AIR INDUCTION

INTRODUCTION

Earle Watson or Charles F. Hall

Although the proper design of air intakes always has been important, the attention given to this phase of aerodynamics has increased greatly during the past few years. This added interest has been due to a new type of propulsion and to the rapid increase in the maximum speed of our airplanes. It is well, therefore, to review briefly the effects that jet propulsion and high speeds have on the design of air intakes.

In the jet engine large quantities of intake air must be exhausted at high velocities to create the propulsive force. This is in contrast to the reciprocating engine and propeller combination for which only sufficient air for the combustion of the fuel is required in the engine. In this chart (fig. 9(b)) the spheres represent the quantities of air required in the combustion chambers of reciprocating, turbojet and ram-jet engines at 40,000 feet altitude. External cooling air is not considered. Note that the quantity of air required by the turbojet engine is about eight times greater than that required by the reciprocating engine. The inlet for the combustion chamber air for the turbojet engine is therefore much larger than that required by the reciprocating engine.

Representative speeds of airplanes using these engines today are indicated by the location of these dots with respect to this axis.

The increase in speed possible with a jet engine accounts for part of the increase in the quantity of air required. Greater speeds mean greater fuel consumption and therefore larger amounts of combustion air.

As previously mentioned, high speeds also have had their effect on intake design. In an internal combustion engine, it is necessary to compress the intake air to obtain good efficiencies. Part of this compression, as for reciprocating turbine engines, or all of it, as for ram-jet engines, can be obtained by reducing the speed of the induction system air with respect to the airplane. The increase in pressure is called ram pressure and is proportional to the reduction in the speed of the intake air. As an example of this pressure increase, it is ram pressure which forces open a paper bag when it is whipped through the air.

To visualize the importance of ram pressure, let us suppose that the ram pressure recovered by the air induction system is replaced by an equivalent pressure supplied by a mechanical compressor. What would be the horsepower required to obtain a pressure equal to the ram pressure? First, this required horsepower would increase in direct proportion to the quantity of air required by the engine. Second, the power for each pound of air required would increase as the square of the velocity of the airplane. The resultant compressor horsepowers for the three types of engines on this chart are shown by the location of the points with respect to this axis. Note that the compressor horsepower for the reciprocating engine is insignificant when compared with those of the turbojet and ram-jet engines. It can be seen therefore, that a large gain in horsepower would be effected in the cases of the jet engines by properly designing the air intake to obtain all of the ram pressure.

Low airspeeds in the airplane's induction system are also required in order to maintain low internal duct losses, high efficiencies for the turbojet compressor, and, in the case of the ram jet, to keep the flame in the combustion chamber from blowing out.

Another important design requirement for air intakes is that their external drag be a minimum.

The intake designer must also consider the location of the inlet. This will depend on the position of the engine, type of airplane, and the structural specifications.

In summary then, the requirements to be considered in the design of air intakes are:

1. Sufficient size to obtain the large amounts of air required at reasonable inlet velocities.
2. High ram-pressure recoveries.
3. Low external drag, and
4. Suitable location of inlet.

Mr. __________ will discuss subsonic air intakes which have been designed to meet these sometimes conflicting requirements.

Mr. __________.

SUBSONIC AIR INLETS

Warren Anderson or Norman Martin

Both subsonic and supersonic air-induction problems may be classified into two general divisions; the first consisting of intakes utilizing the free-stream air only, and the second being those intakes located in a region of considerable boundary layer.

Inlets in the first category, or those which come in contact with the free-stream air are shown on your left; the wing leading-edge intake, the nose inlet on a nacelle, and the cooling scoop on the P-51. This latter type may be placed in either division, depending upon whether the scoop projects far enough from the body to be outside the influence of the boundary layer.

The problems involved in the design of wing leading-edge inlets which meet the free-stream air and so are unaffected by boundary-layer phenomena are analogous to those encountered in the development of airfoils. Such an inlet must be designed not only to give high ram-pressure recoveries but also to cause no deterioration of the lift and drag characteristics of the wing itself. Since what is beneficial for maximum lift is often harmful to the high-speed drag, meeting these requirements involves a compromise of the geometrical design parameters. As an example, preventing separation of the flow over the duct lips requires such features as large nose radii and thick lip sections. High critical speed, however, demands small nose radii and thin lip sections.

The effects of angle of attack on a wing leading-edge inlet can be more severe than on other types of inlets. This is because of the increase in the angle of the air flow as it approaches the wing.

Extensive investigations at low speeds of the many factors affecting the characteristics of wing leading-edge inlets have been made recently. The effects of two of these factors, angle of attack and lower-lip stagger, are shown on the first chart (fig. 9(c)). Here ram-pressure recovery is shown as a function of angle of attack. Notice that with no stagger on the lower lip, there was a sharp reduction in the ram-pressure recovery at angles of attack above about 2°. Such a small angle-of-attack range for good pressure recovery would prohibit the use of this inlet. However, staggering the lower lip greatly improved the recovery characteristics of the inlet. Staggering the lip results in satisfactory characteristics up to an angle of attack of 5°. Here again, however, there must be a compromise. Too much stagger will cause a loss in maximum lift of the wing. This in turn would result in inferior performance during take-off and landing.

The effects of lip radius and inlet velocity on the lift characteristics of the wing section in which the inlet is placed are shown in the next chart (fig. 9(d)). Here section maximum lift coefficient is shown as a function of lip radius. It may be seen that either increasing the inlet velocity, or increasing the lip radius, or a combination of both, increased the section maximum lift coefficient.

The effect of staggering the lower lip of this wing section would be to move these curves over slightly to the right. Thus, with a staggered lower lip, the zero inlet velocity curve would lie approximately here. This loss in maximum lift at low inlet velocities is important when landing with an engine inoperative.

Two subsonic inlets typical of those found in the second category, that is, intakes situated in a region of considerable boundary layer, are shown on your right. This is a model having a wing-root scoop inlet which is analogous to the expanded wing-fillet type. The other model has a completely submerged inlet in the side of the fuselage. On both these airplanes the inlet is far aft on the fuselage so that the boundary layer, a layer of retarded air immediately adjacent to the fuselage, has built up to a considerable thickness along the surface to the inlet. If this retarded, or low-pressure air, is taken into the airplane's air-induction system, low ram-recovery efficiencies will result. These two inlets exhibit separate means of minimizing the adverse effect of the boundary layer in front of the intake. In this type the boundary-layer air is removed by a small scoop inside the main inlet. The other, an NACA submerged inlet with a divergent-walled ramp, receives only a narrow band of boundary-layer air which is allowed to spread sideways, thus counteracting the tendency to thicken.

The effect of the boundary layer on the ram-pressure recovery may best be visualized on the next chart (fig. 9(e)). Here ram-pressure recovery is shown as a function of inlet velocity. These solid curves represent ram-pressure recovery at the submerged inlets for both parallel and divergent ramp walls. It is seen that the maximum ram pressure recovered is almost identical in both cases, but it occurs at a different ratio of the inlet velocity to the flight velocity.

The ram pressure recovered at the inlet of an air-induction system, however, is only part of the picture. It is necessary to know the ram pressure at the engine. The ram pressure of the air in passing from the inlet to the engine is reduced due to friction along the walls of the duct. The dashed curves which show the pressure recoveries at the engine indicate the maximum ram pressure at the engine is much greater for the divergent-walled inlet than for the parallel-walled inlet. These curves also show that a divergent-walled inlet designed for high-speed flight should operate at an inlet velocity of approximately 50 percent of flight velocity.

The effects of Mach number and inlet position on divergent-walled, submerged inlets have also been investigated and the results are shown at an inlet velocity of 0.60 flight velocity in the next chart, (fig. 9(f)). This chart shows ram recovery as a function of Mach number. Here it is shown that as the inlet was moved aft the ram-pressure recovery decreased. This is because the boundary layer is thicker farther aft on the fuselage.

Note that for the inlets in the two forward locations the ram-pressure recovery was almost unaffected as the Mach number increased. With the inlet in the aft location, the efficiency at high Mach numbers was very poor. The sharp reduction in the efficiency above a Mach number of a approximately 0.80 was caused by the poor flow in the wing-fuselage juncture and the influence of the wing shock waves on the flow near the fuselage. These data indicate that this inlet should be placed away from the high-velocity or separated-flow region of the wing.

In this short discussion of air inlets for airplanes flying in the subsonic speed range, it has been possible to touch only the surface of the extensive research program conducted by the NACA. A large program is also being conducted for inlets to be used at supersonic speeds and Mr. ______ will discuss the highlights of the program. Mr. ____________ .

SUPERSONIC AIR INLETS

S. Sherman Edwards or Thomas Canning

As was pointed out, the amount of compression available due to ram increases with flight speed. An airplane flying at 500 mph at 40,000 feet compresses inducted air through a compression ratio of about one and a half by making use of the ram effect alone. At 1200 mph the maximum available ram compression ratio is about six, which is equivalent to the compression ratio attained in automobile cylinders. At 2000 mph this ratio is 36.

At the present time, air-breathing engines capable of driving aircraft at supersonic speeds require that air be applied to them at low velocity as well as with high ram-pressure recovery. Therefore, the problems to be solved for supersonic aircraft are: to decelerate air efficiently from supersonic to high subsonic speeds and then to decelerate it still further so that it can be used in the engine. The first problem is complicated by the fact that the deceleration from supersonic to subsonic speeds generally takes place suddenly through a shock wave that is perpendicular or normal to the stream direction. A sudden ease in pressure and decrease in velocity occurs in this wave. If the speed of the air just ahead of this normal shock wave is much greater than the speed of sound, large losses in the available ram pressure are sustained. Therefore the problem is: to decelerate the air to as low a supersonic speed as possible before it encounters the normal shock wave.

Two general methods for accomplishing this supersonic deceleration have been used successfully. The duct inlet shown here (fig. 9(g)) consists of a convergent followed by a divergent section. The supersonic stream flowing into this converging passage is smoothly decelerated and this is in direct contrast to subsonic flow, where a converging passage causes an increase in speed. At the point of maximum contraction, the air is moving at a low supersonic velocity. It is abruptly decelerated through a normal shock wave to subsonic speed and passes on down the expanding subsonic diffusor. This type of induction system operates well at only one flight velocity and engine throttle setting. If the flight velocity or the mass flow into the inlet is reduced, the shock-wave jumps from a point of low supersonic speed (INDICATE) to a point of high supersonic speed causing instability of operation and a great loss of efficiency.

To stabilize the normal shock wave and improve the performance of the inlet, perforations in the walls of the convergent section have been found to be effective. The perforations provide escape outlets for part of the entering air. This allows the normal shock wave to stand in the convergent section so that no severe fluctuation in ram pressure recovery occurs.

The second method of decelerating air from high supersonic to low supersonic speeds is to pass it through deliberately created shock waves that are oblique to the stream direction. The oblique wave caused by the nose cone of the conical shock inlet (fig. 9(h)) does not cause transition to subsonic speed, but merely decreases the speed suddenly to a somewhat lower supersonic Mach number. This process causes only a small loss of available ram pressure. The air now flowing at a low supersonic speed as before, passes through a weak normal shock wave and flows into the divergent subsonic diffuser. This type of supersonic induction system is efficient over a very large range of operating conditions.

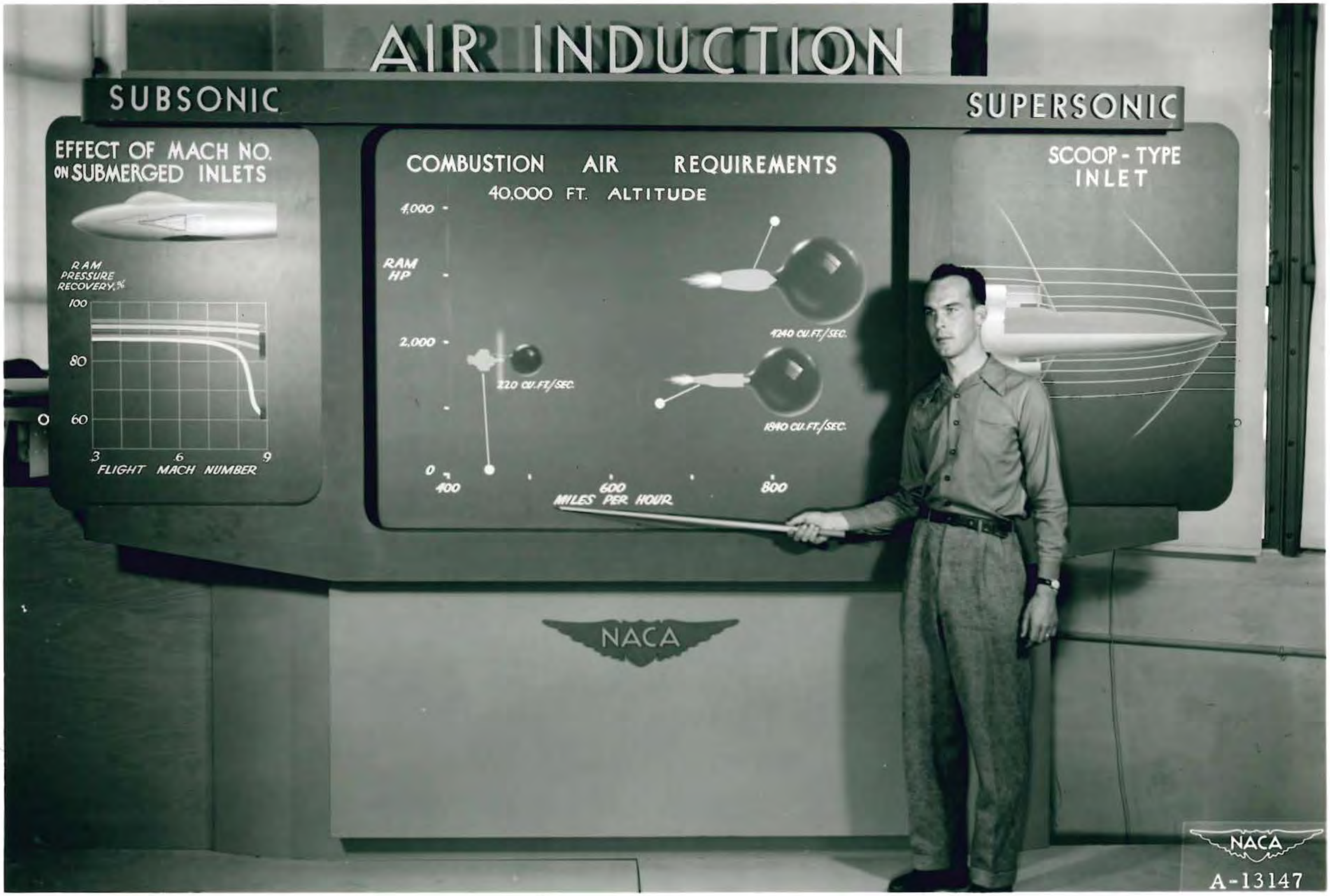
By nature of their design the entrances to the convergent-divergent and conical shock inlets would probably be placed in the nose of a missile or airplane. Inlets so located require a great deal of internal ducting to transport the air to the engines located in the rear. This limits the useful volume of the fuselage and increases the pressure losses in the ducts.

The scoop-type induction system (fig. 9(i)) alleviates this difficulty by locating the scoops aft on the fuselage near the engines. This inlet utilizes oblique and normal shock waves to decelerate the air stream in a manner similar to the conical shock diffuser. The air flowing about the fuselage sustains a small loss in ram pressure in the oblique shock wave from the nose. As the air travels from behind this shock to the inlet, it accelerates to approximately its original Mach number. As at subsonic speeds, a boundary layer builds up along the forebody ahead of the inlets and part of the available ram pressure is dissipated due to friction in this layer. The losses in the nose shock wave and in the boundary layer are unavoidable penalties if additional fuselage space is to be provided and ducting losses reduced.

Immediately ahead of the duct entrance the air encounters an oblique shock wave caused by a ramp and is decelerated suddenly to a low supersonic speed. Transition to subsonic velocity occurs through a weak normal shock wave near the scoop entrance. It was found that slots in the scoop sidewalls allow the high pressure in the duct to force the boundary layer out. Diverting the boundary layer in this manner permits higher pressure recoveries and also stabilizes the inlet performance over a large range of operating conditions.

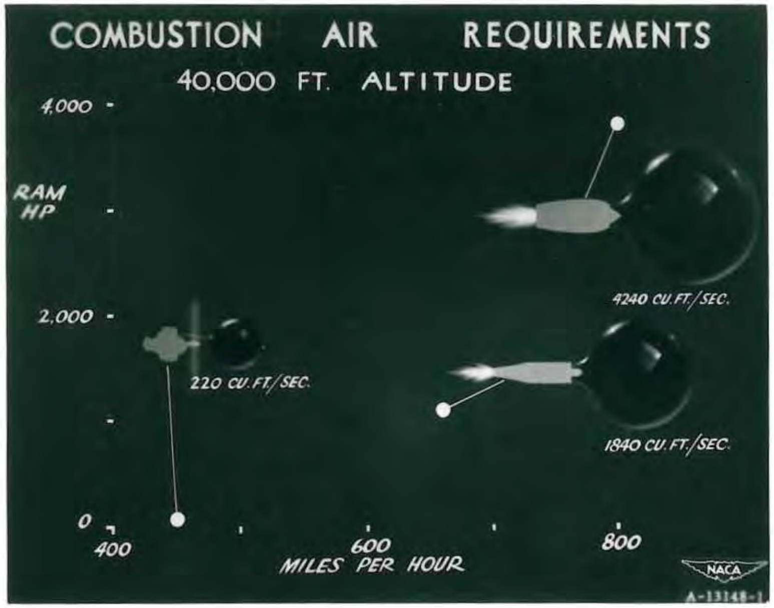
Subsonic induction systems attain compression ratios within 4 or 5 percent of the maximum - theoretically attainable due to ram. At supersonic Mach numbers below about 1.5, comparable ram pressure recoveries are possible with the induction systems described. At Mach numbers higher than 1.5, pressure losses through the shock waves and in the ducts cause the ram compression ratio of the nose type inlets to decrease by nearly 15 percent at twice the speed of sound and 40 percent at a Mach number of 3. Scoop inlet induction systems are not readily adaptable at flight Mach numbers above two because the losses associated with the forebody become prohibitive. However, by proper use of boundary-layer control measures side scoops can be used even in this range.

The three types of inlets we have discussed are idealized designs that show the trend of research being carried on to obtain fundamental information on inlets that will operate efficiently at supersonic speeds. The discussion has been limited to considerations of pressure recovery alone. Practical application of these designs to supersonic aircraft requires extensive information concerning their effect on the performance of the airplane throughout the speed range. The problems of efficient operation of these inlets at subsonic and transonic speed are being studied. Very little is known about the comparative drags of these inlets at the present time, but tests to determine this unknown factor are in progress and will probably determine the types of inlets most likely to be used on supersonic aircraft of the future.

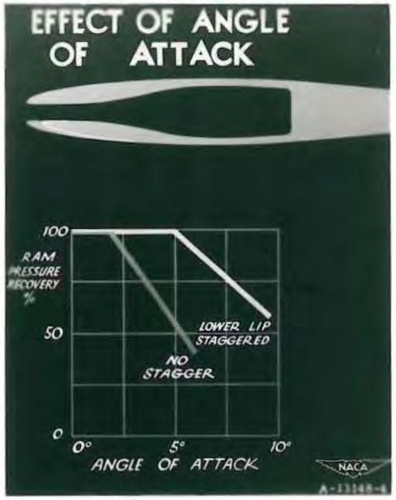


(a) General view

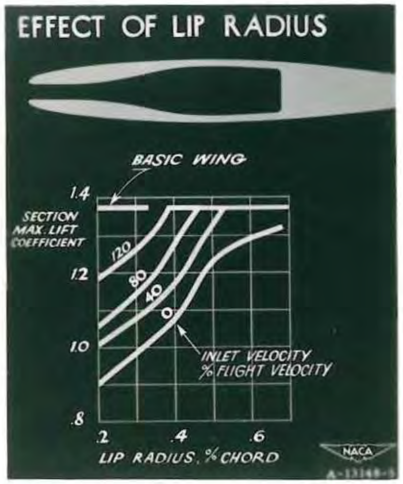
Figure 9.— Air-induction exhibit.



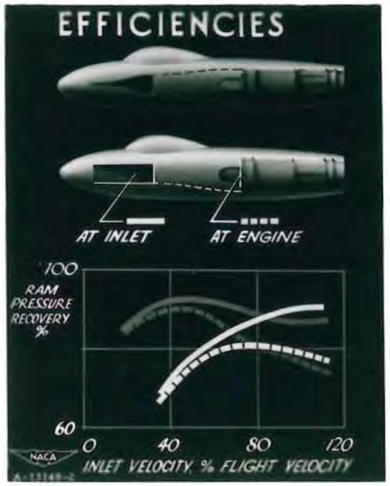
(b) First chart.



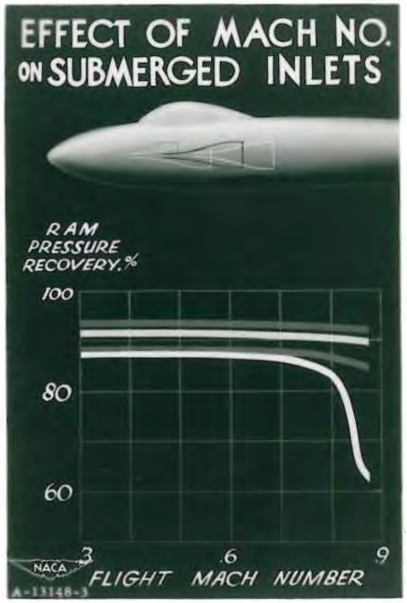
(c) Second chart.



(d) Third chart.

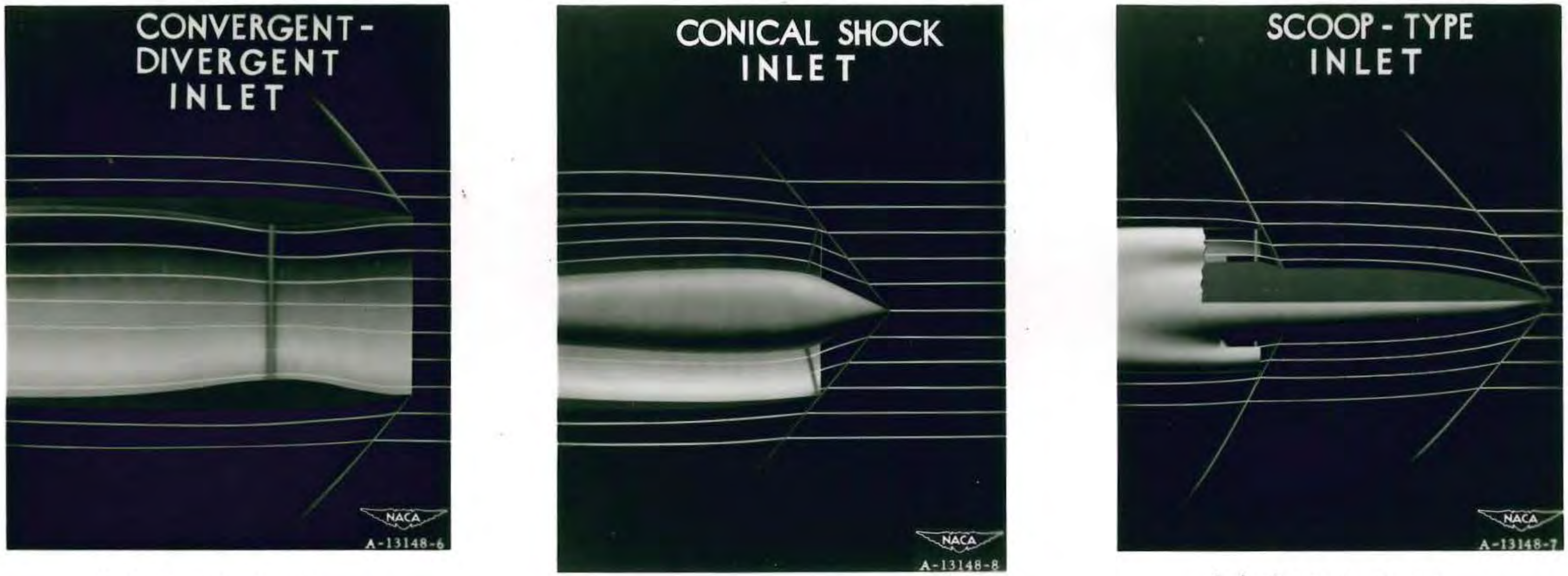


(e) Fourth chart.



(f) Fifth chart.

Figure 9.– Continued.



(g) Sixth chart.

(h) Seventh chart.

(i) Eighth chart.

Figure 9.– Concluded.