attack for the flap setting employed, the needle is horizontal and the resultant airspeed will be optimum for the approach. If the angle of attack is too great, the needle moves up indicating that the nose should be dropped until the needle is again horizontal. If the angle of attack is too small, the reverse is true. Attention is emphasized by the three light systems located to the right of the needle; the unit is adjustable for sensitivity and damping. The reader is referred to the manufacturer or to Reference 48 for detailed information concerning this angle of attack system.

Safe Flight Stall or Drag-Rise Warning System

The Safe Flight stall or drag-rise warning system is essentially a modified SCAT (Speed Condition-Approach/Take-off) system as tested and evaluated in Reference 55. The basic SCAT signal is created by combining a signal which is proportional to the lift ratio ($C_L/C_{L_{max}}$) known as the lift signal and a signal proportional to the forward acceleration of the aircraft, known as the acceleration signal. The lift signal is obtained from the lift transducer located near the leading edge of the wing. The forward acceleration signal is obtained from a gyro stabilized horizontal (ground plane) accelerometer, referred to as a GPA. The accelerometer consists of a pendulum free to move in pitch, having a potentiometer pickoff which generates a signal proportional to the angular deviation of the pendulum from a line normal to the longitudinal axis of the aircraft. This signal is proportional to the attitude of the aircraft with respect to the angle of acceleration

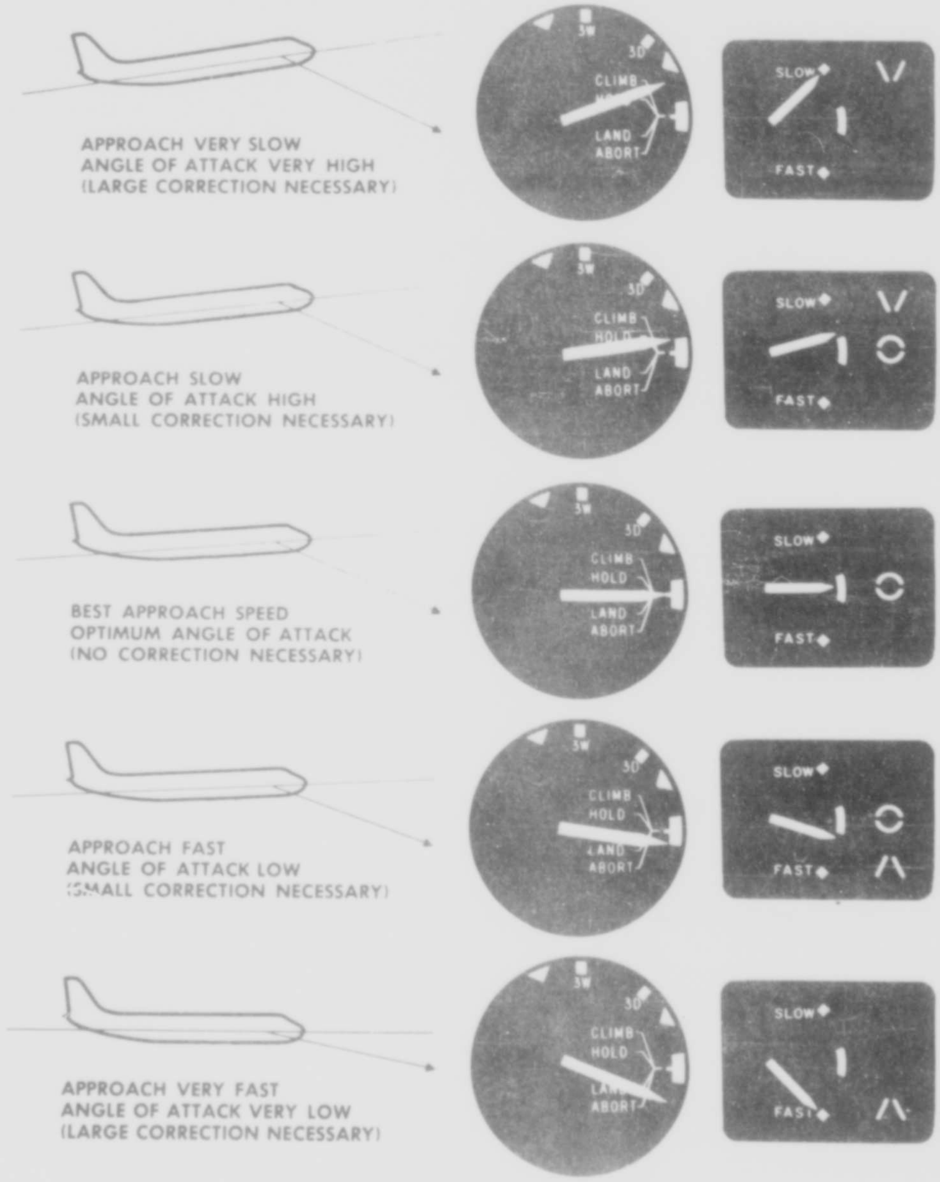

Fig 44
Specialties Angle of Attack Approach Index with Angle of Attack Indicator
(From Ref 51:10)

forces acting on the pendulum, including gravity. A similar signal is developed from the pitch gimbal system of a vertical gyro. This signal is proportional to the attitude of the aircraft with respect to gravity. The difference between these two signals is a measure of the forward acceleration of the aircraft. The SCAT indicator contains two displays: a pointer which informs the pilot of the combined lift and acceleration condition, and an "Off" flag to warn of malfunction of the system (See Figure 45).

Fig 45
Safe Flight Speed Control After Take-off (SCAT) Indicator

The stall or drag-line warning portion of the system consists of a suitable warning device, such as a control column shaker, with associated circuits and controls. The dual SCAT system with indicators is provided with an additional unit called a SCAT signal comparator which informs the pilot that the two SCAT indicator signals do not agree by a predetermined tolerance. The reader is referred to the individual manufacturer or to Reference 45:2-11 for detailed information concerning the system operation.

Other Type Sensors

The Giannini Model 2811 gust probe is a differential pressure flow-direction sensor that was originally developed by Douglas Aircraft Company to measure angle of attack, replacing the vane type sensor in testing new aircraft. Because of advantages of the differential probe over the vane sensor, Douglas recently adapted the probe to make it suitable for measuring air turbulence or gust velocity. It incorporates, in a single installation, sensing devices for indicated airspeed, angle of attack, angle of sideslip, normal acceleration, and lateral acceleration. Critical for such use are ruggedness and high frequency response. The probe has no moving parts and is extremely rugged and practically invulnerable to damage by careless handling (Ref 20:1-3). The Douglas-Giannini 5-probe differential pressure sensing head is among the many types of angle of attack sensors mentioned in the University of Southern California studies on angle of attack--angle of sideslip--pitot static probes (Ref 49:8 and Ref 50:77).

WADD presently has study contracts investigating the feasibility of re-entry air data sensors. One study is being made to establish techniques for sensing vehicle skin temperature and to evaluate the feasibility of determining, from temperature measurements, angle of attack, heating rate, margin of safety for structural temperature boundary and similar inputs to the control system for re-entry and descent. The other current effort is to develop a Mach 5 to Mach 20 double compression cone type probe sensor. This sensor will also determine Mach number, pressure altitude, angle of attack, and angle of sideslip for a manned re-entry vehicle.

VI. Future Uses For Angle of Attack

There will be many applications for use of angle of attack information in the approaching space age. Within the scope of this paper there will be discussed only a limited number of those considered possible as well as those which are presently being tested today for tomorrow's space flights. Use of angle of attack information in the X-15 rocket research vehicle and future lifting body type re-entry vehicles will be covered.

X-15 Rocket Research Vehicle

One of the early instrumentation problems with the X-15 rocket research vehicle was that of sensing and displaying angle of attack and angle of sideslip information to the pilot. This information was needed for the critical exit and re-entry periods of flight. From previous experience it was known that any sensing device would have to be well out ahead of the vehicle in the area of least flow disturbances, would have to be capable of withstanding extreme temperatures, and would have to be accurate at low ambient pressures. These requirements led to the development of the "Q"-ball differential pressure null-type sensor, which was designed by Nortronics Division of Northrop Aircraft to comply with NASA requirements for the X-15. This technique offered a promising solution to the space flight problem of directional and angle of attack control during the re-entry phase of flight. (See Figure 46).

The "Q"-ball is a servo-positioned gimbaled sphere which keeps a stagnation pressure port pointed into the relative wind. In the X-15,

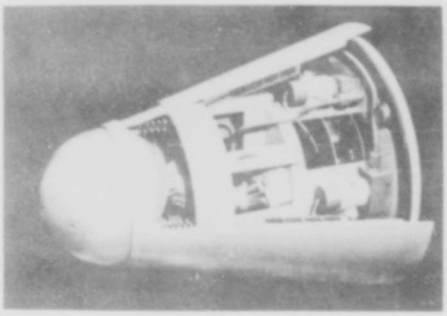

Fig 46
"Q"-Ball System for the X-15
Rocket Research Vehicle

cockpit indicators of the orientation of the sphere relative to the pitch and yaw axis of the aircraft are among the pilot's primary flight instruments at extreme altitudes and during re-entry. Angle of attack and angle of sideslip will have to be closely controlled because of their important effects upon speed, range, duration of flight, angle and rate of descent, structural loads and aerodynamic heating. Direct measurement of dynamic pressure "q" at the true stagnation point will also supply valuable information to the pilot since it will control the limits upon speed and angle of attack.

First flights of the X-15 used the conventional boom-and-vane type sensor, rather than the "Q"-ball, as initial flights were not expected to encounter extreme environments in which vane type sensors could not operate. The pressure-nulling spherical sensor was designed especially so that it would be useful through a wide range of temperatures, altitudes, and speeds. Comparatively little development would be needed to incorporate the sensor into an autopilot loop in order to provide good automatic control of aerodynamic attitude in typical ballistic missile environments. The "Q"-ball was designed to meet the following specifications: dynamic pressure (q) 15-2500 psf; ambient temperatures of 4000°F; altitudes of 300,000 ft; and speeds of Mach 10 (Ref 22:56-60, and Ref 38:1-4).

A typical X-15 profile was produced on August 12, 1960, when the vehicle was launched from the B-52 at 45,000 ft., and initial lightoff was conducted while maintaining an angle of attack of 8 degrees. After an initial altitude loss of approximately 6,000 ft., the vehicle climbed to 60,000 ft. At this altitude the X-15 was accelerated to Mach 1.9 and a 1.5g pullup was begun. Full back stick at 18.5 degrees of angle of attack was maintained during this portion of the profile, which corresponded to 35 degrees of stabilizer deflection and a pitch angle of 48.5 degrees. Engine burnout occurred at 118,000 ft. with an angle of attack of 10 degrees. (Figure 47 shows one configuration of the X-15 rocket research vehicle's instrument panel. The angle of attack quantitative instrument is located left of the attitude instrument which is in the center of the panel. The angle of sideslip quantitative instrument is located directly above the attitude instrument).

Following the zero-lift trajectory at burnout 10 degrees rather than zero degree, angle of attack was maintained due to suitable dynamic stability of the vehicle at low dynamic pressure. An angle of attack oscillation of plus and minus 3 degrees within an 8 second period was noted during the apex of the trajectory. (After passing the peak altitude, the pilot must concentrate on stabilizing for entry). The aircraft rotated easily to 2.6g and leveled out at 50,000 feet. Stabilizer angle required to maintain angle of attack during the entry maneuver was 20 degrees out of 35 available degrees (Ref 42:81-82).

During a previous flight the 8-degree angle of attack was maintained during the climbout phase of flight for maximum lift/drag ratio. During the pushover to zero angle of attack and zero pitching velocity, the vehicle developed a slight lateral oscillation. A gradual increasing

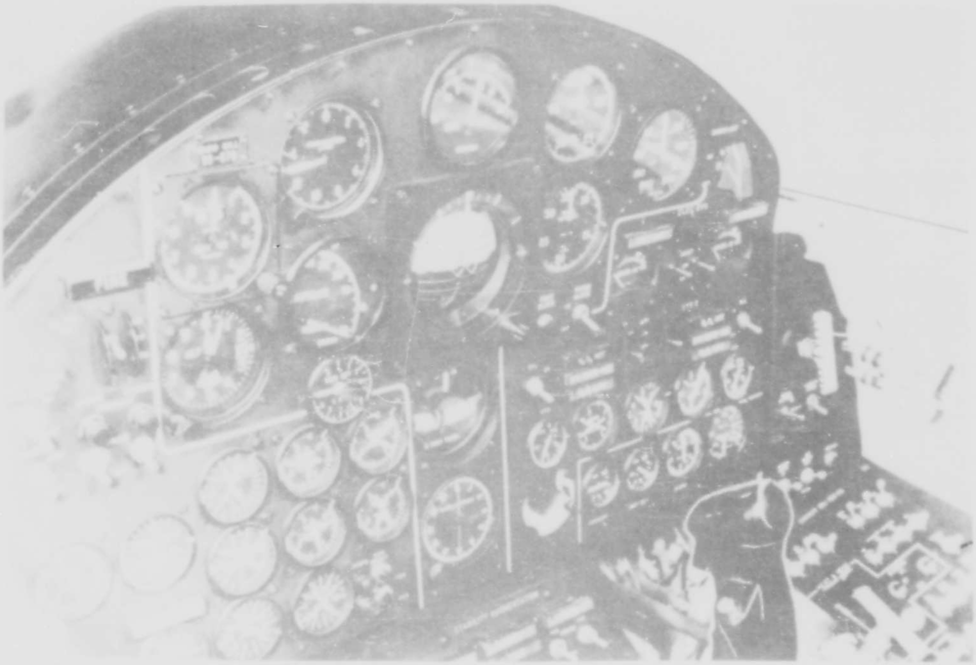

Fig 47
The X-15 Rocket Research Vehicle Instrument Panel

dive angle was observed during acceleration to maximum speed. (Figure 48 depicts the three-axis attitude director indicator, a production version similar to that used in the X-15).

Director information, found to be so effective in easing the pilot's task in accomplishing certain of his more complex mission modes of flight, (such as ILS and LABS), having been applied to many of today's aircraft, is now being applied to the X-15. The displacement pointer on the left of the instrument measures the displacement from a preselected pitch angle, which is adjustable within the cockpit. The horizontal pitch director needle shows a deviation from a predetermined angle of attack value for zero lift; its full scale displacement being adjustable from 3 to 20 degrees angle of attack. The vertical bank director needle shows a deviation from a predetermined zero sideslip angle; its full scale displacement being approximately 3 degrees. The critical aspect of this information merits its being seen continuously by the pilot with a minimum of cross checking in high g maneuvers.

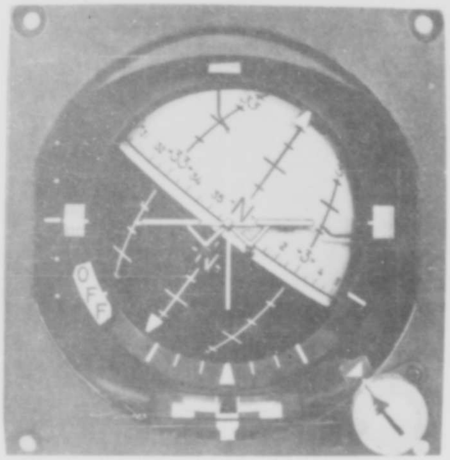

Fig 48
Three-Axis Attitude Director Indicator

Future Re-entry Vehicles

Many study programs have been completed and others are being made on the re-entry problem for a lifting-body glider type space vehicle. (The angle of attack display informational requirement is only a portion of the entire control-display subsystem for such a vehicle). Prior to re-entry the operator must concentrate heavily on vehicle attitude, angle of attack and lateral acceleration. From this point on to touchdown the operator's primary objective is to manage properly energy available such that the vehicle will impact within a prescribed area. (WADD TR 60-695, Ref 16).

There are a number of approaches the operator may take to control the vehicle within the safe re-entry envelope: (1) maintain a fixed angle of attack throughout the re-entry, the angle maintained being based on pre-computed conditions and vehicle responses; (2) maintain the vehicle on a pre-computed velocity-altitude profile by directly controlling these two parameters; or (3) control the angle of attack of the vehicle as a function of skin temperature, vertical velocity, and range deviation. Of the three choices the third is the more flexible and with the exception of range information the parameters need not be based on precalculated conditions. (Figure 49 shows typical pilot control of vehicle temperature during re-entry). By varying angle of attack and bank angle (and hence direction and magnitude of lift), the pilot is able to control his trajectory in a manner required to avoid overheating, to properly utilize energy, and to navigate to his destination (Ref 46:2, 8).

For the sub-orbital entry condition to avoid over-heating under severest permissible entry conditions (high downward vertical velocity and/or nearness to the recovery ceiling), maximum lift is used until the bottom surface temperature has approached its limit. Then angle of attack is reduced at the rate required to maintain a near limit temperature on the lower surface until recovery is effected. Having nose cone temperature available reveals information which shows that reducing angle of attack at too high a rate could result in nose over-heating and recovery without further temperature problems on the lower surface. (Figure 50 shows pilot management of re-entry kinetic energy). Greater rates of reducing angle of attack, of course, could (though initial effort was to cool the bottom), result in eventual over-heating of the bottom as well as the nose, prior to recovery. From temperature standpoint, the best technique is to maintain the highest angle of attack (up to limit of maximum lift) that the temperature of

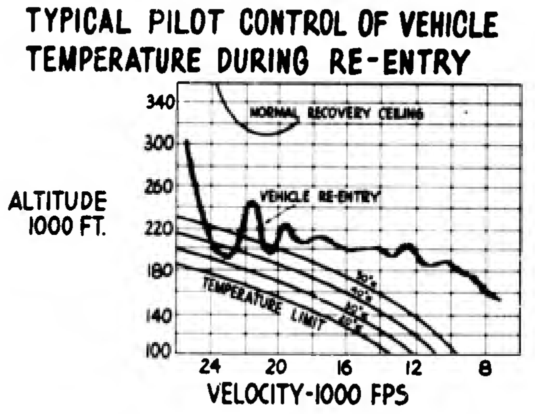

Fig 49
Typical Pilot Control of Vehicle Temperature During Re-entry
(From Ref 46:26)

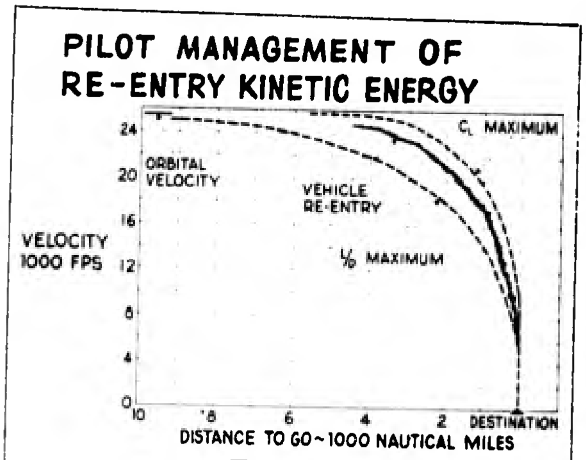

Fig 50
Pilot Management of Re-Entry Kinetic Energy
(From Ref 46:27)

the lower surface permits until recovery is effected. Following recovery from entry conditions, the first "bounce" (occurring at minimum lift), used while the vehicle is climbing, minimizes altitude increase and temperature problems on subsequent descent. Vertical velocity display is the primary indication for controlling angle of attack or lift to effectively dampen the "skipping" motion (phugoid) which follows entry. That is, maximum lift is used when vertical velocity is negative (sink), and minimum lift used when it goes positive (climb).

Vought Astronautics conducted a study on a lifting-body vehicle entering the atmosphere at both sub-orbital and super-orbital velocities, which was simulated on a six-degrees-of freedom fixed base simulator. A human operator performed the task of controlling the vehicle, the vehicle's trajectory, and energy management and navigation to a given destination. A majority of the tests was performed for the sub-orbital entry condition. Various combinations of starting conditions to produce heating and/or energy management problems were investigated to determine the ability of the human operator to recognize problems and to effect proper control procedure. Other than the possible exception of energy management and navigation to a given destination, the display parameters did not provide the pilot with anticipatory information. This made operator knowledge of the vehicle flight characteristics

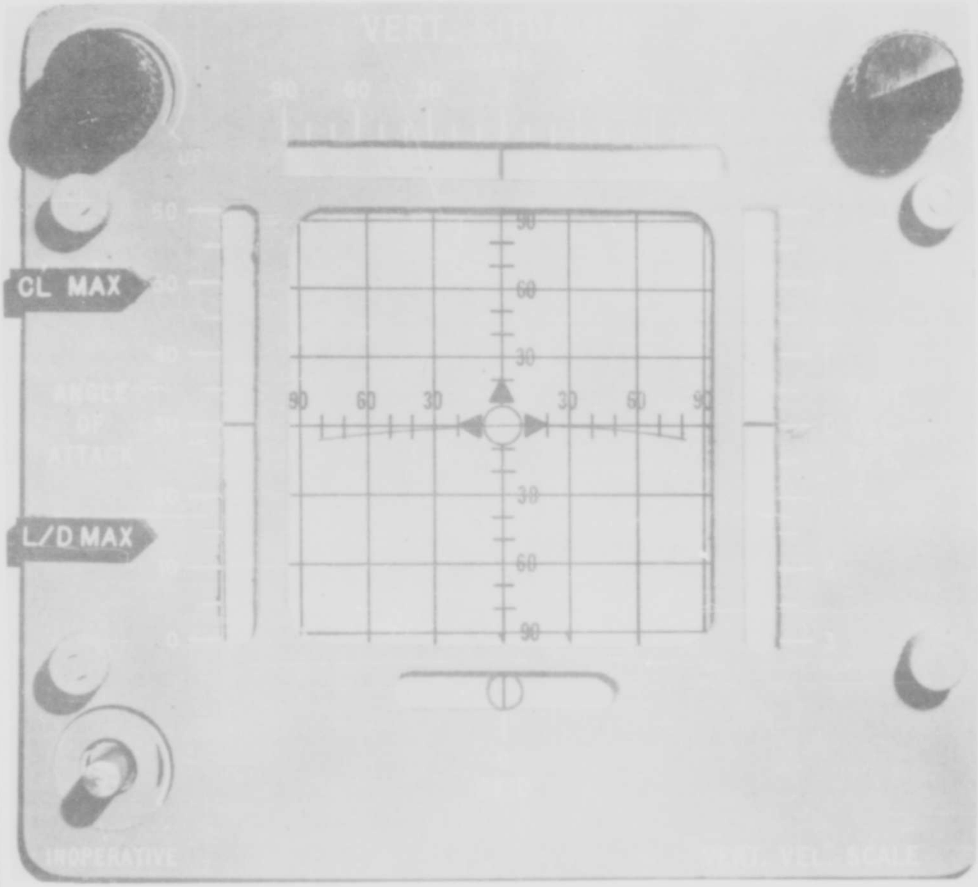

Fig 51
Vought Astronautics Angle of Attack Display for Re-entry
(From Ref 46:15)

and limitations an essential quantity in performing the required task with a minimum of control effort and probability for producing a costly error.

The vertical situation display is shown in Figure 51, which gives the pilot angle of attack (α), angle of sideslip (β), vertical velocity (V_v), pitch (Θ), roll (ϕ), skid (Ψ) information along with attitude. The instrument display provides the pilot with information regarding attitude and motion of the vehicle, vehicle temperature situations, and energy management and navigation.

For the vehicle simulated, where for normal operating range from $(L/D)_{max}$ to $(C_L)_{max}$ (L/D varied inversely with lift), the energy management display (not shown) shows changes in commanded angle of attack resulting from skipping motion, which would, if followed, tend to dampen this phugoid. At the minimum altitude of a phugoid cycle the vehicle was below the equilibrium glide altitude and thereby realized a higher dynamic pressure with resultant higher drag and a more rapid decrease in energy (Ref 41:10).

Results from the study indicated that changes in angle of attack while the vehicle was essentially in an equilibrium glide induced an oscillation (phugoid) in altitude similar to that resulting from entry. For those cases where an increase in angle of attack (reduction in L/D) was called for, a technique of banking the vehicle to off-set the increase in lift (attempting to minimize the lift change in the vertical plane), was used. If the vehicle were banked and a reduction in angle of attack called for, a reduction in bank angle would accomplish the same purpose. Bank was used in this manner for relatively short periods without an appreciable effect on the navigation turn (Ref 16:66).

The purpose of these tests was to evaluate the human operator's ability to utilize the display provided in effecting an entry into the atmosphere and in gliding the vehicle to a given destination. For this particular concept the display of angle of attack played an important part. The feasibility of manual control was demonstrated for a vehicle which entered the atmosphere at super-orbital and near escape velocities, and which utilized aerodynamic lift and drag to remain in the atmosphere, thus decelerating to sub-orbital velocities. The altitude corridor is quite small between the maximum value to remain captured and that limit where excessive heating occurs. This is dependent on vehicle design, requiring rather precise altitude control (Ref 46:14-15, 18).

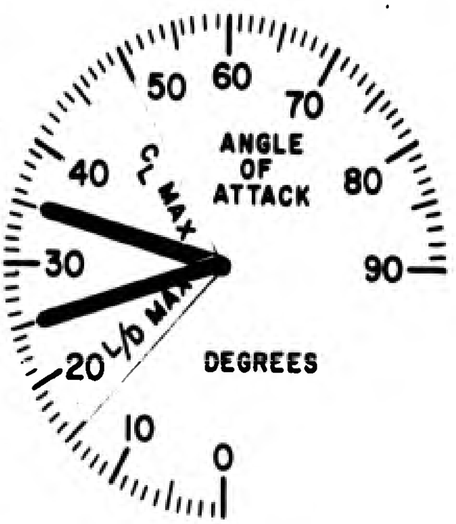

Fig 52
Vought Astronautics Dial
Presentation for Angle of Attack

Vought Astronautics is currently designing and building a moving base space flight simulator to investigate further control display requirements. The cockpit will include the angle of attack display shown in Figure 52. One needle indicates angle of attack; another needle travels with the first as a function of vertical acceleration. Thus, in equilibrium flight the needles are together. If an upward acceleration exists, the second needle reads a lower value than the first, indicating that angle of attack must be reduced for equilibrium, and vice versa. Once in equilibrium, changes in angle of attack and/or bank angle are made only at the rate that will keep the needles together, thus avoiding vertical accelerations which produce phugoid oscillations.

A systematic procedure for cockpit design, which took into consideration requirements and human engineering aspects as well as other design needs, was conceived by the Flight Control Laboratory, WADD, of ARDC and developed by Lear, Inc. Application of this cockpit design method was applied to the Mark IV orbital vehicle, a hypothetical vehicle which is capable of launch, orbit, re-entry, and landing.

Figure 53 gives a moving tape presentation of five parameters, two of which include variable limits. Flight path elevation angle, percent of allowable nose cone, underbody temperature, and angle of attack are displayed on four moving tapes. For both flight path elevation angle and angle of attack there are upper and lower limit indications in the form of amber

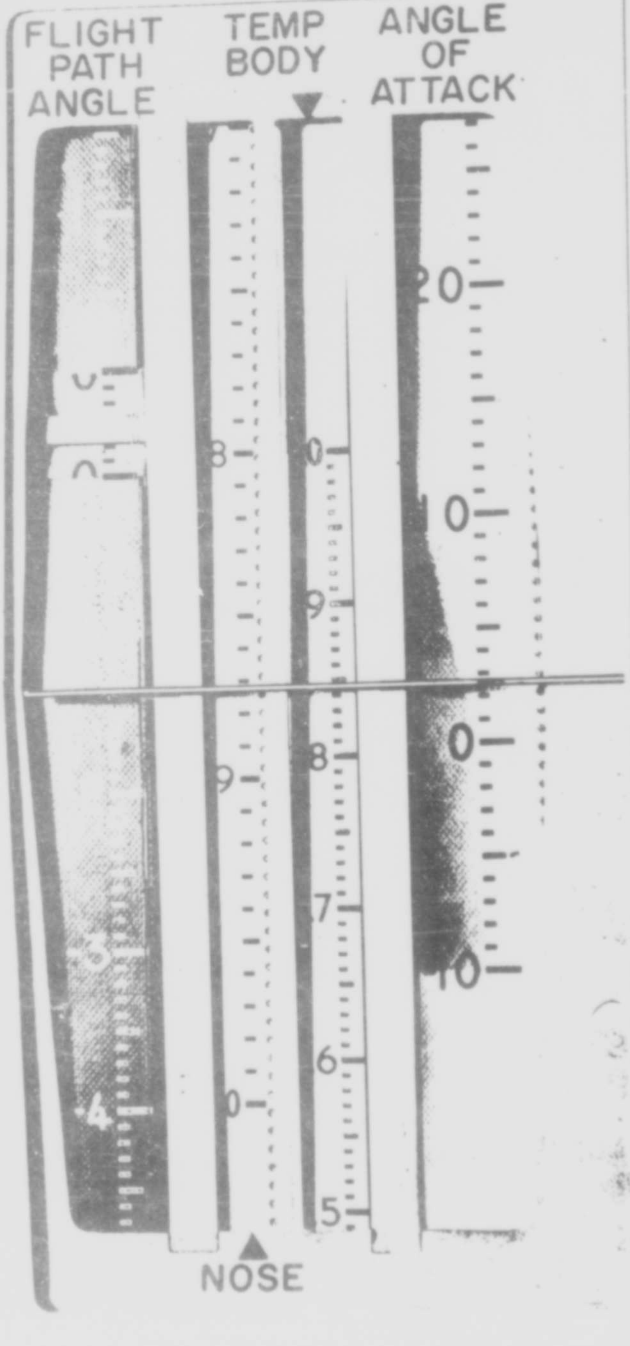

Fig 53
Lear Mark IV Pitch Axis Group Indicator
(From Ref 28:102)

transparent tapes. Each of these may be individually positioned. In addition, the two center tapes may be driven to a different position and used to indicate the position of a variable drag device.

The re-entry energy planning display is available on both the pilot's and the co-pilot's viewers and fills a vital link in the re-entry and landing phase of the mission (See Figure 54). This is displayed within a necessarily distorted, rectangular reference frame representing the possible landing area of the vehicle. Thus, the scale of the display is continually changing as the vehicle approaches its base. When the latitude of the landing field have been inserted into the computer, it causes the circled marked positioned on the display to indicate the necessary bank angle and angle of attack which must be flown to reach this particular point. The vehicle's present angle of attack and bank angle are indicated by a dart-shaped symbol (Ref 28:79, 102).

These particular displays are currently being mechanized by Lear, Inc. for a follow-on study program to determine the problem areas and solutions for orbital attitude and re-entry flight control for a simulation test program planned for 1961.

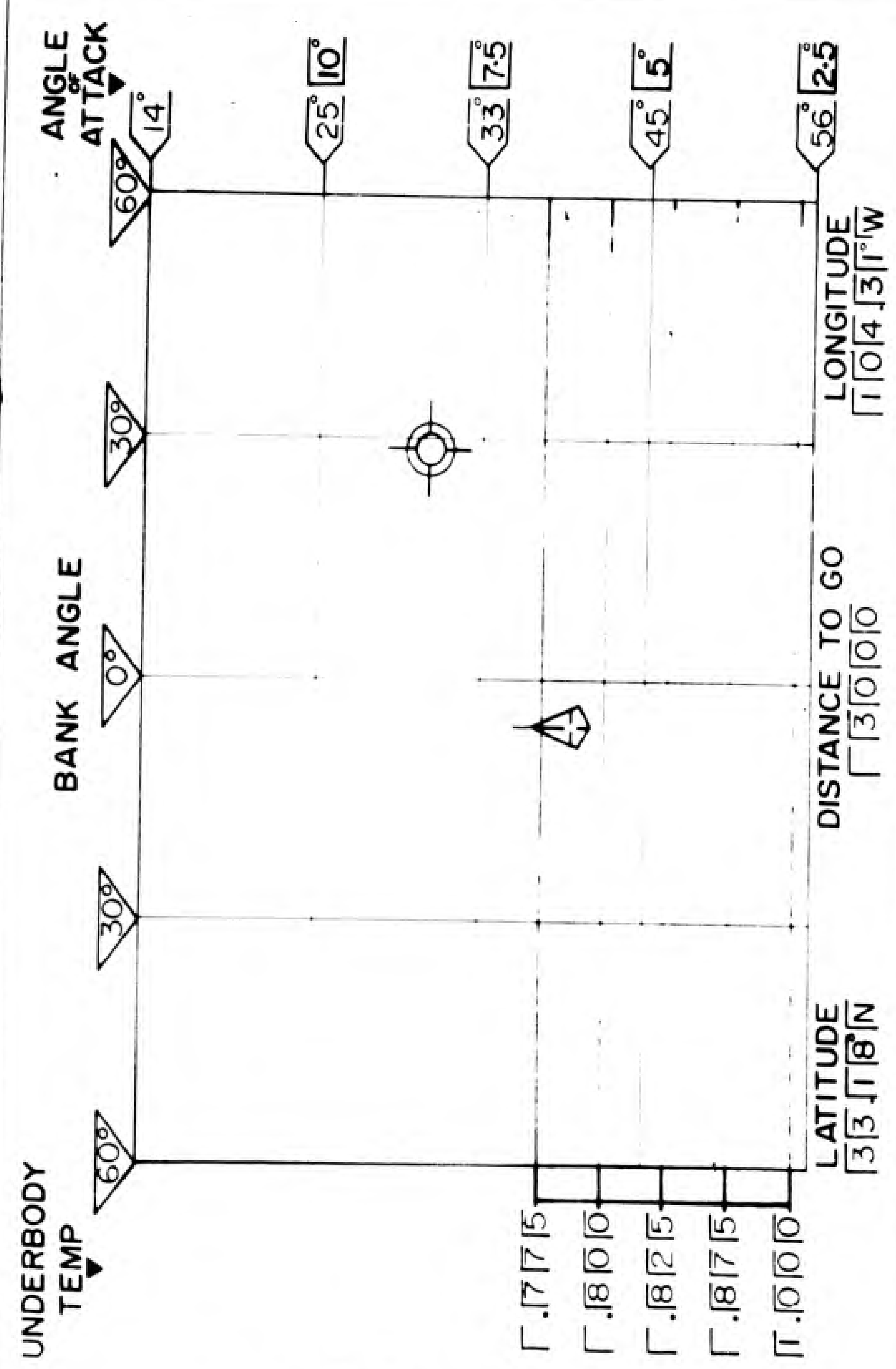

Fig 54
Lear Mark IV Energy Planning Display
(From Ref 28:79)

VII. Conclusions

As a consequence or result of reasoning, thought, and evaluation angle of attack in aerodynamic theory has been shown by aircraft designers to be a very well known and helpful paramenter; however as a flight control instrument its use has not been fully accepted by pilots. There is a definite lack of education as to the use of this information, particularly when manually controlling the aircraft. Throughout this paper, while reviewing angle of attack systems used during the years with resultant specific evaluations, it becomes increasingly evident that the parameter of angle of attack is important and useful. From the time of its introduction in early heavier than air flights, to its present role in today's rocket research and proposed future aerospace vehicles, it has remained a controversial instrument.

Conclusions drawn from this study on uses of angle of attack as a flight control instrument are:

(1) Many previous angle of attack devices have been rejected because of recommendations based solely on subjective opinions of test pilots.

(2) Operational requirements do exist for the sensing and/or displaying of angle of attack information in current and proposed weapon systems.

(3) Evaluations of angle of attack systems have not included well controlled static, dynamic, and flight test procedures.

(4) Angle of attack systems become particularly useful during constant speed maneuvers at relatively high angles of attack.

(5) Angle of attack has less resolution for pitch attitude control

than has other available parameters.

(6) Pilots have difficulty using angle of attack as a flight instrument due to the transient change in response of the angle of attack sensor resulting from stick control movement.

(7) Ground check time and calibration techniques are complicated and laborious procedures which do not assure reliability in flight.

(8) Angle of attack displays are usable as a stand-by pitch attitude instrument during high speed maneuvers; as a primary pitch attitude control instrument during final approach.

(9) A tremendous amount of effort, time, and money have been spent on angle of attack devices, but in reviewing efforts of the past 20 years, it would seem that no concentrated effort has been put forth by any one agency or group to develop and evaluate in a systematic way an angle of attack system suitable for the special mission phases of a vehicle for any given period of time. Yet, this effort is reflected in a variety of displays. (This report contains pictures of some of these displays, as well as pictures of some of the sensors and mechanizations required to drive the instrument). An awareness of the status of mechanization and sensing reveals that the desired state of accuracy, reliability, and serviceability is in the offing.

(10) Each vehicle is either designed or modified to fulfill some specific purpose, this purpose being equivalent to an operational mission. In assessing an angle of attack display or system there must be an interest in the extent to which it enables the accomplishment of the mission.

(11) There is a definite lack of human engineering input to the many angle of attack displays and pilot performance evaluations.

(12) The use of lift instrumentation relegates the airspeed indicator to a secondary reference flight instrument, which, when considering its inaccuracies and deficiencies, may eventually become its proper classification. .

(13) Pilot acceptance or use of angle of attack information has varied widely in the past according to such interrelated and overlapping factors as: display, sensitivity, reliability, environmental conditions, maintenance procedures, individual pilot training and experience, as well as the using agency's policies and procedures.

(14) In many cases the final display presented to the pilot in the cockpit was unacceptable due to poor scale factor, erroneous pointer movement, poor repeatability and sensitivity; consequently the entire system was rejected.

(15) Much criticism of angle of attack during flight tests was due to the fact that it is still a relatively new flight control parameter to the average military and civilian pilot, and that its significance is not realized nor are its potential uses known. There does not exist a training nor an indoctrination program required of pilots that teaches them to use this parameter in various phases of flight.

(16) Pilot procedures which would best exploit the information content presented by the angle of attack display in all different modes of flight need to be defined--based on analytical and computer studies which involve all influencing parameters.

(17) There is need for simplification of present calibration techniques used in many of today's angle of attack systems in order for them to be usable and reliable.

(18) One possible way to bring the status of various angle of attack devices up to date is to list studies and evaluations that have been performed on each system, pointing out if they were favorable or unfavorable during various flight phases. Table 1, Appendix B lists the evaluator, facility, date, type of sensor, type of display, method of evaluation, results (favorable or unfavorable), and recommendation for future work (if such was the case), remembering that no single angle of attack device has emerged as the final answer to flight control problems in using this parameter.

VIII. Recommendations

The following recommendations are made for further study on or development of angle of attack systems for use on existing or future weapon systems:

(1) Determine that a requirement for angle of attack information does exist for the particular vehicle being considered; consider the whole mission and how the information will be used after it is sensed and possibly displayed to the operator.

(2) Establish an objective and systematic approach to the solution of display problems for angle of attack including: a survey of available literature; an assessment of operational requirements and applications, sensor, and calibration techniques; studies on evaluation methodology and evaluation criteria; a thorough and systematic screening of display types; design of new types of angle of attack systems based upon past experience and new requirements as well as a thorough and systematic evaluation of these systems (using static, dynamic, and flight test methods of evaluation); and finally a development of application or techniques for using angle of attack information under any given condition.

(3) Place more emphasis on display and human engineering aspects of angle of attack systems shown in the vehicle's cockpit as well as more emphasis on engineering methods of improving sensor and mechanization techniques.

(4) Put the system into production and install it in a weapon system only after acceptance of the system by the engineer, the human factors specialist, and the flight test evaluator concerned with its evaluation.

In addition, it is recommended that the following action be taken with existing angle of attack systems:

(1) That the USAF Instrument Pilot Instructor School at James Connally AFB, Texas, continue investigation of uses that can be made of angle of attack information during instrument flight. The specific purpose of these investigations should be to develop procedures for employing this information for future inclusion in the AF Instrument Flying Manual and applicable Flight Manuals on specific aircraft using angle of attack flight instruments.

(2) That WADD continue to evaluate the latest production model of the Safe Flight SCAT system as installed on the KC-135 S/N 55-3121 to determine if this device is suitable for take-off, initial climb, approach, landing, and stall phases of flight.

(3) That WADD investigate the possibility of using angle of attack information as input to the horizontal pitch director needle and/or the glide slope displacement pointer on the two or three-axis director attitude indicator for take-off, initial climb, approach and landing phases of flight.

(4) That WADD conduct an analytical and computer study to determine dynamic conditions that exist between interrelated flight parameters during all phases of flight and conditions of flight (such as steady state, acceleration, maneuvering, turbulence, and transitory conditions), in order to ascertain where angle of attack information is usable.

(5) That WADD investigate the feasibility of utilizing angle of attack information during the zero-g maneuver with the optimum solu-

tion being a completely automatic controlled flight profile.

(6) That the AF continue to exchange information relative to angle of attack projects with other US military services as well as interested Canadian and British counterparts in connection with the international aircrew cockpit standardization committee.

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APPENDIX A

(Figure 1)

APPENDIX A

(Figure 1)

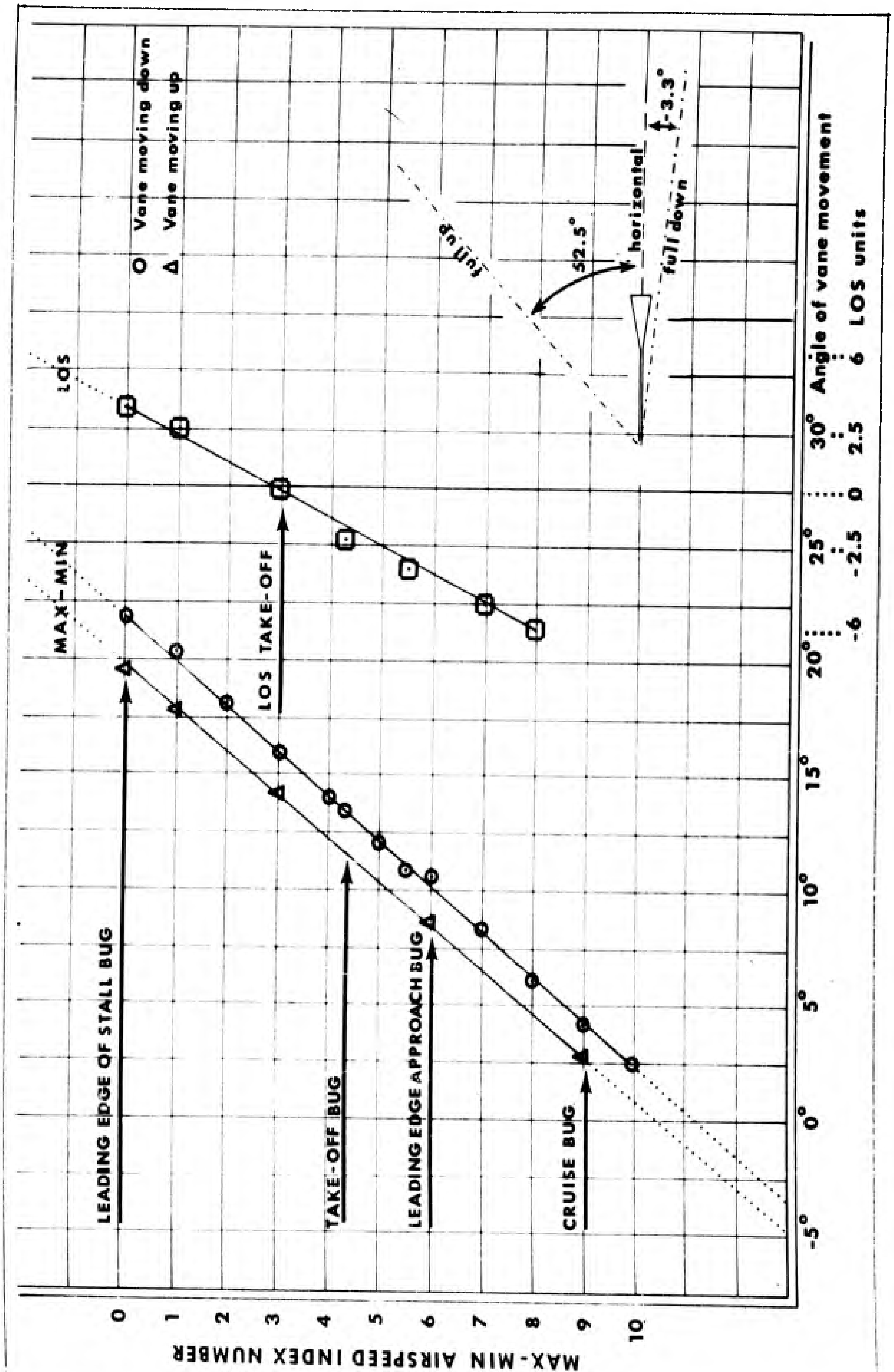
O Vane moving down
Δ Vane moving up
LOS
MAX-MIN
LOS TAKE-OFF
LEADING EDGE OF STALL BUG
TAKE-OFF BUG
LEADING EDGE APPROACH BUG
CRUISE BUG
full up
52.5°
horizontal
full down
-3.3°
-5°
0°
5°
10°
15°
20°
25°
30°
Angle of vane movement
-6
-2.5
0
2.5
6
LOS units
0
1
2
3
4
5
6
7
8
9
10
MAX-MIN AIRSPEED INDEX NUMBER

Figure 1

APPENDIX B

(Table 1)

EVALUATOR (AGENCY) DATE	TYPE OF SENSOR	TYPE OF DISPLAY	FLIGHT TEST A/C	PHASE OF FLIGHT					ADD WORK RECOM	REF
				TAKEOFF	CLIMB	CRUISE	APPR&LDG	STALL		
Andresen (Kollsman)	SMI (vane)	Kollsman (MaxOMin)	KC-135	U*	U	U	U		Yes	(2)
Ball (SAC)1954	Safe Flt (Tab)	(Safe Flt) LDC Sp Ind	B-47		U	U	F*		Yes	(4)
Ball (SAC)1954	Specialties (Probe)	(Specialties) Dial	B-47		F	F	U		Yes	(4)
Ballentine (Convair)	SMI (Vane)	(EP) Tape Instr	F-106				F	F	Yes	(5)
Brandenburg (WADC)1954	Kollsman (Vane)	(Kollsman) Dial	T-33		U	U	U		No	(6)
Brandenburg	Specialties	(Specialties)	T-33		U	U	F		Yes	(6)
Carlquist (NATC)1960	Daystrom (Vane)	Bendix dial/index	A4D-2N	U	U	U	F	F	Yes	(9)
Carlquist (NATC)1960	SMI (vane)	Bendix dial/index	F-8U	U	U	U	F	F	Yes	(9)
Carlquist (NATC)1960	Specialties (probe)	Specialties dial/index	F-9F F-11F	U	U	U	F	F	Yes	(9)

* F- Favorable
** U- Unfavorable

Table I Comparison of Systems Evaluated

EVALUATOR (Agency) DATE	TYPE of SENSOR	TYPE OF DISPLAY	FLIGHT TEST A/C	PHASE OF FLIGHT Takeoff	CLIMB	CRUISE	APPR&LDG	STALL	ADD WK RECOM	REF
Carlquist (NATC)1960	Topps (probe)	Specialties dial/index	F-4D-1	U	U	U	F	F	Yes	(9)
Crawford (WADC)1950	Young (Probe)	(Young) Dial	B-29		U	U			Yes	(10)
Decker (NATC)1954	Specialties (probe)	Specialties (dial)	F7U	U			F	F	Yes	(11)
Decker (NATC)1954	Specialties (probe)	Safe Flt (LdgSpInd)	F7U	U			F	U	Yes	(11)
Johnson (WADD)1960	SMI (Vane)	(NAA) Projection	F101		U	U	U	U	No	(23)
Maddox (ATC)1960	SMI (Vane)	Kollsman (Max-Min)	T-29	U	F	F	F		Yes	(30)
Moore (WADC)1959	SMI (vane)	Kollsman (Max-Min)	F-102	F	F	F	F		Yes	(32)
O'Neal (NATC)1959	SMI (vane)	Specialties (dial)	F-8U	F			F		Yes	(39)
O'Neal (NATC)1959	Specialties (probe)	Specialties (dial)	F-8U	F			F		Yes	(39)
Siegenthaler (SWISSAIR) 1954	Specialties (probe)	Specialties (dial)	DC-6B	U	F	U	F	F	Yes	(48)
Spencer (WADC)1959	Specialties (probe)	Specialties (dial)	F-100C	U	F	F	F	F	Yes	(55)

EVALUATOR (AGENCY) DATE	TYPE OF SENSOR	TYPE OF DISPLAY	FLIGHT TEST A/C	TAKEOFF	PHASE OF FLIGHT CLIMB	CRUISE	APPR&LDG	STALL	ADD WORK RECOM	ADD REF
Stockdale (WADD)1950	SMI (vane)	Kollsman (Max-Min)	KC-135	U	U	U	U	F	No	(58)
Stockdale (WADD)1960	(Tab) Safe Flt	(SCAT) Safe Flt	KC-135	F		U	F	F	Yes	(58)
Svimonoff (WADC)1958	Topps (Probe)	(EP) Tape Instr	T-33				F	F	Yes	(59)
Svimonoff (WADC)1958	Topps (Probe)	(EP) Tape Instr	TF-102				F	F	Yes	(59)
Tucker (AFFTC)1959	SMI (vane)	Kollsman (Max-Min)	F-106	U		F	F	U	No	(61)
Tucker (AFFTC)1959	Specialties (prove)	Specialties dial/index	F-106	U		F	F	U	Yes	(61)
Wilvert (WADC)1952	Kollsman (Vane)	(Kollsman) Dial	B-26		F	F	F		Yes	(62)
Wilvert (WADC)1952	Seaboard (Probe)	(Kollsman) Dial	B-26		U**	U	U		No	(62)
Wilvert (WADC)1952	Specialties (Prove)	(Kollsman) Dial	B-26		F*	F	F		Yes	(62)

Vita

Willard Ellsworth Wilvert was born on [redacted], [redacted], the son of Arthur Ellsworth and Kathryn [redacted] Wilvert. He completed two years of engineering at Ventura College, Ventura, California, before entering the service in 1941. Upon graduation from flying school in 1942 he was commissioned a 2nd Lieutenant. Further schooling by the Air Force resulted in his receiving the degree of Bachelor of Science in 1949 from the United States Air Force Institute of Technology, Wright-Patterson Air Force Base, Ohio, and the equivalency of the degree of Master of Science from the same institution in 1952. He has served as an aviator (having logged over 6,000 hours, 1,000 of which were jet time), as flying safety officer and operations officer for the Tactical Air Command and the Alaskan Air Command, and as an aeronautical engineer and mechanical engineer for the Air Research and Development Command and United States Air Forces Europe.

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