TEST PILOT'S NOTEBOOK

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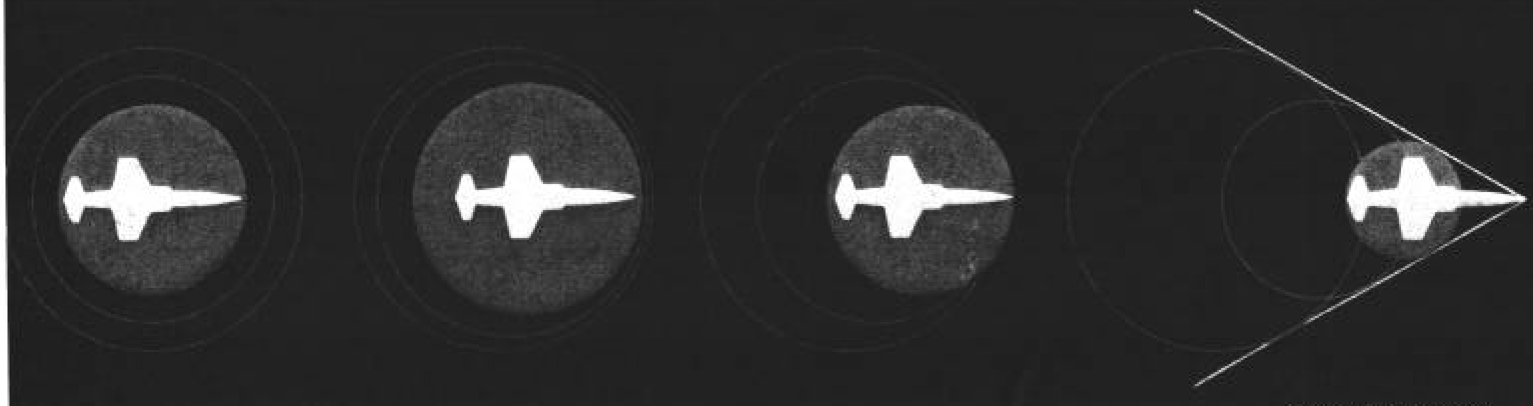
THE F-104 STARFIGHTER



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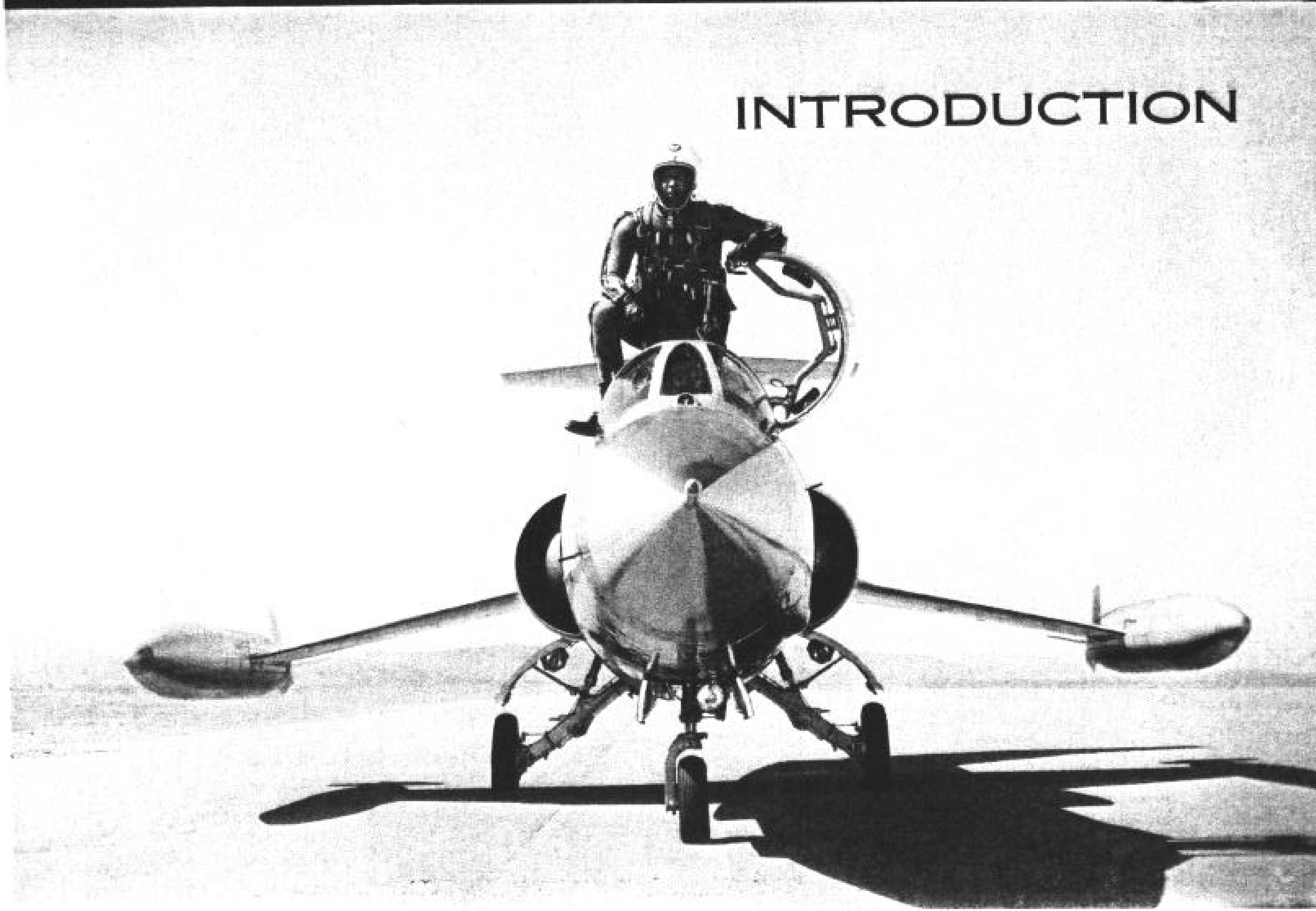
INTRODUCTION



From the days of Rickenbacker and Von Richthofen, pilots who fly to fight have recognized the advantages of altitude and speed. But the fighter pilot's dream has always been something more than a great hulking brute of a machine that would stagger up to some height and blunder on at a fair speed. Above and beyond mass power, the fighter pilot's vision has always embodied the concept of lightness – a fighter plane that could truly "dance the skies on laughter-silvered wings."

A fighter pilot wants the plus factors – the long reach in altitude, the long stretch in speed – and more than that, an airplane that "fits." A plane that fits the pilot and fits the mission.

This is the Starfighter, the F-104 air superiority fighter, a proud descendant of a noble lineage that dates back through the Lightning, the Shooting Star and the Starfire.

Lockheed engineers stretched their sliderules to give the plus factors to the Starfighter. And they made it a fighter pilot's airplane. It's lean and hungry. The Starfighter goes like no airplane has ever gone before. It is more than 1200 mph faster than a World War I Spad. Yet the Starfighter "fits" the pilot like few planes have done since the days of the Spad. It has the real "fighter feel."

Still better, it was designed for maximum flying and minimum monitoring of systems – as well as easy ground maintenance.

With the entry of the Starfighter into many squadrons of the Free World's Air Forces, it opens new regimes of flight to pilots of these countries. That's why this book has been prepared. We'd like to acquaint pilots who fly the Starfighter with the aerodynamic behavior, characteristics, and performance of this airplane that leaps out to Mach 2.

I. MACH NUMBER EFFECTS

In designing an aircraft for an extensive speed regime, Mach number is still the most important design parameter. Mach number, of course, is, by definition, simply the ratio of the speed of the aircraft to the speed of sound. Our drawings *(Fig. 1)* can depict this relationship by showing an aircraft traveling at various speeds and, therefore, having various speed ratios to the speed of sound. As an aircraft begins to travel faster than the expanding waves of pressure, a shock wave forms at or near the bow of the aircraft. If the aircraft has not been designed for supersonic flight, bad effects of the shock wave will be noticeable, such as tucking, wing dipping, and buffeting. Due to the pure supersonic design of the STARFIGHTER, however, it literally slips through Mach one without a tremor. The only indications *(Fig. 1a)* are the "Jumps" on the Mach number and altitude instruments. The reason for the delay and then the surge on the instruments is that the static pressure at the nose boom rises as the shock wave approaches the nose and then the pressure drops to true static as the wave moves past the pick-up.

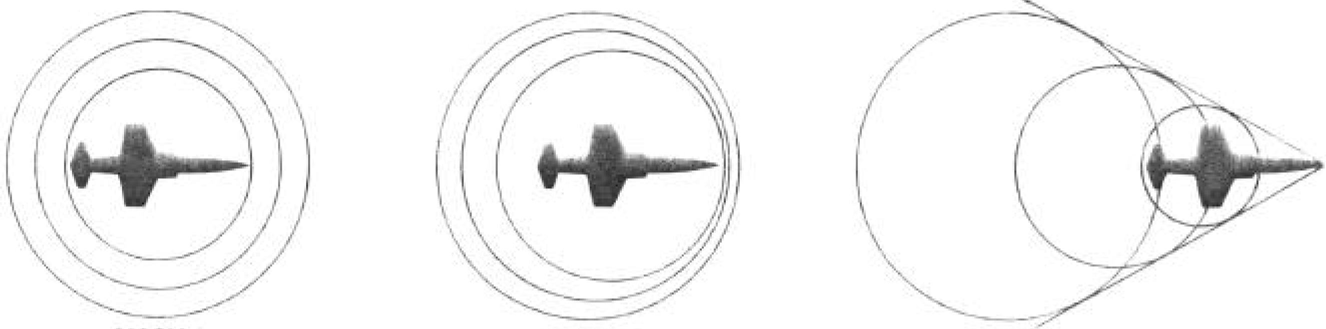


FIG. 1

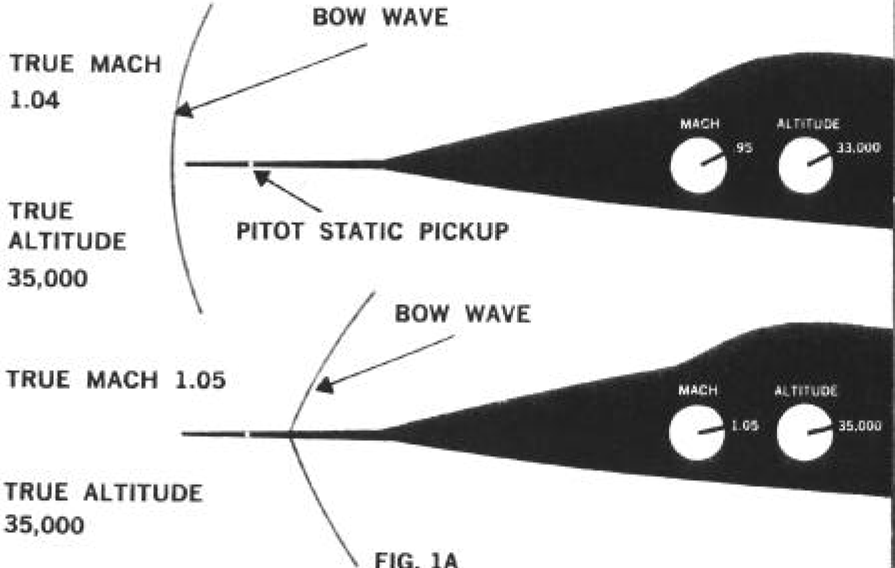


FIG. 1A

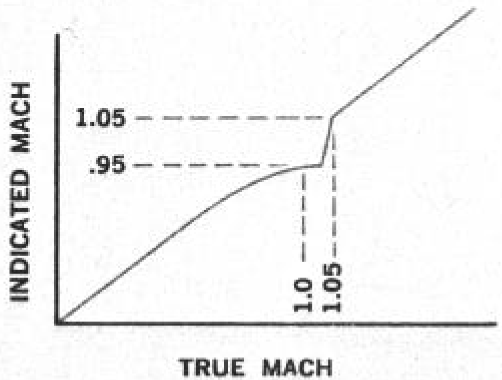
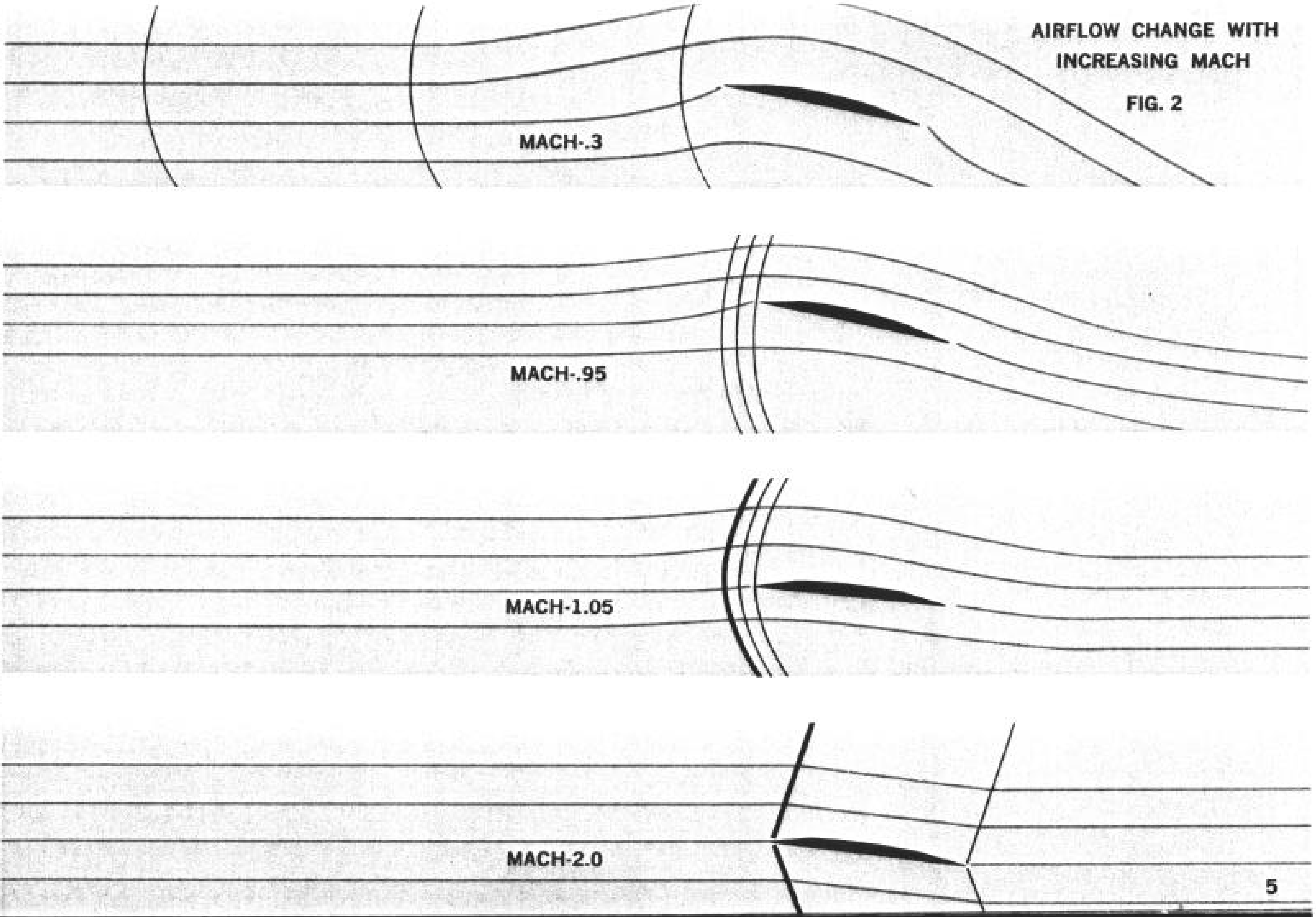


FIG. 1A

The effects of Mach number are handled smoothly and efficiently by the STARFIGHTER'S overall aerodynamic design. By Mach number effects we mean the difficulty of the wing or airfoil to move the air aside without paying an extreme penalty in drag. We can see that to do this we need a sharp, straight leading edge wing. As an aircraft wing is accelerated slowly through the air *(Fig. 2)*, the flow developed over the wing is reflected into the air as pressures. This communication process from the wing to the air, in essence, says, "Get ready to get out of my way—here I come!" The warning message consists of a pressure signal and, therefore, travels at the speed of sound. When the wing is moving well below the speed of sound, the air has been informed of what to do. As the wing approaches the speed of sound the air has not had sufficient warning and does not act until the wing is much closer than before. At Mach 1.0, the piling up of the communication signals causes the shock wave to form ahead of the wing. The position of this shock wave depends on the bluntness of the wing. When a high Mach number such as 2.0 is reached, the shock wave will be at or near the leading edge of the wing. Also, the air just above and below the wing will not know the wing is coming until it has already passed so the airflow becomes straight-line patterns from shock wave to shock wave. Since the thin, straight wing of the STARFIGHTER utilizes sharp leading edges, the wing literally knifes through the air at high speed and pays minimum penalty in drag.



AIRFLOW CHANGE WITH INCREASING MACH

FIG. 2

II. THERMAL LIMITATIONS

Even though the STARFIGHTER is considered as being primarily a Mach 2.0 fighter, there is another limitation that can take precedence. This is the engine air inlet temperature limitation. In channeling the air into the compressor section, the inner chambers have the problem of dissipating large amounts of heat. This heat is generated by the air-compressing function of the inlets and ducts. The dissipation problem causes the engine compressor section to absorb more and more heat until the temperature effects exceed design limits. In flying the STARFIGHTER the temperature limit might be reached in level or climbing flight in the lower regions of the STARFIGHTER'S altitude range, depending on the outside ambient temperature.

For this reason, an instrument called Engine Air Inlet Temperature is in the cockpit. You should observe the red line on the Engine Air Inlet Temperature Gauge at all times. In case you fail to see the Engine Air Inlet Temperature as it goes past the red line, a flashing warning light on the forward panel will come on when the design limit is reached or exceeded. This flashing warning light indicates the word "SLOW," telling you to slow the aircraft until the engine air inlet temperature is below design limits. Constant work is being done to raise this thermal limit, but the fact must be recognized, the STARFIGHTER is more than capable of pushing itself to this thermal region of flight. Therefore, the STARFIGHTER is considered as the first thermosonic fighter.

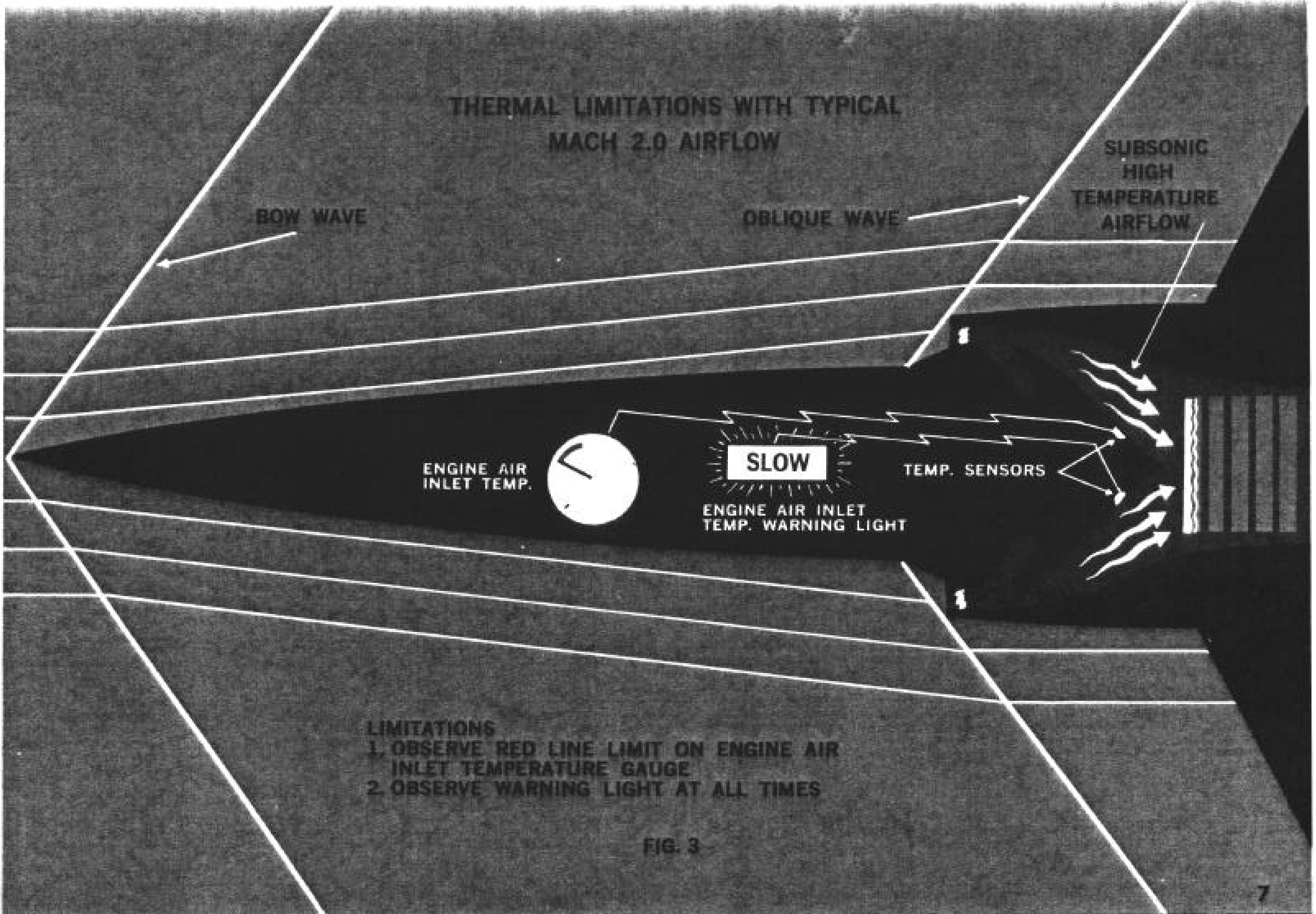

THERMAL LIMITATIONS WITH TYPICAL MACH 2.0 AIRFLOW
BOW WAVE
OBLIQUE WAVE
SUBSONIC HIGH TEMPERATURE AIRFLOW
ENGINE AIR INLET TEMP.
SLOW
ENGINE AIR INLET TEMP. WARNING LIGHT
TEMP. SENSORS
LIMITATIONS
1. OBSERVE RED LINE LIMIT ON ENGINE AIR INLET TEMPERATURE GAUGE
2. OBSERVE WARNING LIGHT AT ALL TIMES

FIG. 3

III. CONFIGURATION

The configuration of the STARFIGHTER is undoubtedly the most unique of any of the Century series. The accompanying sketch *(Fig. 4)* shows these features. Advantages of this configuration are (1) minimum drag, (2) high maneuverability and (3) stable weapons platform at all speeds. It's hard to delineate the purpose of each feature since they all complement one another but a quick description follows:

CONFIGURATION FEATURES OF THE STARFIGHTER

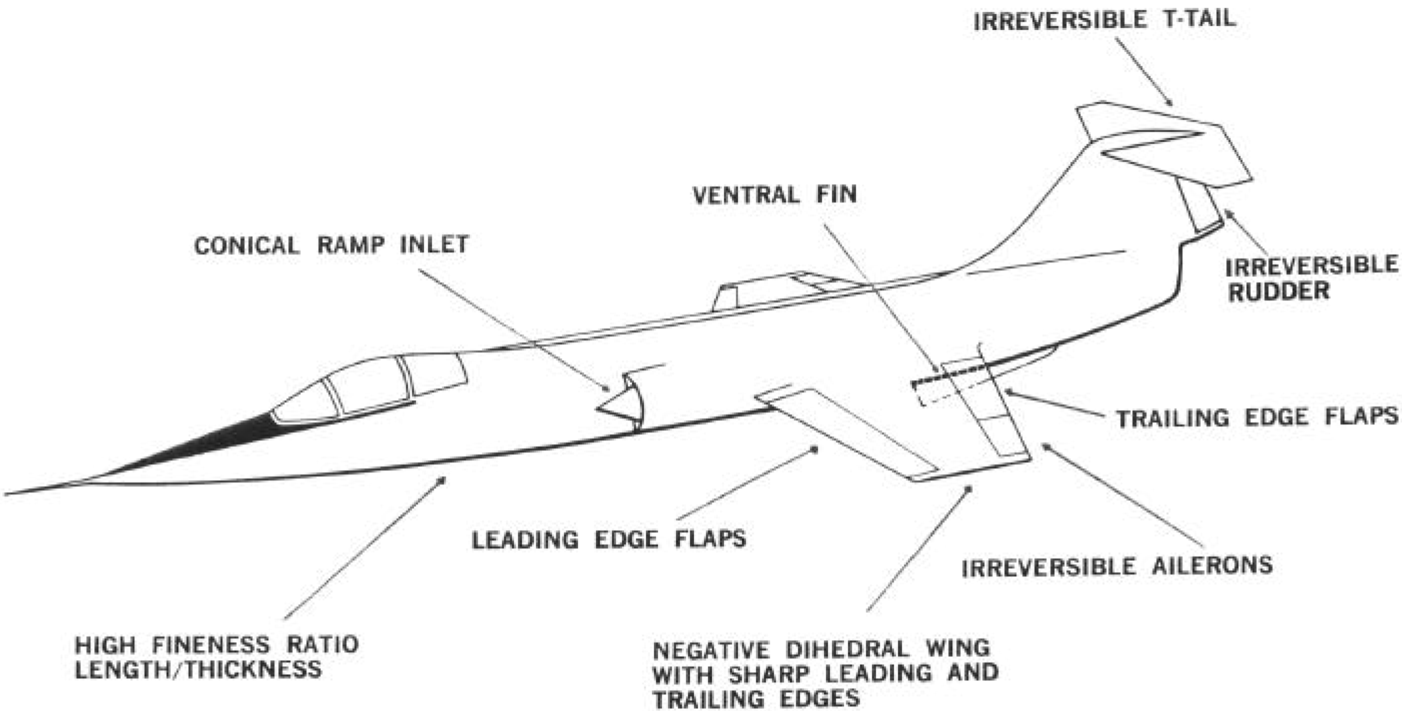


FIG. 4

A. THIN AIRFOILS

The thin surfaces primarily reduce the drag. In reducing the drag, less thrust or energy is required to accelerate the STARFIGHTER. Also, as we have stated, the sharp leading edges slice through the air and eliminate the various Mach number effects, such as buffeting and tucking.

B. HIGH TAIL POSITION

The high tail position was selected during the preliminary design stage after extensive wind tunnel tests. These tests proved that the high location was necessary to obtain optimum stability and control about the pitch axis throughout the wide Mach range. The position also results in a minimum of transonic trim changes when accelerating to supersonic. By moving the high tail rearward on the vertical stabilizer, interference drag was reduced appreciably. This saving in drag amounts to several thousand feet in ceiling and considerable fuel saved during accelerations.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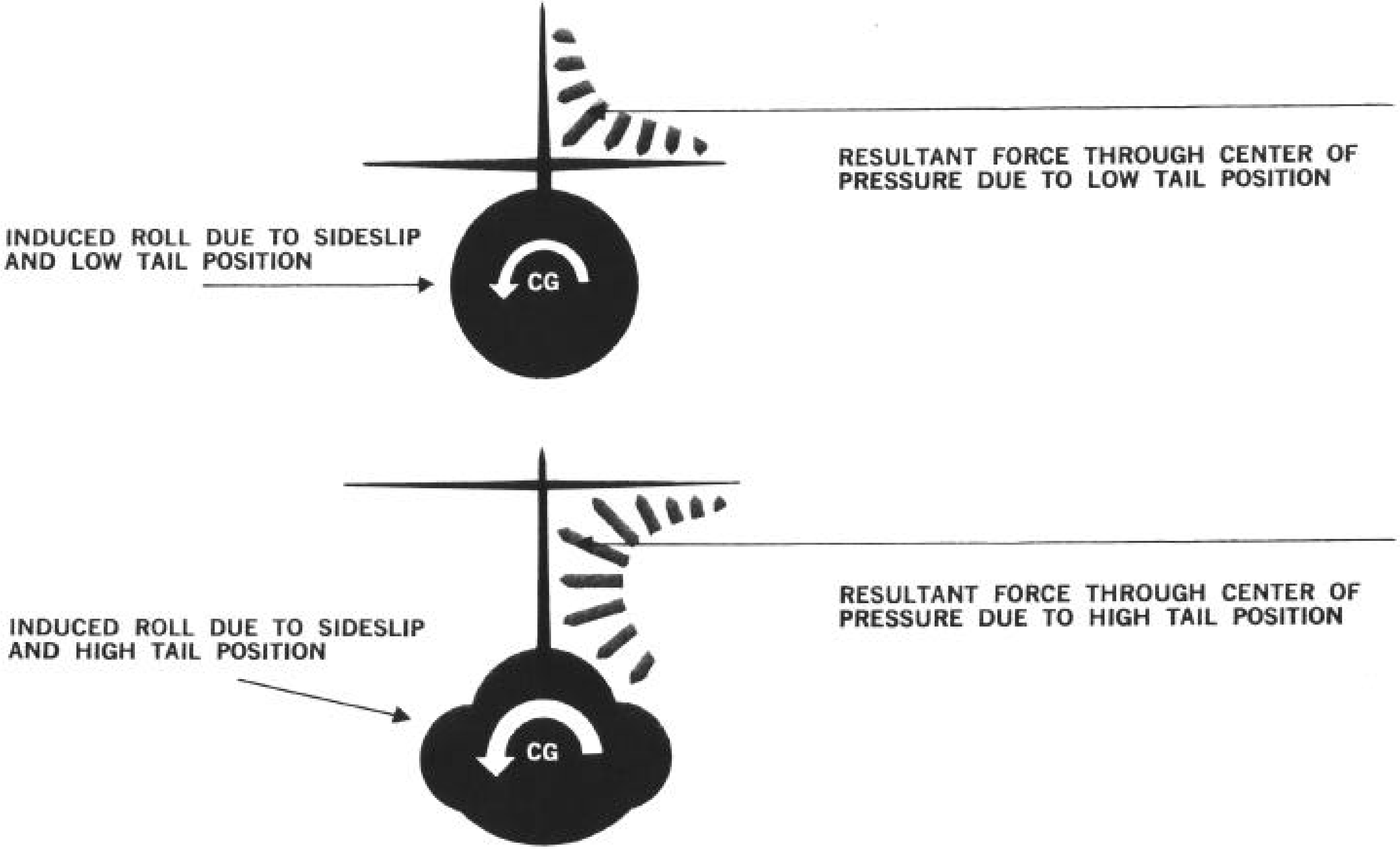
C. NEGATIVE DIHEDRAL

At the time of selecting the T-Tail configuration, the design engineers knew that they would have to put negative dihedral in the wings. This was simply because the high tail position of the horizontal stabilizer raised the center of pressure. A comparison of pressure profiles *(Fig. 5)* over a low and high tail position portrays this shift in center of pressure. In case it's not quite clear, let's review what the aerodynamicists call dihedral effect. Past experience has told us that whenever we sideslip an aircraft, a rolling moment is induced which resists the sideslip. This induced rolling moment is generally termed dihedral effect. Looking at our low tail and high tail configurations, it can be seen that with any sideslip, the restoring force acting through the center of pressure does not act through the C.G. of the aircraft. Therefore, a sideslip condition actuates the restoring force on the tail but at the same time induces a roll. Since the induced roll in this case is resisting the original roll we call it a positive dihedral effect. But now that we've raised the tail and consequently the center of pressure the positive dihedral effect has been increased considerably. To decrease the large positive dihedral effect of the tail, tests were made and the wings were then given enough negative dihedral to reduce the overall dihedral effect. Upon flying the STARFIGHTER you will notice that the overall effect is a desirable amount of good positive dihedral.

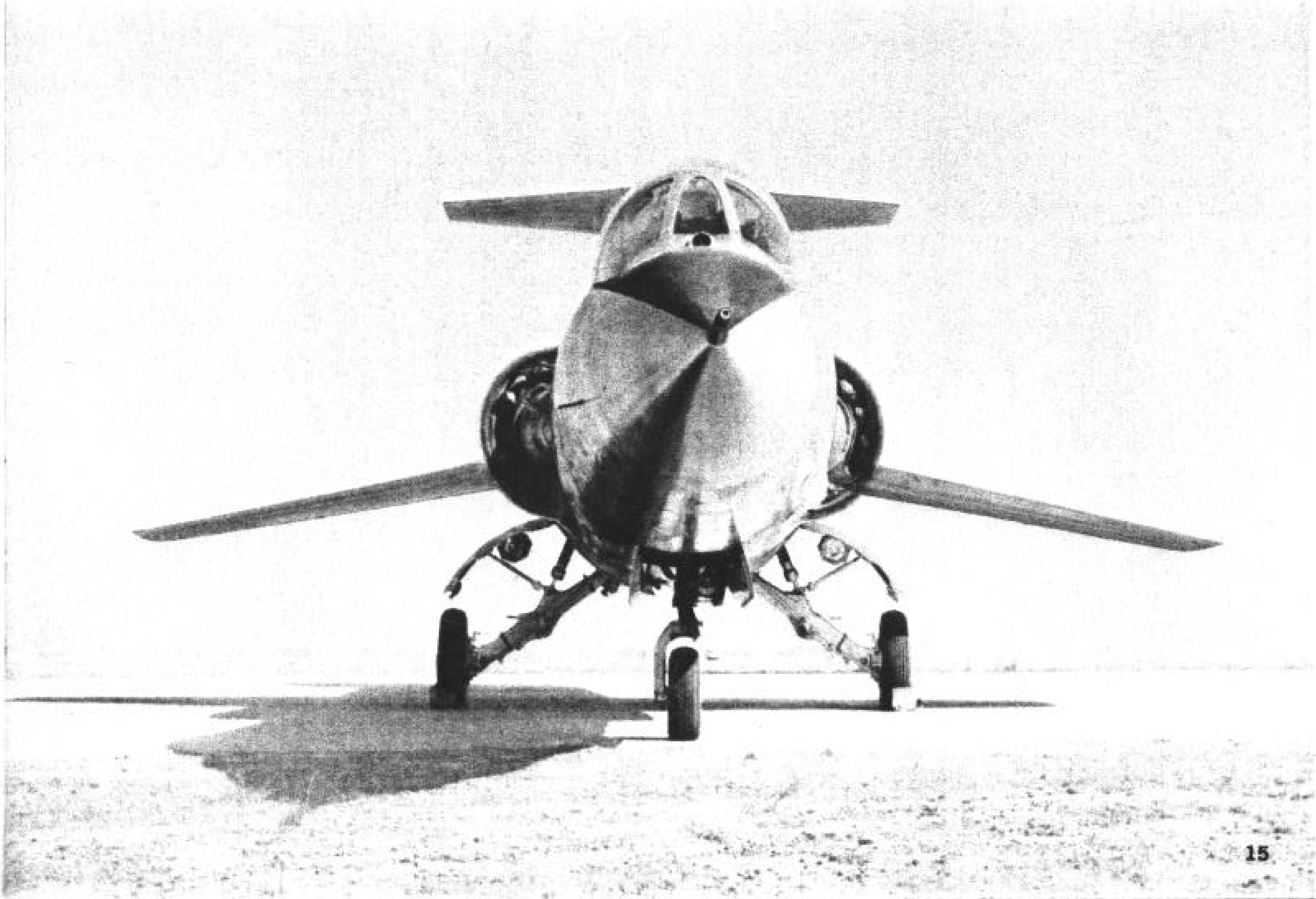


SHIFT IN CENTER OF PRESSURE WITH HIGH TAIL POSITION

FIG. 5

D. SHORT STRAIGHT WINGS

In order to design a wing for the STARFIGHTER, numerous rocket tests were made which disclosed a very important fact. Of all the different types of airfoils attached to the supersonic rockets, data film revealed the short straight wing to have better aerodynamic features. Swept back airfoils required thick chord and long span, with the attendant high drag, in order to give comparable performance as the short straight wing. Also, extreme sweep resulted in deteriorated handling characteristics. The shortness of the wing reduces the extended area and diminishes the drag, but remember, the effective wing area includes the amount of wing buried in the fuselage. With this point in mind, you can see that the wing is more effective than it appears.



E. LEADING AND TRAILING EDGE FLAPS

Designed as integral parts of the wing are precision-hinged, flush-lined leading and trailing edge flaps. These flaps *(Fig. 6)* convert the thin airfoil into a cambered high lift airfoil for take-off and landing. If the flaps are utilized to their full travel, flow separation over the wing will occur at extreme angles of attack. To delay the flow separation, a boundary layer control system using high pressure air blows over the trailing edge flaps through orifices along the flap hinge line. The high velocity boundary layer air greatly reduces the pressure just adjacent to the flaps and entrains the outer level of air causing it to bend through the flap deflection angle. Airflow provided by the BLC system has a large variance from 66% to 100% RPM. Even though the STARFIGHTER has high idling RPM, if you fly the aircraft with BLC, at minimum airspeed and high angle of attack, you must keep the high power setting until close to the runway. Use of the BLC in conjunction with the flaps will substantially lower the approach and landing speeds of the STARFIGHTER.

TYPICAL AIRFLOW OVER STARFIGHTER WING

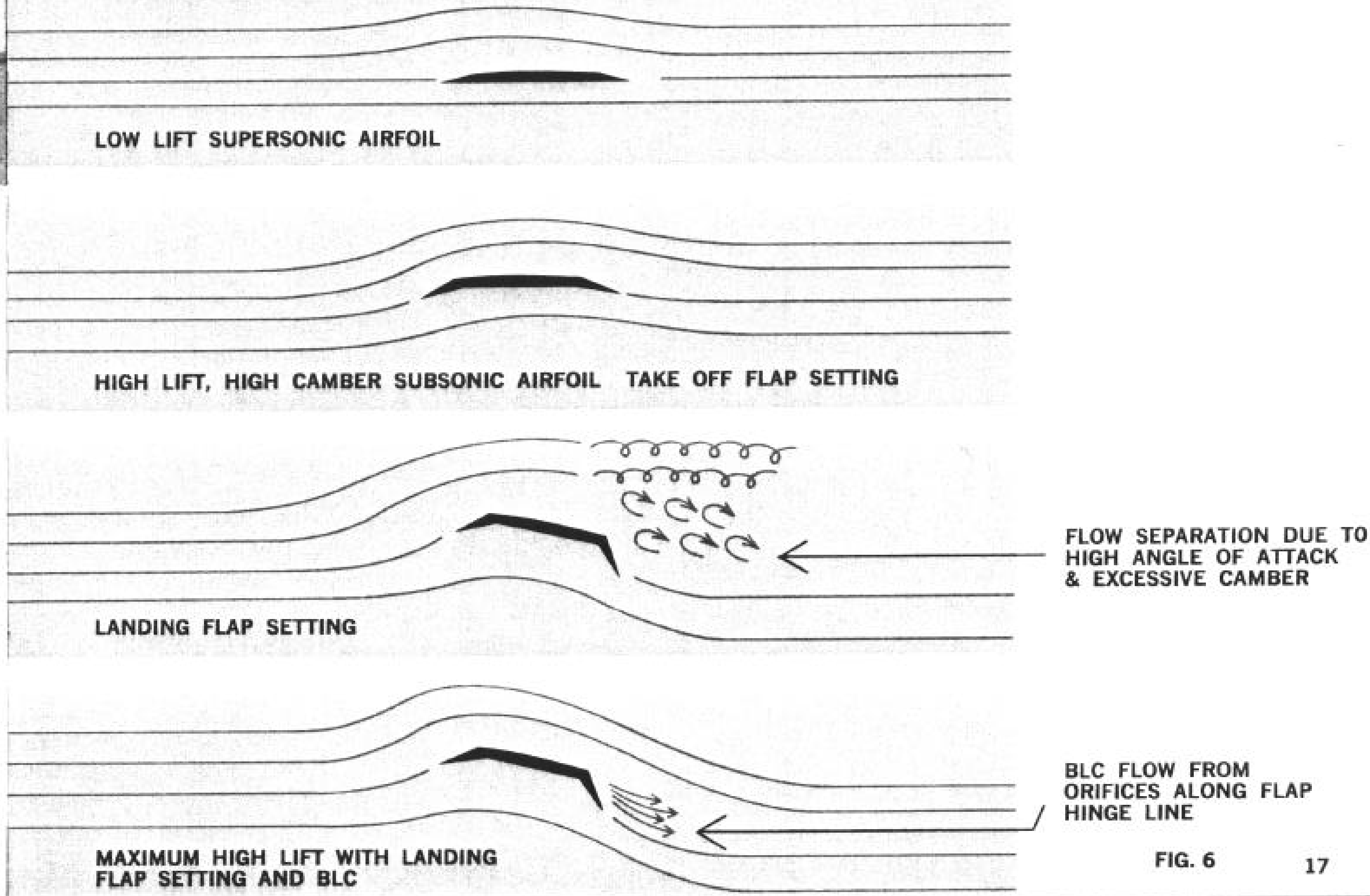
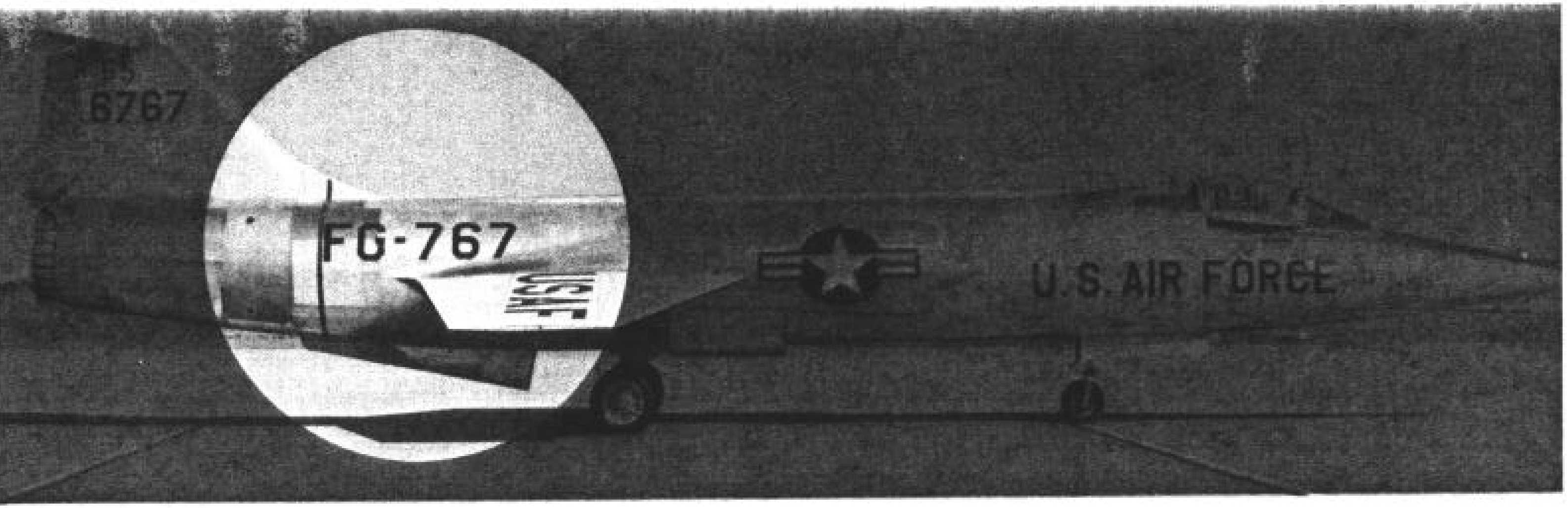


FIG. 6

F. VENTRAL FIN

All modern supersonic aircraft display one main characteristic in common. From around Mach one to peak speed, the directional stability begins to diminish. This is a supersonic airflow problem which requires increasing surface area in the vertical plane to maintain the same amount of directional stability as speed is increased. To obtain the additional area needed in the peak Mach regime, a ventral fin was added below the fuselage of the STARFIGHTER. The ventral fin increased the static directional stability throughout the supersonic regime. A graph *(Fig. 7)* of directional stability shows that at higher Mach numbers, the percentage of stability contribution by the ventral fin becomes more predominate. In flight, the ventral fin acts as a large vortex generator which spoils the circular flow around the fuselage. As the aircraft is yawed, the vortices generated by the fin cause a pressure differential on the fuselage which resists the yaw. The center of pressure of this pressure differential acts just above the ventral fin on the fuselage, therefore part of the fin can be made of plastic for antennas.



EFFECT OF VENTRAL FIN ON DIRECTIONAL STABILITY

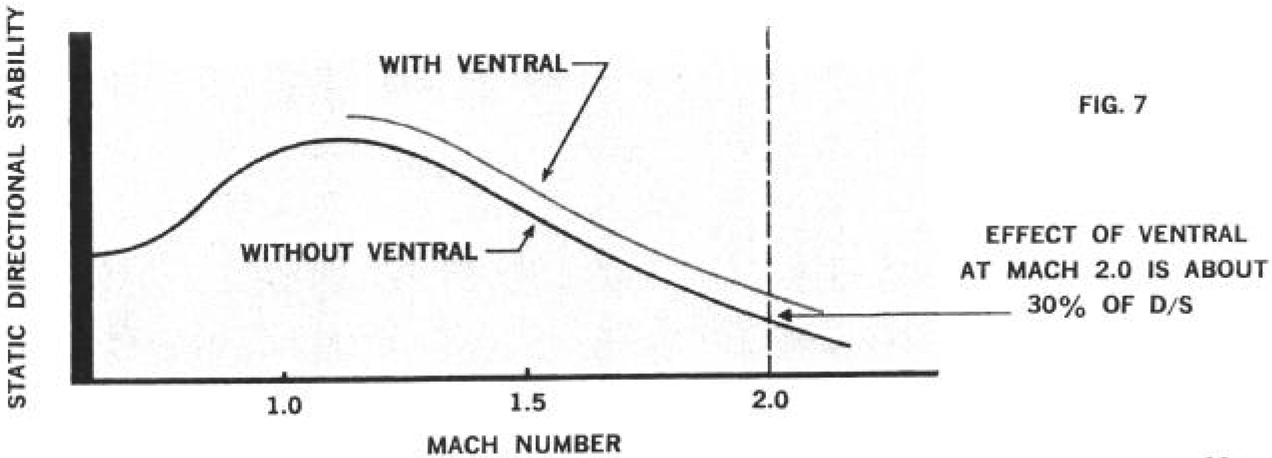


FIG. 7

G. CONICAL RAMP INLETS

In designing for supersonic flight, the powerplant problem becomes formidable, due to air compressibility and the requirement of handling tremendous quantities of air. An outstanding feature of the STARFIGHTER is the matching of engine inlets with the performance of the aircraft. The large size of the inlets reflects the engine airflow requirements while the geometry reflects the design Mach number. The conical ramp projecting ahead of the inlet is to get high ram pressures for the engine at high supersonic speeds. Our illustration *(Fig. 8)* shows how the ramp prepares the air for the inlet by the formation of an oblique shock wave. Behind the oblique wave is the normal wave and these two work in conjunction to efficiently shuttle the air into the engine. It's just like a gearing process. The oblique wave slows the high supersonic air to a low supersonic condition and the normal wave slows the low supersonic air to a subsonic condition. Each step is slowing the air and ramming it into the engine with higher pressures.

One other problem we have is that the size of the inlet required to feed the engine decreases as Mach number increases. Rather than tackle the mechanical complexity of changing inlet area with Mach number, the inlets simply swallow the excess air at high speed and by-pass it around the engine. After serving as engine cooling, the excess air is ejected with engine exhaust so that minimum penalty is paid for taking aboard and handling the excess air.

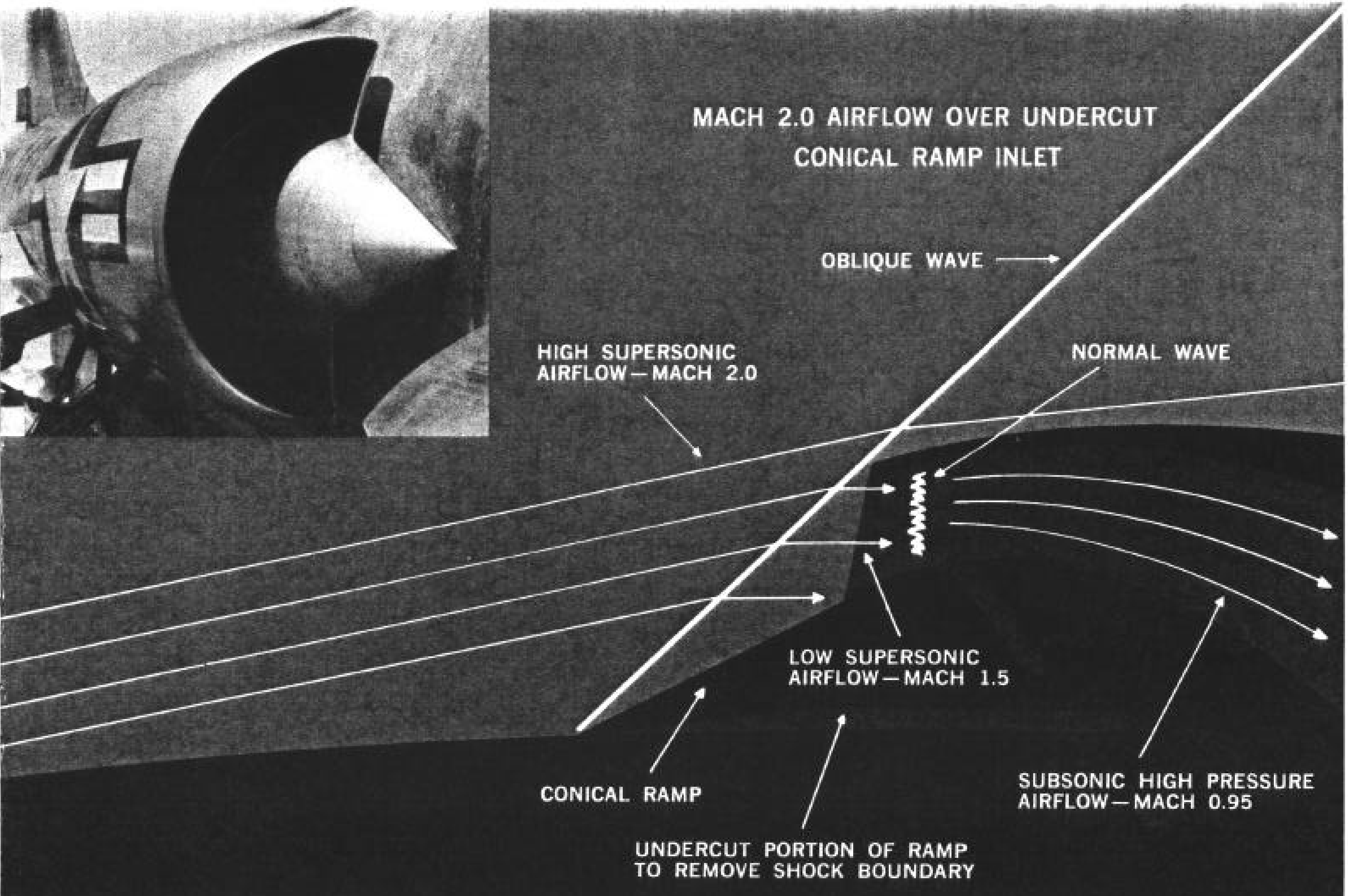
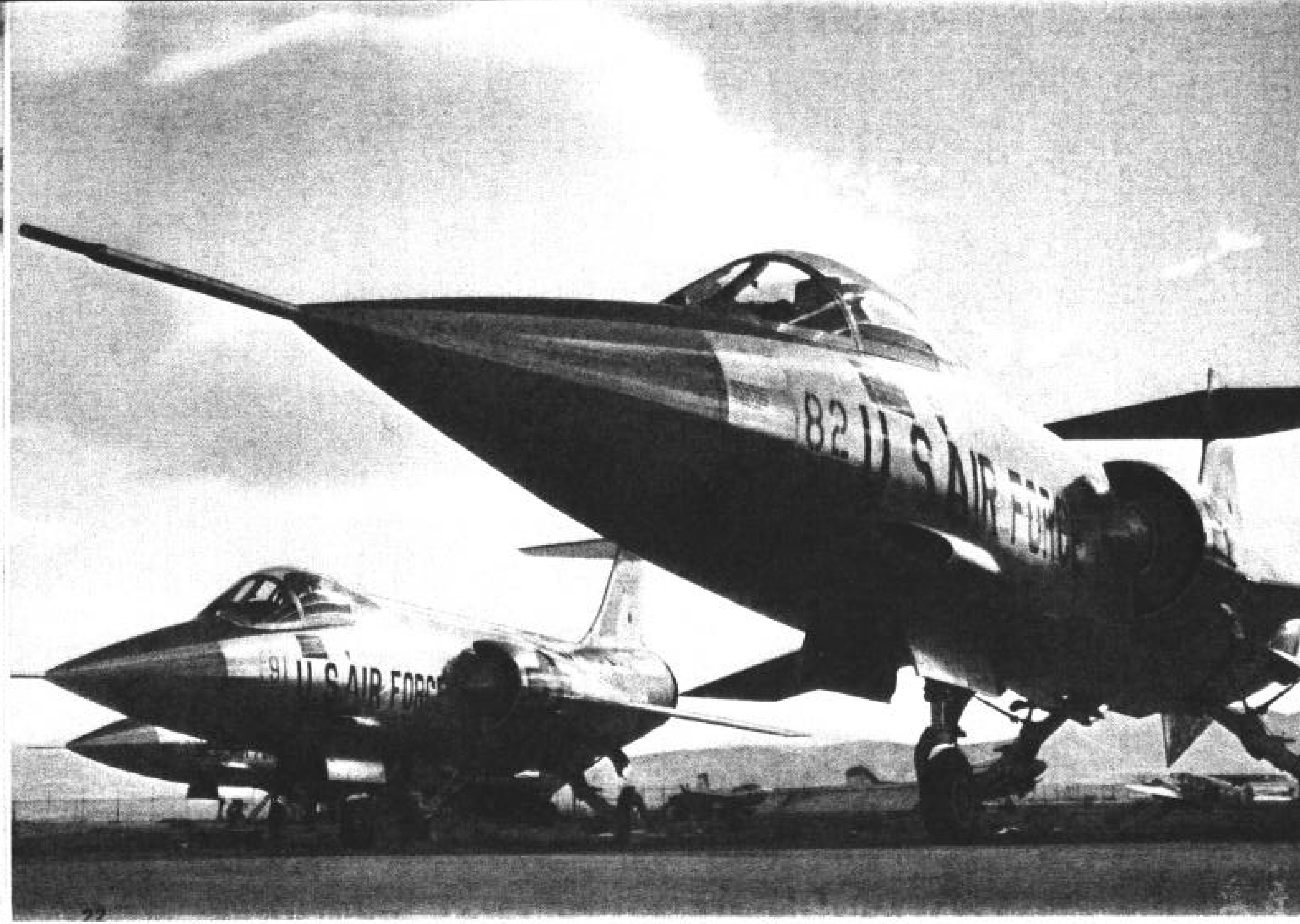

MACH 2.0 AIRFLOW OVER UNDERCUT
CONICAL RAMP INLET
OBLIQUE WAVE
HIGH SUPERSONIC
AIRFLOW—MACH 2.0
NORMAL WAVE
LOW SUPERSONIC
AIRFLOW—MACH 1.5
CONICAL RAMP
SUBSONIC HIGH PRESSURE
AIRFLOW—MACH 0.95
UNDERCUT PORTION OF RAMP
TO REMOVE SHOCK BOUNDARY

FIG. 8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IV. CONTROL SYSTEMS

We can't escape it, men. As new fighters are designed and built to go ever faster and higher, new ideas and refinements come into being. Of course, these systems are all designed to carry out one important task—that of making the fighter a stable weapons platform at all speeds. To realize this objective throughout the broad performance band of the STARFIGHTER, an irreversible control system with stability augmentation is utilized. Also, a device called Automatic Pitch Control has been incorporated to extend the pilot's maneuvering range.

A. IRREVERSIBLE CONTROLS

The STARFIGHTER has irreversible hydraulically powered controls on the ailerons, horizontal stabilizer and rudder. What do we mean when we say irreversible in relation to the flight control system? Simply that the air loads encountered by the control surfaces during deflection cannot be fed back through the flight control system to the stick and rudder pedals and felt there by the pilot. The necessity for irreversible controls in order to obtain precise handling characteristics can be seen from the pressure distribution on the horizontal stabilizer at various speeds. As our illustration *(Fig. 9)* shows, the pressure distribution changes as the speed is increased from subsonic to supersonic. The component of force resulting from this shift in pressure distribution moves aft and thus for the same unit load requires a proportionately higher moment to deflect the control surface. The required moment is in excess of what you can easily exert so the irreversible system is necessary for fast maneuvering in supersonic flight.

A spring and the bob weight effect of the stick provides artificial feel. Although the ailerons and horizontal stabilizer are irreversible, they still have full trim control by positioning the control surface without moving the stick. Therefore, the stick remains centered while trimming the aircraft for any phase of flight.

The rudder on the STARFIGHTER is fully powered and irreversible. For taxiing, the rudder is tied in with the nose wheel steering. During taxiing you will note that you have full throw or maximum nose steering effect. After you are airborne and the gear is up, the allowable rudder travel is greatly restricted. This engineering design is a safety feature to prevent excessive deflections during supersonic flight that might exceed the allowable sideload on the vertical stabilizer and high T-tail. However, there is ample rudder deflection for all desired maneuvers. Yaw trim is accomplished by using the entire rudder and is therefore very effective. In the supersonic regime, it is recommended that yaw trim be used immediately as it becomes needed. If a yaw condition is allowed to build up, it seems to take more trim than if trim is applied at once.

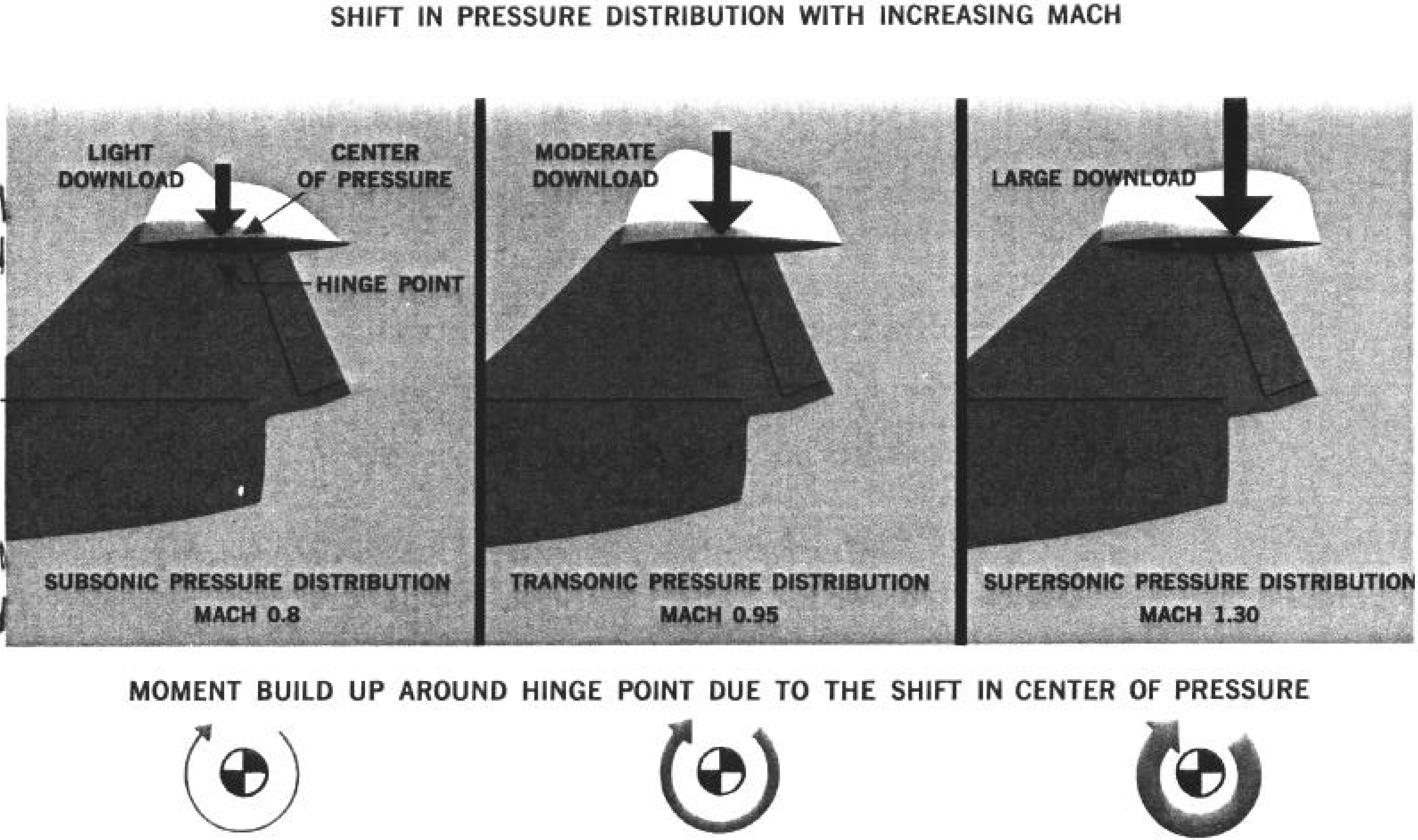
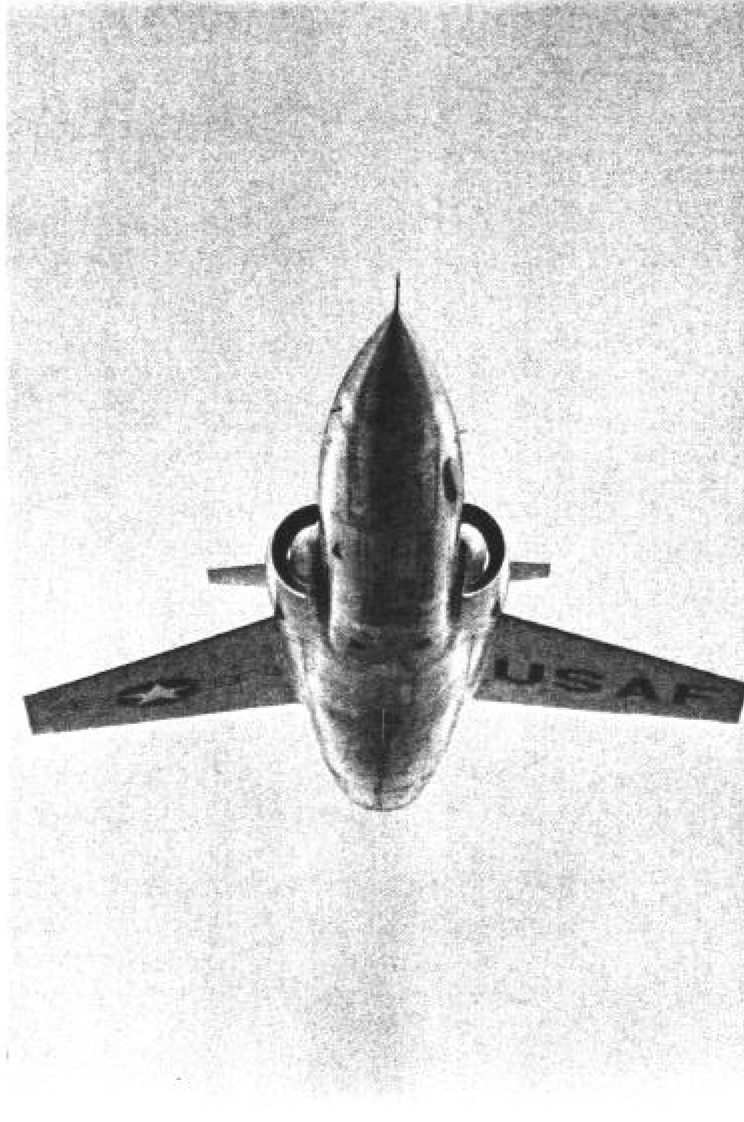

SHIFT IN PRESSURE DISTRIBUTION WITH INCREASING MACH
LIGHT DOWNLOAD
CENTER OF PRESSURE
HINGE POINT
SUBSONIC PRESSURE DISTRIBUTION
MACH 0.8
MODERATE DOWNLOAD
TRANSONIC PRESSURE DISTRIBUTION
MACH 0.95
LARGE DOWNLOAD
SUPERSONIC PRESSURE DISTRIBUTION
MACH 1.30
MOMENT BUILD UP AROUND HINGE POINT DUE TO THE SHIFT IN CENTER OF PRESSURE

FIG. 9

B. STABILITY AUGMENTATION SYSTEM

The STARFIGHTER has excellent stability and has been flown to its speed and altitude limits without the assist of any additional stability system. But as we explained before, in supersonic flight the flow pattern is from shock wave to shock wave. This means that the pilot is physically unable to compensate for the small random variations that occur, because human reactions are not as fast as mechanical reactions. An automatic control system, on the other hand, is ideally suited to supply the corrective action required for stability augmentation. The response and sensitivity of an automatic control system can be made to exceed that of a pilot and, therefore, requires but a limited range of action with the control surfaces of the aircraft. In operation then, the three-axis stability system senses



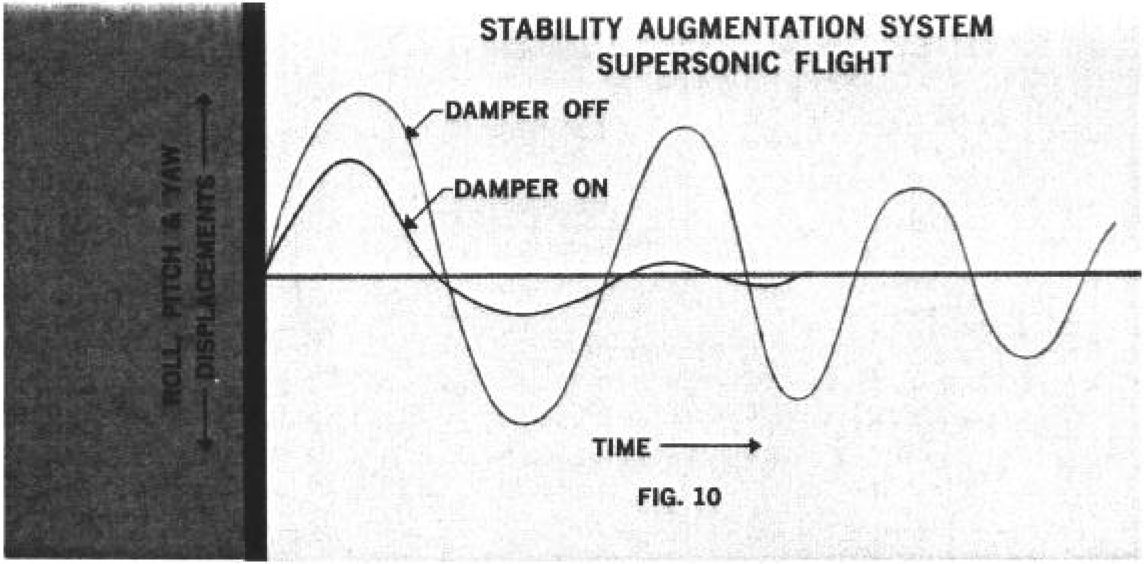


FIG. 10

undesired motion of the aircraft in roll, pitch and yaw and makes rapid precise corrections to eliminate the motion. Our graph *(Fig. 10)* of a small displacement in supersonic flight readily shows the increased damping using the three-axis damper system. In normal flight, then, the ailerons, horizontal stabilizer and rudder are constantly making small, finite deflections to smooth out the flight.

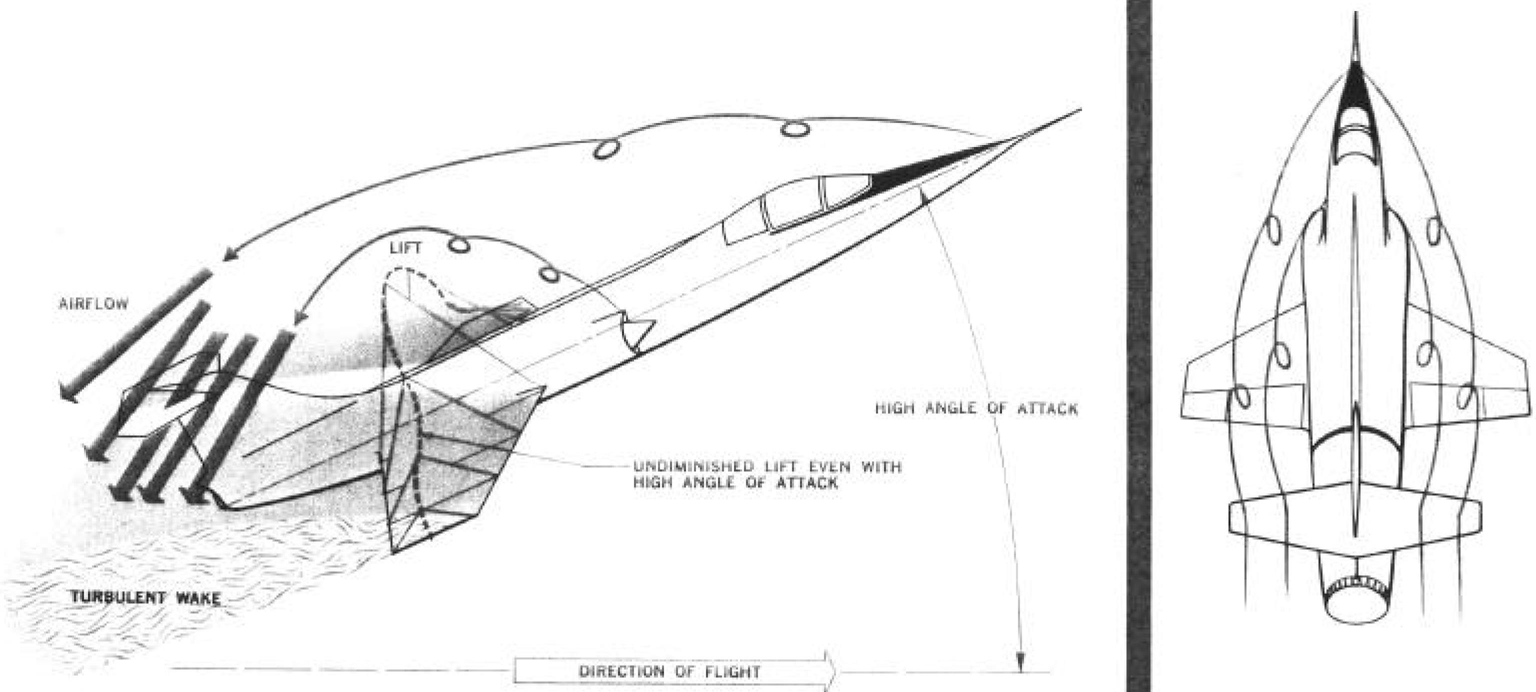
The three-axis damper system, however, does not interfere in any detrimental manner with the pilot-actuated maneuvers. Also, failure of the damper system does not prohibit the STARFIGHTER from being flown in any type of operation but the flight will probably not be as smooth as desired. With the damper system operating, the end result is a rock-steady weapons platform in all combat phases.

C. AUTOMATIC PITCH CONTROL

The undesirable maneuver called "pitch-up" is one of the aspects of supersonic flight we mentioned previously that should be understood by pilots of the STARFIGHTER. Pitch-up comes from a number of general supersonic design characteristics and some specific design configuration items in regard to the STARFIGHTER. Any supersonic aircraft design continues to fly at angles of attack greater than subsonic designs because of the undiminished lift characteristic. The lift produced by the STARFIGHTER does not decrease as angle of attack goes up to above the stall *(Fig. 11)* but instead continues to increase. In this case *(Fig. 11)* the undiminished lift characteristic can carry the aircraft into an extreme angle of attack condition where the horizontal stabilizer is acted upon by all the airflow vortices and wing downwash. With this combination, the STARFIGHTER will pitch-up instead of down when the full-stalled condition is reached.

To prevent the aircraft from getting into a pitch-up condition, the Automatic Pitch Control (APC) is utilized. The APC senses pitch rate and angle of attack and prevents penetration into the flight area where pitch-up would be encountered. Our illustration *(Fig. 11-a)* of the APC envelope shows how the stick shaker and stick kicker will allow you to fly the STARFIGHTER to its maximum useful performance.

FIG. 11 AERODYNAMIC FORCES RESPONSIBLE FOR PITCH-UP



Typical Variation of F-104 Pitching Moment with Angle of Attack Showing Point of Auto Pitch Control Operation

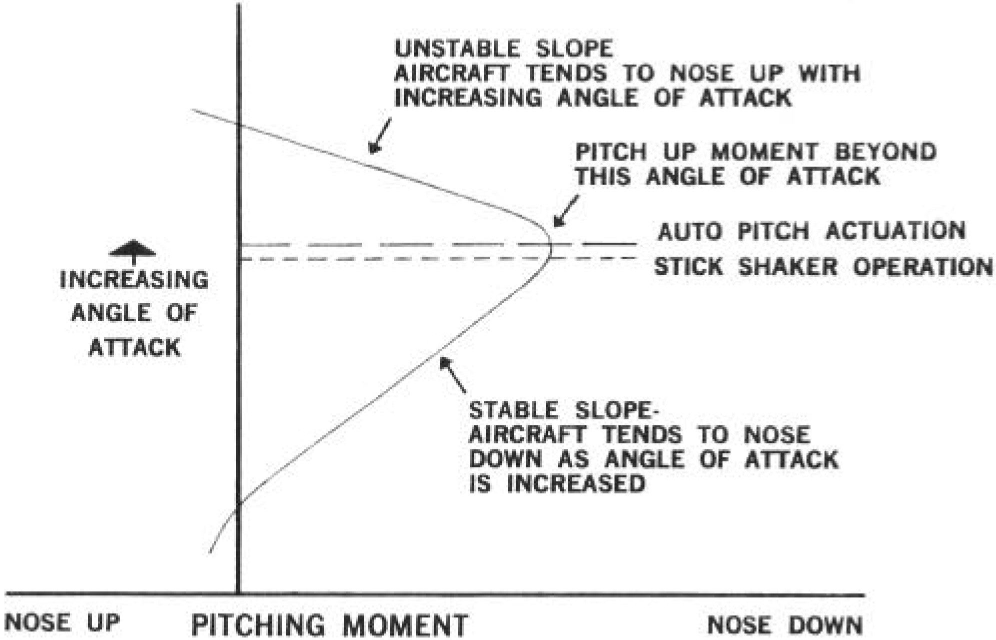
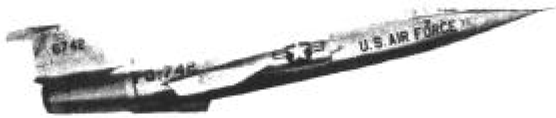
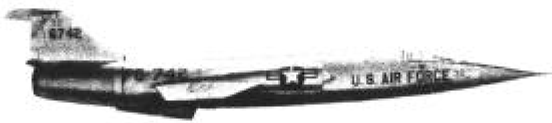


FIG. 11A





V. THRUST AND DRAG

An understanding of the thrust and drag relationship of the STARFIGHTER is necessary in knowing the performance capabilities. With this in mind, a close scrutiny of the family of curves *(Fig. 12)* depicting thrust and drag at various altitudes is in order. The difference between the thrust and drag curves, T-D, is the excess thrust available for developing rate of climb and accelerating to higher speeds. Where the thrust and drag curves cross or intersect are points where the thrust and drag are equal and where speed and altitude stabilize. At low altitude and in the transonic speed range the drag rises rather steeply and requires a relatively high level of thrust to attain supersonic Mach numbers. This is the old compressibility drag rise that has held back aircraft speeds for some time. At intermediate altitude and maximum thrust, however, the thrust exceeds the drag over the complete Mach spectrum. Since excess power is excess thrust, T-D, multiplied by velocity, (T-D)V, we can see from the curves that there is more excess power available at high supersonic speeds than subsonic. The result is that higher rates of climb and aircraft ceiling are available at the high speeds. In other words, maximum performance is obtained at high supersonic Mach. The thrust and drag curves also show that the highest "power limited" ceiling exists at high supersonic Mach because it is in this speed range *only* that thrust exceeds the drag at the higher altitudes. Remember that "power limited" ceiling is where you have some amount of excess thrust so that you can maintain

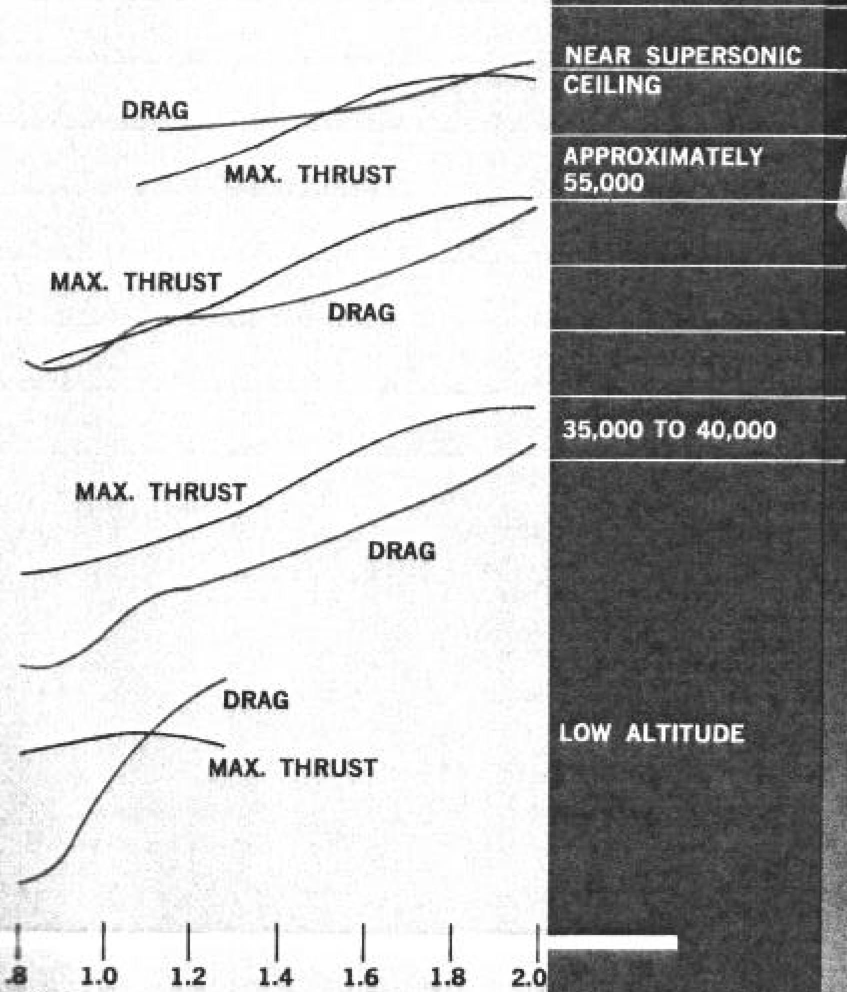
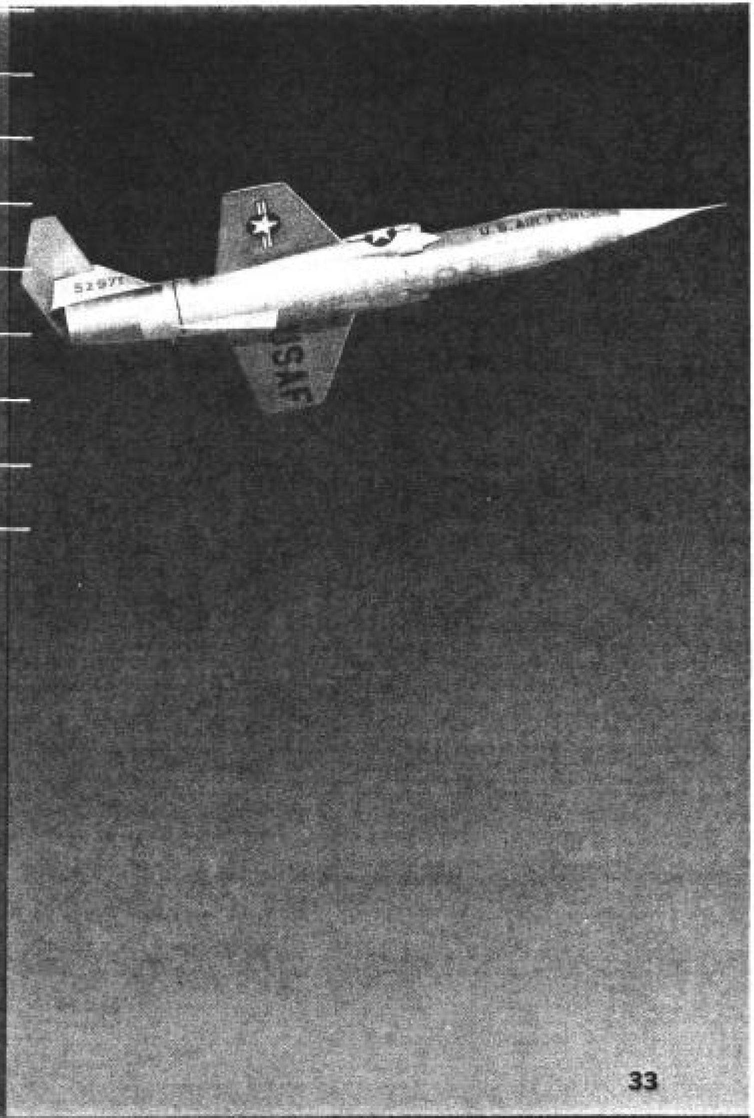

NEAR SUPERSONIC CEILING
DRAG
MAX. THRUST
APPROXIMATELY 55,000
MAX. THRUST
DRAG
35,000 TO 40,000
MAX. THRUST
DRAG
DRAG
LOW ALTITUDE
MAX. THRUST
.8
1.0
1.2
1.4
1.6
1.8
2.0
MACH NUMBER

FIG. 12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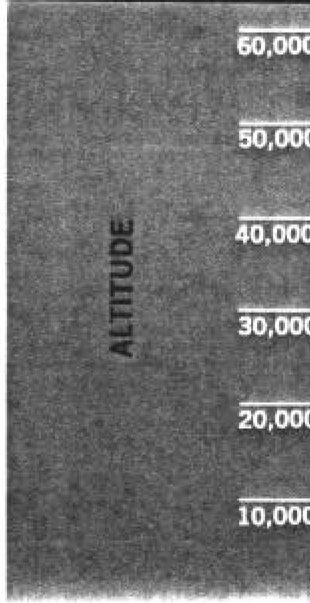
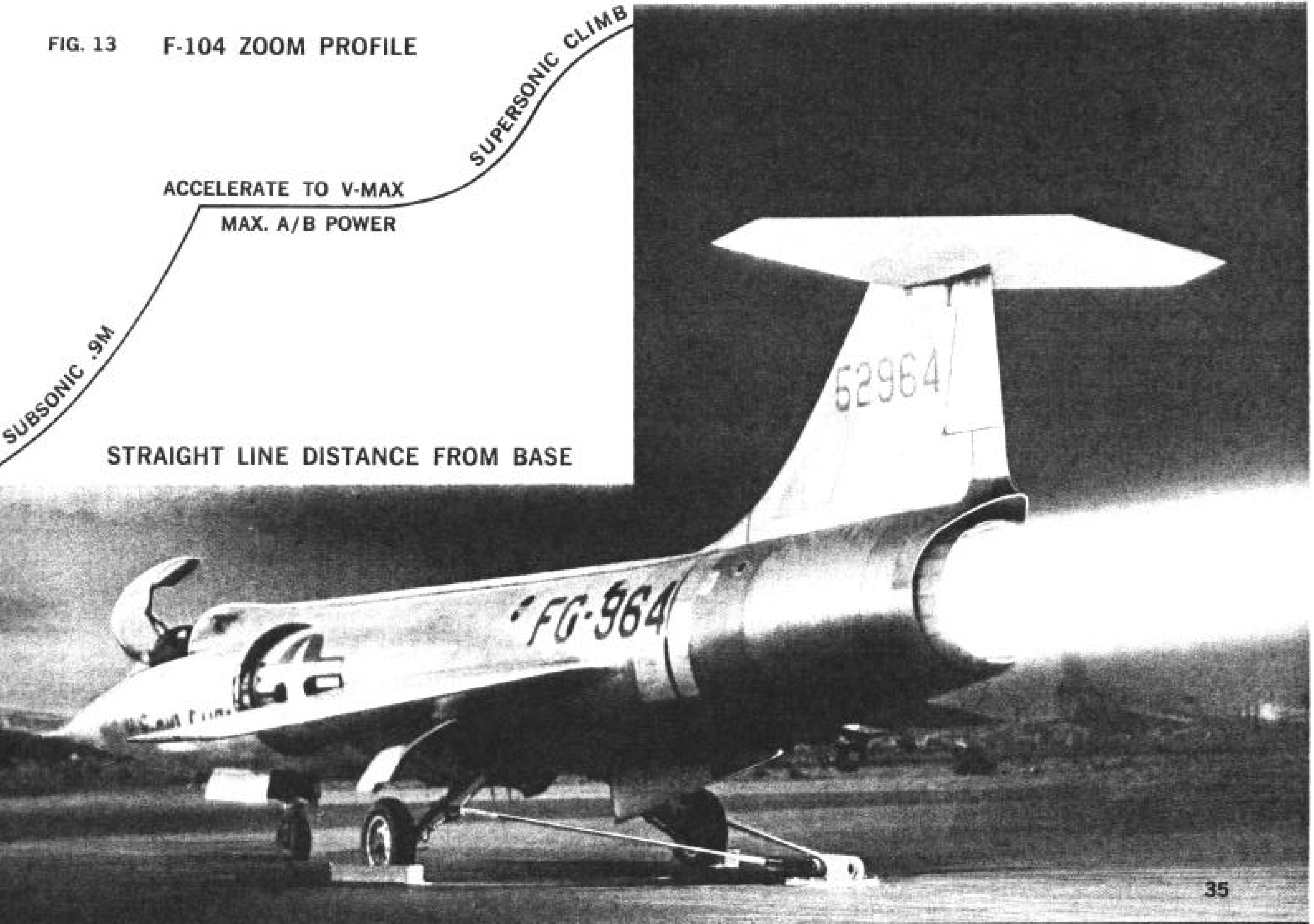
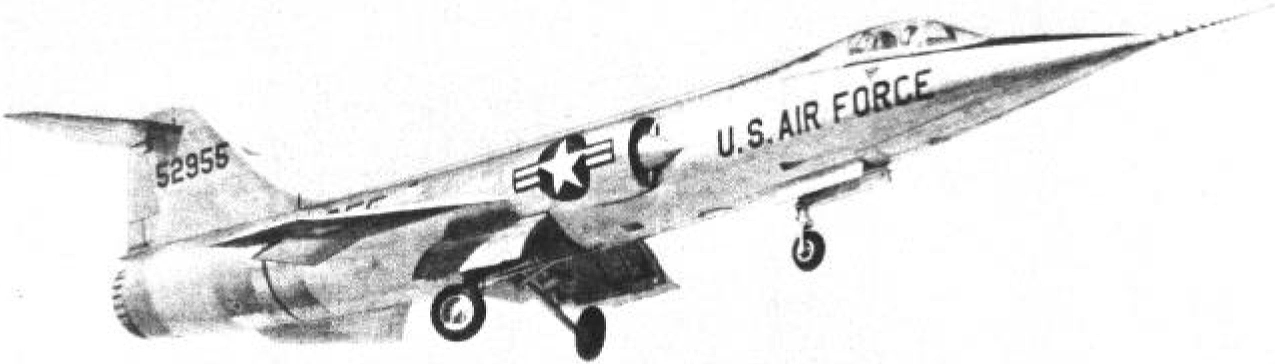
altitude without exchanging speed. To attain this ceiling, the aircraft must accelerate to the high Mach at some altitude where there is sufficient excess thrust at all speeds. The curves show that this is from 35,000 to 40,000 feet, depending on the ambient temperature. After you have accelerated at this altitude you can climb the aircraft up to the "power limited" ceiling and maintain this ceiling. If you do a great amount of maneuvering though, and in so doing decrease the airspeed back around Mach 1.1, you will not be able to maintain altitude without a further exchange of speed. In this situation, the only thing to do is to drop back down to an altitude where you can again accelerate. Since this is impractical in most cases from the fuel required standpoint, the high Mach and high altitude portion of a flight must be carefully pre-planned. For planning a flight of maximum altitude, the zoom profile should be closely followed. A perusal of this profile *(Fig. 13)* will disclose some interesting facts. A subsonic climb at .9 Mach to the acceleration altitude is the best because of climb rate



available and fuel used for climb. At the acceleration altitude which has been determined by winds aloft and ambient temperature, maximum A/B should be used to accelerate to highest allowable velocity. After attaining V-Max, a rotation of the aircraft to about 45° will give the highest rate of climb available. For a better understanding of this technique, let's go to the flight performance envelope.

FIG. 13 F-104 ZOOM PROFILE





VI. FLIGHT PERFORMANCE

Now that we understand the thrust and drag curves let's see how all this adds up in terms of the overall performance envelope of the STARFIGHTER. By Performance Envelope *(Fig. 14)* we mean the boundaries of flight limitations and aircraft capabilities which define the operational speed and altitude spectrum of the aircraft.

The curve defining the Military Power Envelope is essentially similar to that for aircraft prior to the current Century Series of supersonic aircraft except that maximum level flight speeds close to and slightly above Mach

F-104 FLIGHT ENVELOPE

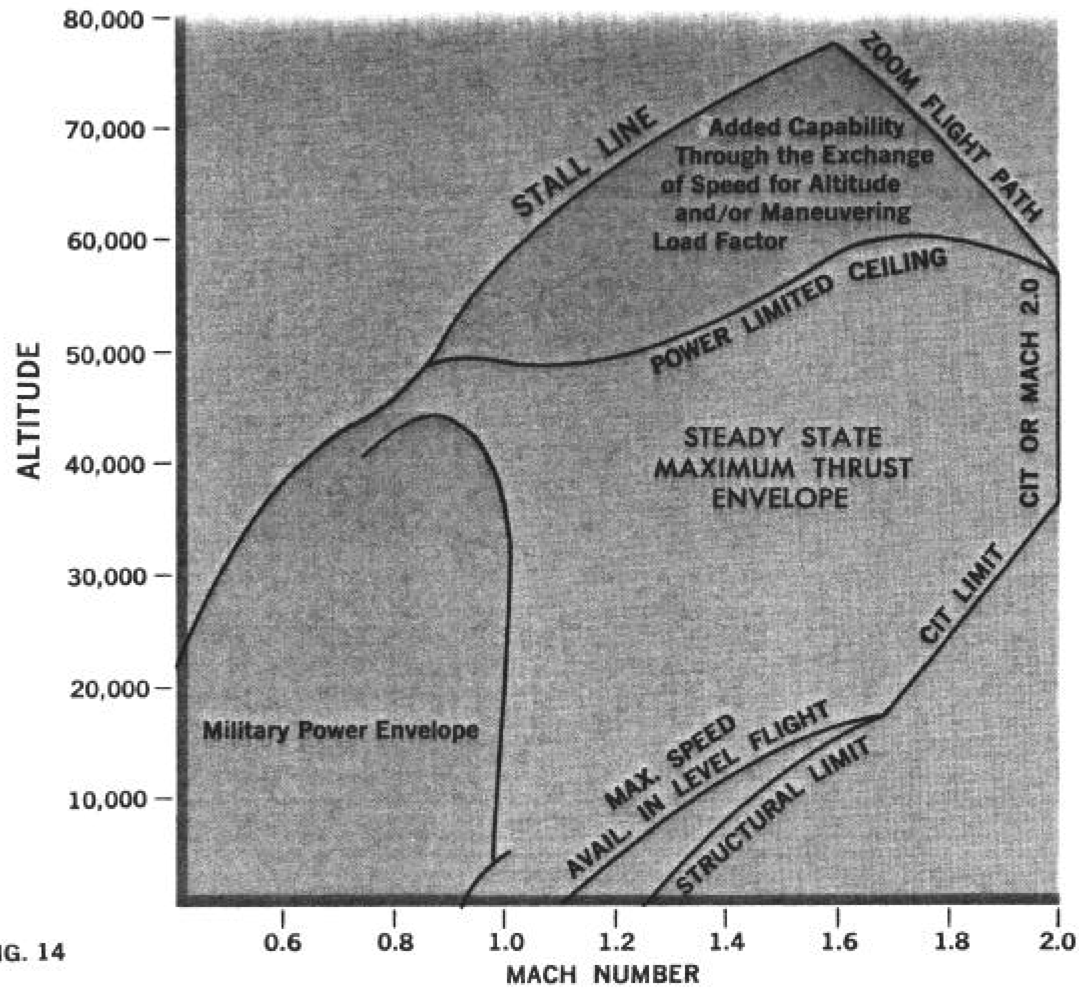
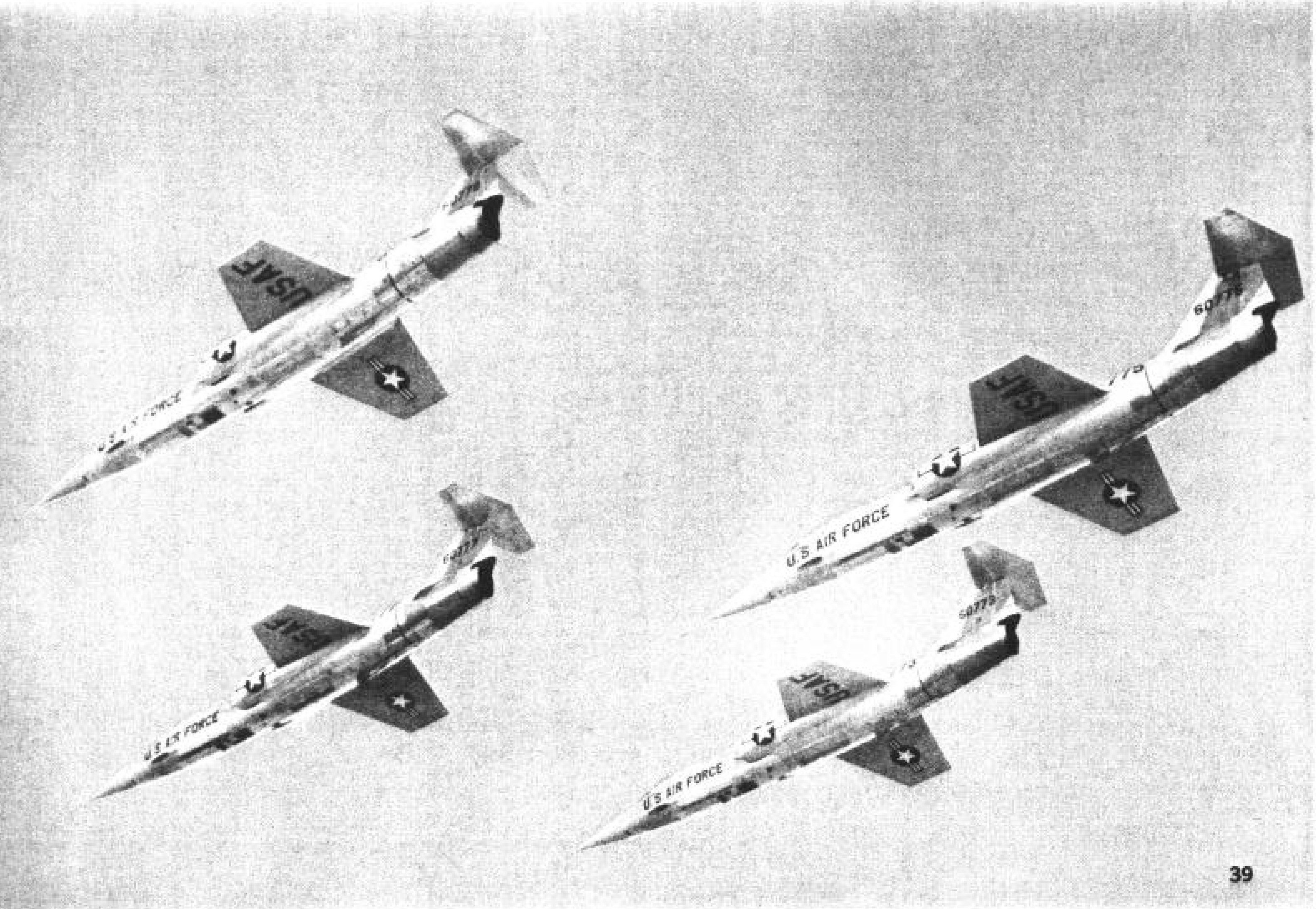


FIG. 14

1.0 are possible. The maximum power spectrum, however, exemplifies the considerable expansion accomplished by the STARFIGHTER'S aircraft and engine combination. The maximum level flight or dive speed capabilities are one and the same over most of the altitude range and are limited not by power but by design limitations on the engine and the airframe. In this region, the STARFIGHTER can, within power and load factor limitations, climb, dive, accelerate and maneuver in the same manner as aircraft you are accustomed to flying. Going on up in altitude, now, notice how the power limited ceiling reflects the shape of the drag curves previously discussed and illustrates the increase in aircraft ceiling with high supersonic Mach numbers. The top curve illustrates the increased envelope made possible by virtue of the high speed of the STARFIGHTER. Let's discuss this concept a little further. When we arrive at our "power limited" ceiling, at any speed, this means that the thrust and drag are equal and there isn't any excess power to climb higher. Steady straight flight is possible but maneuvering results in an exchange of speed for altitude if altitude is maintained. Heretofore this occurred at subsonic speed and all the aircraft could do was stagger around on the ragged edge of the stall.

However, an investigation of the Mach 2.0 and 40,000 foot point of our performance envelope shows some remarkable performance due to our high level of energy. At this point, there exists an excess of around 14,000 thrust horsepower which can be traded for work. This exchange will be roughly about .1 Mach for each 4,000 feet of altitude. So, an exchange from Mach 2.0 down to Mach 1.0 should yield another 40,000 feet to put you around 80,000 feet. Becoming familiar with the zoom technique is all-important in attaining utilization of the most important area of the envelope—from 40,000 to above 90,000 feet.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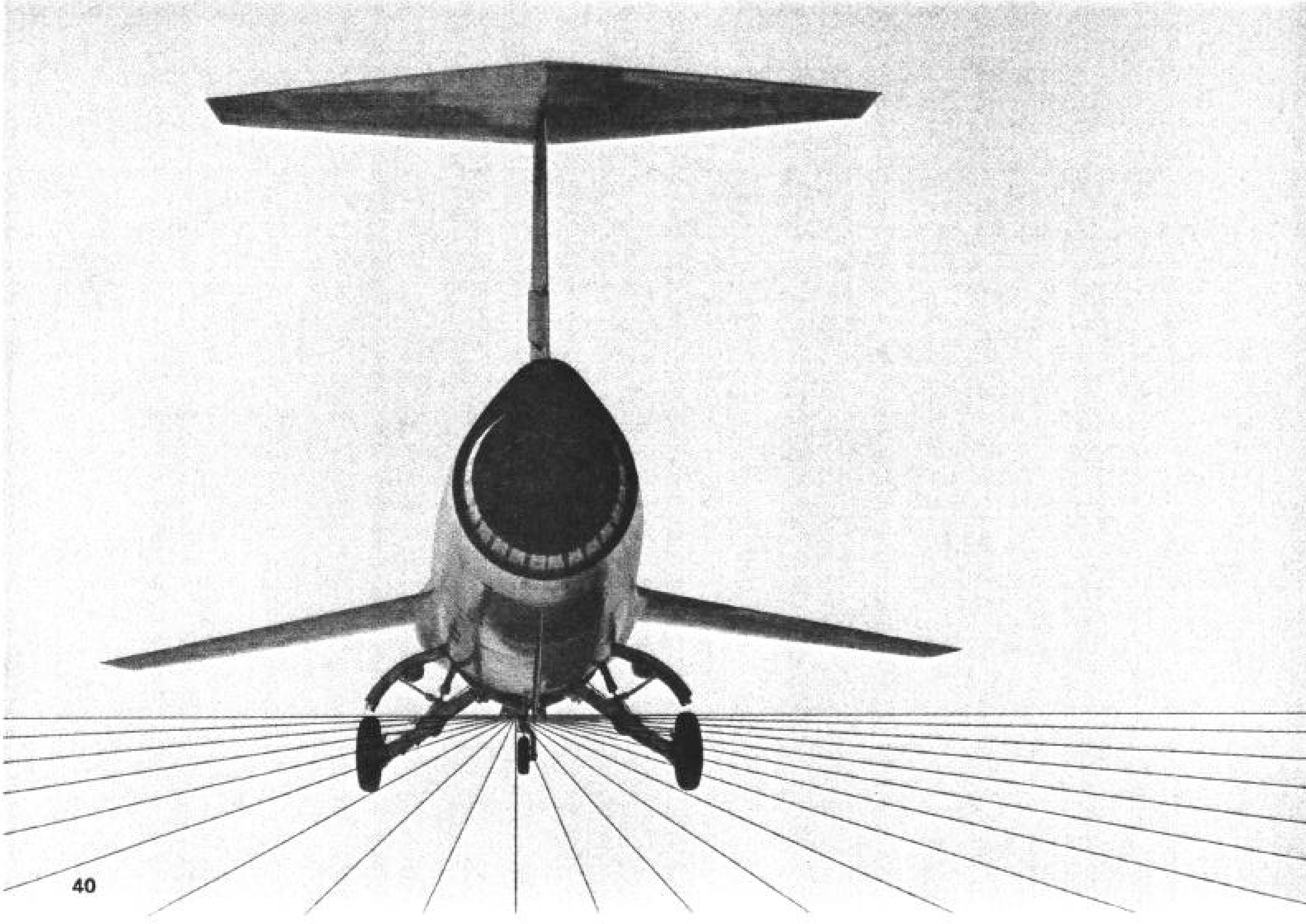


VII. FLIGHT CHARACTERISTICS

A. GENERAL

Now you're ready for the most important flight of your life. Since the STARFIGHTER will accelerate beyond some pretty wild dreams there are a couple of things to be aware of. Upon getting set to release the brakes on that first flight—be sure you're lined up with the runway. As you start to roll—light the afterburner in the first sector and then go to full A/B. A rolling A/B light is best because the brakes just can't hold all that power. On the initial roll a very slight torque effect will be noticed, but nose wheel steering will easily control this. Above 70 knots ground speed, rudders may be used if necessary for directional control. The nose will have to be lifted off, but once the take-off attitude is established—you're on your way. After lift-off and the gear has been raised—you will quickly accelerate to flap speed. A slight feeling of mushing will be noticed upon raising the flaps but the airspeed will be building so rapidly that rotation must be started to maintain climb schedule. You'll find that to maintain climb schedule, a healthy pitch angle of around 45° must be attained. As you level off a couple of minutes later somewhere around 40,000 feet and start an acceleration to Mach 2.0, you're in for a pleasant surprise. In the design of the STARFIGHTER, particular effort was exerted to abolish any transient inputs and the associated trim changes from minimum to maximum Mach number. As a result, pitch trim changes are so light you will probably not even detect them on your first flight and the directional or lateral trim changes are practically non-existent.

Let's take the STARFIGHTER from around .9 Mach where we're trimmed for straight and level flight and go up to Mach 2.0 and observe the mild stick forces that will occur. These forces can be shown on our graph *(Fig. 15)* of stick force as Mach number is increased. Here, we're using the trimmed position as zero

PITCH CHANGES DURING ACCELERATION AT 40,000 FEET

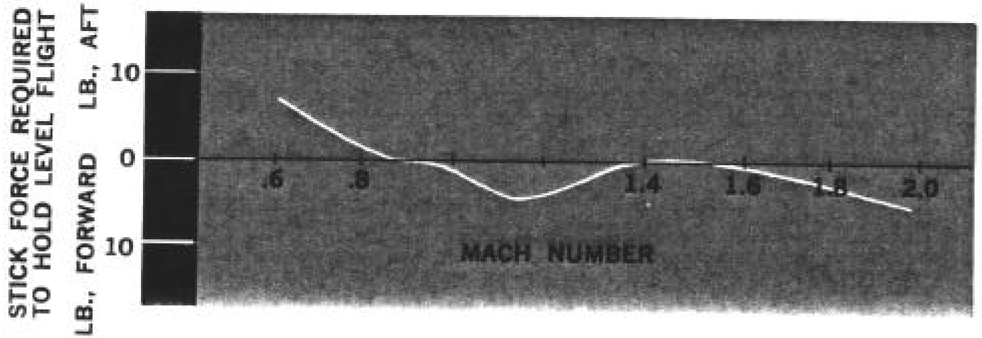
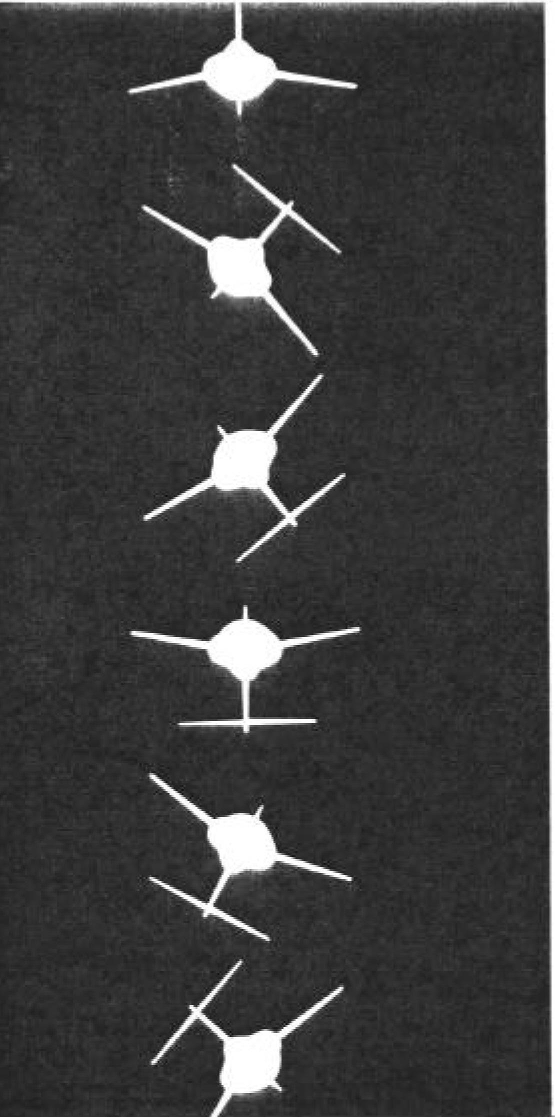


FIG. 15

pounds stick force at .9 Mach. As Mach 1.0 is approached, the nose wants to rise slightly and the required stick force forward is on the order of 2 pounds. At Mach 1.1 we reach the maximum amount of forward force required and it is approximately 4 pounds. From 1.1 Mach to 1.4 Mach the force is slowly relieved back to the trimmed position. Then from 1.4 Mach to 2.0, again the nose wants to rise and the stick force forward to hold level flight reaches the staggering sum of 6 pounds. Undoubtedly, you can understand now why we say that on your first few accelerations you'll probably trim out these mild stick forces without even noticing them.

After you've accelerated to peak Mach, you'll probably want to shake out the kinks a bit to get the "feel" of supersonic flying. The quick response and smooth handling will definitely increase your respect for the STARFIGHTER. Your rolls will be nice and the rate of roll completely adequate. If you happen to notice that the maximum aileron deflection with the flaps up is not as much as with the flaps down, here's why:



B. INERTIAL COUPLING

Surprisingly enough, inertial coupling has existed for some time in fighter type aircraft that have high rates of roll. However, the fighters did not have the speed potential to carry them into the flight area where inertial coupling could develop. We'd like to explain inertial coupling and how we've attempted to prevent it in the STARFIGHTER.

Roll instability is experienced as a result of the design requirements for a supersonic fighter. The mass weight has been concentrated in the fuselage resulting in high inertial moments in yaw and pitch with very low inertia in roll. At high rolling velocities, the forces and moments generated due to rolling are transmitted into pitch and yaw through inertial coupling, resulting in centrifugal forces which tend to displace the aircraft fuselage normal to the flight path. Noting this, let's look at our illustrations *(Fig. 16)* of a STARFIGHTER going through a left roll with different angles of attack and see how inertial coupling can develop. The first series shows a high angle of attack entry. It can be seen that the aircraft will initially develop a left sideslip in a left roll and a right sideslip in a right roll. Our illustrations show all left rolls so in the first series there is left sideslip. Due to the sideslip, the high tail effect which we discussed previously in the Negative Dihedral section, now comes into effect. The component of force high up on the tail resists the sideslip but also induces a right roll which will resist the initial left roll. This is beneficial to the aircraft with respect to retarding divergent characteristics in that the roll rate is reduced. As the aircraft continues its roll, in the first series, the angle of attack has decreased by the time the STARFIGHTER is inverted but it is still positive.

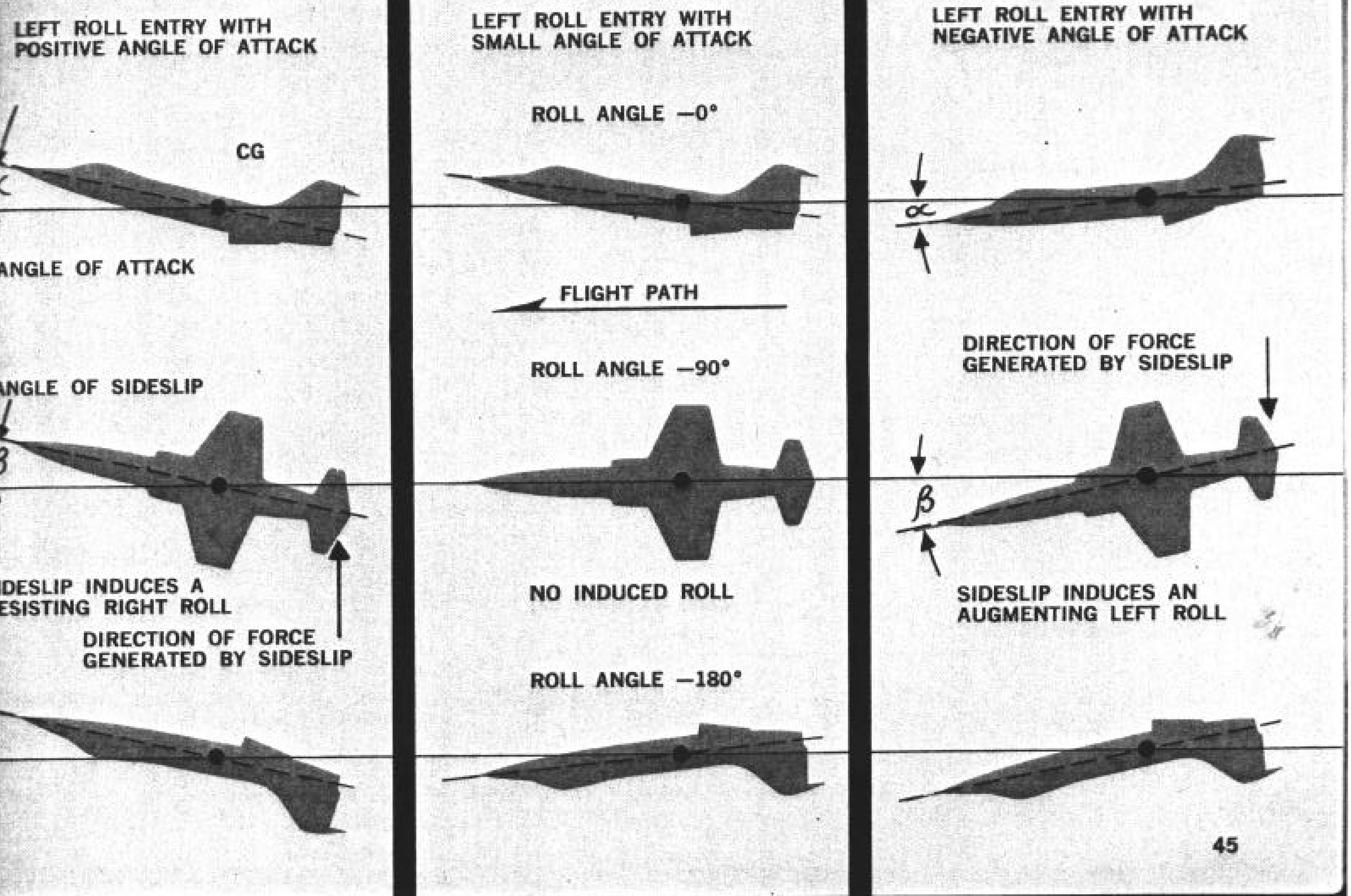
In the second series, the aircraft is being rolled with the angle of attack almost nil. Here we see that no sideslip or additional rolling moments are generated. This is the type of roll we all strive for.

In the third series, the aircraft is entering a roll from a negative angle of attack. From this condition of entry, sideslip buildup will be to the right. Again, a rolling moment is induced by the high tail configuration, but in this case, the component of force high up on the tail induces a *left* roll which *augments* the original roll. If we now consider two facts about these rolling maneuvers, it will become clear how inertial coupling builds up:

1. The sideslip build-up is controlled by the induced rolling moment.
2. As sideslip builds up, the centrifugal or rolling forces increase and this tends to displace the aircraft fuselage perpendicular to the flight path.

So now it is apparent that entering a roll with a positive angle of attack is beneficial to the STARFIGHTER. The induced rolling moment dampens the sideslip build-up. In a nega-

FIG. 16



LEFT ROLL ENTRY WITH POSITIVE ANGLE OF ATTACK
CG
ANGLE OF ATTACK
ANGLE OF SIDESLIP
SIDESLIP INDUCES A RESISTING RIGHT ROLL
DIRECTION OF FORCE GENERATED BY SIDESLIP
LEFT ROLL ENTRY WITH SMALL ANGLE OF ATTACK
ROLL ANGLE —0°
FLIGHT PATH
ROLL ANGLE —90°
NO INDUCED ROLL
ROLL ANGLE —180°
LEFT ROLL ENTRY WITH NEGATIVE ANGLE OF ATTACK
α
DIRECTION OF FORCE GENERATED BY SIDESLIP
β
SIDESLIP INDUCES AN AUGMENTING LEFT ROLL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tive angle of attack entry, however, the induced roll increases the sideslip. The sideslip build-up then couples with the centrifugal or rolling forces and the fuselage axis begins to diverge from the flight path. Need we say that this maneuver can have a rather abrupt ending? Therefore, we issue this note of warning:

1. Use caution when entering a supersonic roll with a negative or "Zero G" pushover.
2. Attempt only one 360° supersonic roll in one direction.

There are two things we have done to prevent inertial coupling in the STARFIGHTER. One is the restriction of roll rate. Since you do not need the maximum roll capability that the STARFIGHTER has with full aileron deflection, the ailerons have been limited so that ample but not extreme rates of roll are available. The second preventive was the ventral fin with its increase in directional stability, especially at the higher Mach. This combination will make it very difficult to encounter inertial coupling in the STARFIGHTER.

F-104 MANEUVERING "G"

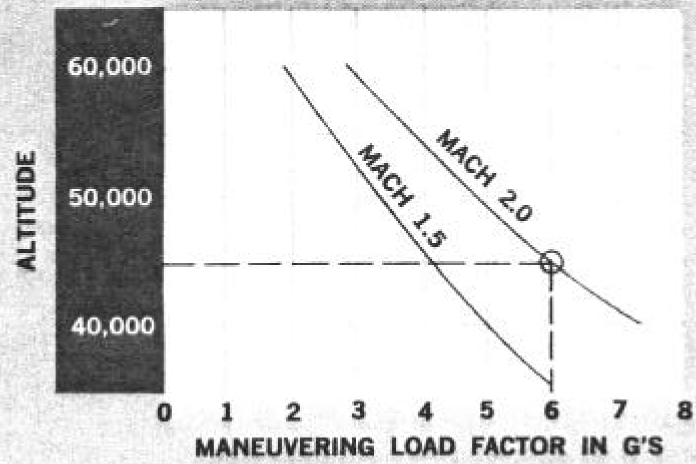

FIG. 17

But let's get back to our STARFIGHTER which is high up in the blue and find out a bit more about its flight characteristics.

A lot of you, I am sure, have had your fighters up at a goodly altitude and have been satisfied with its performance up to that point. But as you approached the region around 45,000 feet the aircraft had to be handled with kid gloves or you'd stall in a tight turn and lose precious altitude and airspeed. Well, the STARFIGHTER has increased its maneuvering capability by the existence of its wide speed range. An illustration we have drawn up *(Fig. 17)* has curves for two Mach numbers and maneuvering load factor. Actually a family of curves would be needed to portray the entire picture. But these curves show that if you are flying at 45,000 feet and Mach 2.0 you can easily pull 6 g's in maneuvering. The fiercest of you tigers will agree that this is a healthy hunk of maneuvering "g" to be able to play with. Use it skillfully and employ it wisely.

Upon completion of your high altitude work, you can pop the boards and come screaming down if you desire. Actuation of the speed boards can take place at any time you prefer. Up to Mach 1.8, a mild nose up occurs upon extension of the boards and from Mach 1.8 to 2.0, a mild nose down occurs. Although the pitch changes are very mild, we recommend that above Mach 1.8 the boards be deployed in increments for positive control. After slowing down to subsonic flight, if you decide to make a clean let-down, be careful you don't accidentally slip back through Mach 1.0 and "Boom" the populace.

In the traffic pattern, you'll probably carry a little more power than you're used to and you'll fly the pattern a little wider and faster, too. But if you're on the stick and make a smooth pattern, the landing will be a dream. You can actually land the STARFIGHTER and not know you've touched down until suddenly you are aware of rolling along the runway. Wait until the nose gear is definitely on the runway before pulling the drag chute. If the nose is still high when you pull the drag chute it forces the nose gear down onto the runway pretty hard. Drag chute deployment and reaction is better if actuated right after letting the nose down. Nose wheel steering is effective and should be used as needed. Braking action is firm and effective and the brakes alone are completely adequate to stop the STARFIGHTER after a normal landing.

After shutting down and climbing out of the pit, we believe that you will be proud to have become a member of The Royal Order of Starfighters.

CONCLUSION

Well, gentlemen—we have tried to give you what we think is the poop that you need to know on the F-104. She's an aircraft we have enjoyed testing and flying. We hope that you will share our enthusiasm about the STARFIGHTER and study her at every opportunity so that you will know her more fully. As you become more proficient we believe you will agree that the STARFIGHTER is the hottest fighter anywhere in the world and can truly be flown high, wide and handsome.

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