F-12 Series Aircraft Aerodynamic and Thermodynamic Design in Retrospect

Ben R. Rich*
Lockheed-California Company, Burbank, Calif.

A brief description of the F-12 series aircraft, and the concepts behind the design are presented. An aerodynamic discussion of some of the unique features of the aircraft, such as the blended body or chine, the all-movable verticals, and flight characteristics are shown. A review of the thermodynamic procedures and a comparison of estimated and flight test data are presented. A series of miscellaneous factors related to Mach 3 flight experience, such as the effects of ambient temperature, sonic boom, weather balloons, and in-flight refueling are discussed.

Nomenclature

C_L = lift coefficient
C_m = moment coefficient
$\bar{c}$ = chord length, ft
C_f = skin friction coefficient
c_p = specific heat at constant pressure, Btu/lb°F
c.g. = center of gravity
$Cn\beta$ = yawing moment due to sideslip
$Cl\beta$ = rolling moment due to sideslip
D = drag, lbs
h = altitude, ft
L = lift, lbs
hc = heat transfer coefficient, Btu/hr ft.^{2}°F
M = Mach number
p = static pressure, psf
Re = Reynolds number
q = dynamic pressure, lbs/ft^2
T = static pressure, °R
W = weight, lbs
Sw = wing area, ft^2
V = velocity, fps
x = distance, ft
KIAS = knots, indicated air speed
KEAS = knots, equivalent air speed
MAC = mean aerodynamic chord
WRP = wing reference plane
β = sideslip angle
ρ = density, lbs/ft^3
α = angle of attack

Subscripts
aw = adiabatic wall
L = local
Ref = reference
w = wall

Introduction

THE F-12 series of aircraft, commonly referred to as the "Blackbirds," were designed in the early sixties.[1] The aircraft is a product of Lockheed's Advanced Development Projects, known as Kelly Johnson's "Skunk Works." The airplane is the world's only operational Mach 3.0+ aircraft, and holds numerous high-speed and high-altitude records. The maximum cruise speed, altitude, range, performance, weight, mission equipment and capabilities, and the number of F-12 series aircraft produced, are still classified and therefore are not presented. In service, the airplane has performed several thousand supersonic flights, of which 40% have been at Mach 3.0 or above. The airplane has provisions for aerial refueling and has performed several thousand refuelings from KC-135 aircraft. The YF-12's are currently flying as part of the NASA Advanced Supersonic Technology program at the Flight Research Center at Edwards Air Force Base. The purpose of this paper is to present a few of the unique aerodynamic and thermodynamic features of the F-12 series of aircraft.

Aircraft Description

The Blackbird aircraft is a modified, tailless delta aircraft with a blended forward wing called a "chine," shown in Fig. 1. The aircraft is the size of a B-58. It has a two-man crew consisting of a pilot and a reconnaissance system operator in tandem. It is approximately 110 ft long, has a wing span of approximately 60 ft, and a height of approximately 20 ft. The nominal wing area of the delta planform is 1800 ft.^{2} The delta wing leading edge has approximately 60° sweep and approximately $-10°$ trailing edge sweep. The extremely thin, biconvex wing is attached midfuselage at slight negative incidence.

The forward portion of the fuselage is a blended body; the wing portion is referred to as the chine. This surface tends to act as a fixed canard surface. It is such an effective lifting surface that at cruise speeds, the aerodynamic lift reduces the forward fuselage bending moment to half. For the YF-12A, it was necessary to cut the forward chine

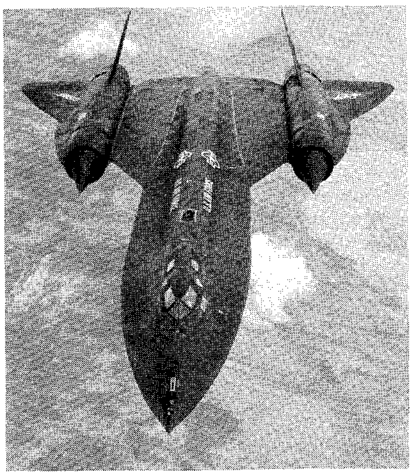

Fig. 1 YF-12C aircraft.

Presented as Paper 73-820 at the AIAA 5th Aircraft Design, Flight Test and Operations Meeting, St. Louis, Mo., August 6–8, 1973; submitted August 17, 1973; revision received April 12, 1974.

Index categories: Aircraft Aerodynamics (Including Component Aerodynamics); Aircraft Handling, Stability, and Control; Military Aircraft Missions.

*Vice President, Fighters and Preliminary Design, Advanced Development Projects. Associate Fellow AIAA.

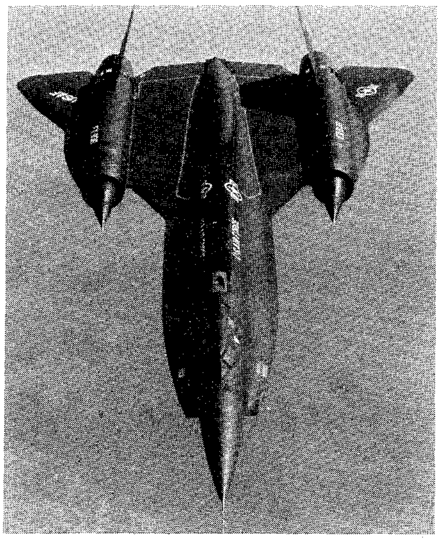

Fig. 2 YF-12A aircraft.

back to aft of the radome and increase the nose size as shown in Fig. 2. The increase in forebody lateral cross section resulted in a stability loss at high speed requiring the addition of three ventral surfaces.

The aft delta wing has preformed longitudinal corrugations to ensure the wing skin expansion and to reduce skin stresses and drag. The outboard portion of the wing's leading edge is designed with conical camber to reduce the outboard wing bending moment and torsion.

The aircraft is essentially a flying fuel tank. Fuel is carried principally in five fuselage integral tanks and integral wing tanks. The wing tanks are used in climb, that is, first, due to the high ratio of surface area to volume for thermodynamic reasons. Fuel sequencing is automatic and provides center-of-gravity control.

The aircraft has an extremely simple control system. There are two thin movable slab vertical stabilizers, which also act as rudders. The verticals are canted inward 15° from vertical and have a maximum movement of ±20°. There are four elevon surfaces, two inboard and two outboard, which act both as elevators and ailerons. Aileron capability is ±12°. There are no leading edge flaps or slats. The flight control system is described in Ref. 2.

The F-12 series of aircraft are powered by two Pratt & Whitney (JT11D-20) J-58 bleed bypass turbojet engines, located midspan on the wing, each developing over 30,000 lb of thrust at sea-level static conditions. Just as a comparison, each engine produces horsepower equivalent to that of the Queen Mary. The propulsion system, Fig. 3, consists of an axially-symmetric mixed compression inlet, followed by the J-58, and uses an aerodynamic convergent-divergent ejector nozzle as the exit. This is described and discussed in Ref. 3.

Over 93% of the airplane structure and skin surface are titanium. The ejector flaps are made of Hastelloy X, and the ejector throat ring is made of Rene 41. All air conditioning ducts and lines are aluminum, and all hydraulic lines are steel.

The maximum gross takeoff weight is over 140,000 lb. The aircraft empty weight is approximately 60,000 lb and it carries over 40 tons of low vapor pressure hydrocarbon fuel called JP-7. A nitrogen atmosphere is used to pressurize and inert the fuel tanks.

Aerodynamics

The F-12 type aircraft were designed for maximum performance at a cruise Mach number in excess of Mach 3.0 and at altitudes above 80,000 ft. The role of stability and control in achieving this capability is to minimize all aerodynamic factors affecting drag and weight. Therefore, stability margins and the sizes of the control surfaces, as well as load factor, had to be minimized to reduce weight and still maintain safe operation. This meant accepting the lowest static margin possible at cruise Mach number. This, coupled with the low inherent aerodynamic damping at the high mission altitudes, made it necessary to incorporate a triple-redundant stability augmentation system which is completely fail-operational.[2] These design requirements resulted in the first blended wing-body configuration with a control system approaching that of a control-configured vehicle.

Chines

The chined forebody of the YF-12C is approximately 40% of the aircraft length. With the high-sweep delta wing, the chine has a significant effect on both longitudinal and directional static stability. A characteristic of delta wings is the large rearward shift in aerodynamic center which occurs when the aircraft passes from subsonic to supersonic flight. If a safe static margin were provided for flight at subsonic speeds, a large static margin, and

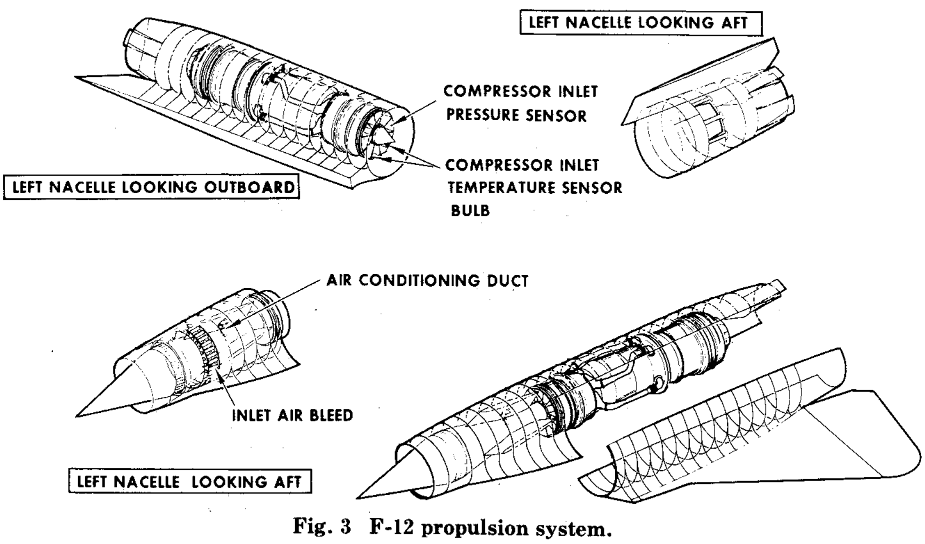

Fig. 3 F-12 propulsion system.

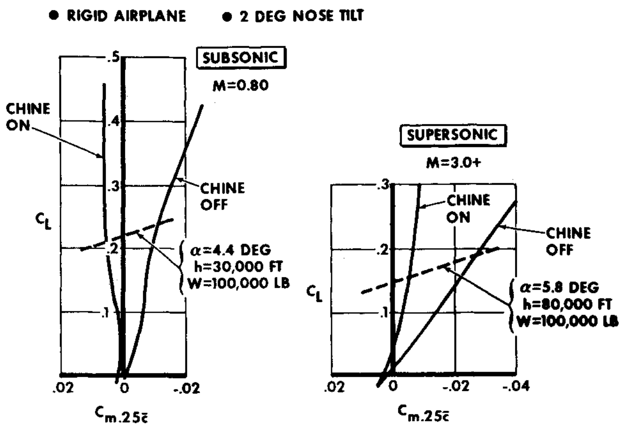

Fig. 4 Effect of chines on pitching moment.

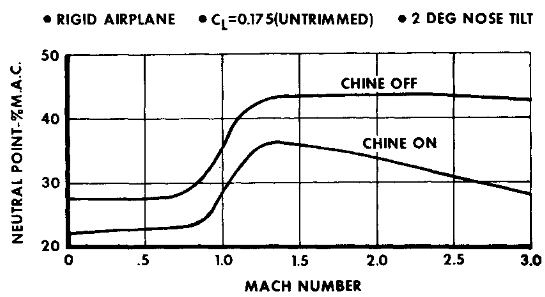

Fig. 5 Effect of chines on neutral point.

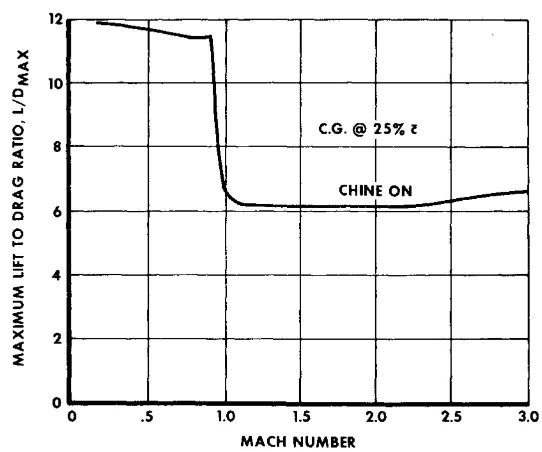

Fig. 6 Trimmed maximum L/D with chine on.

therefore, high trim drag would exist at supersonic cruise. The forebody chine is very effective in reducing this problem. Figure 4 shows the effects of the chine on pitching moment at subsonic and supersonic cruise Mach numbers. Data show the effects of chine "off" and chine "on." The chine acts as a very low aspect ratio high-sweep wing which produces lift as a function of the square of the angle of attack and becomes more effective as Mach number increases. The long moment arm of the forebody to the center of gravity combined with this lifting function makes the chine an effective destabilizer where it is needed most, at high Mach number. The result is that the chine reduces static longitudinal stability to an acceptable level for minimum trim drag throughout the flight envelope.

Figure 5 shows the effect of the chine on the neutral point. To further reduce the aircraft trim drag, the nose of the airplane just forward of the canopy was tilted up two degrees. This produced a positive Cm_0 shift which resulted in reduced elevon angles to trim, thus reducing trim drag.

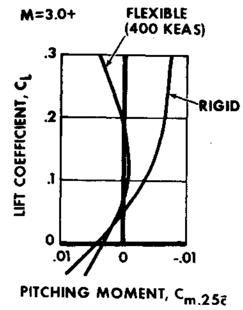

Fig. 7 Aeroelastic effects on pitching moments.

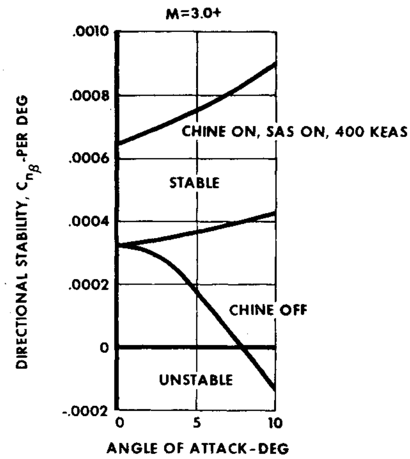

Fig. 8 Effect of chines and SAS on directional stability.

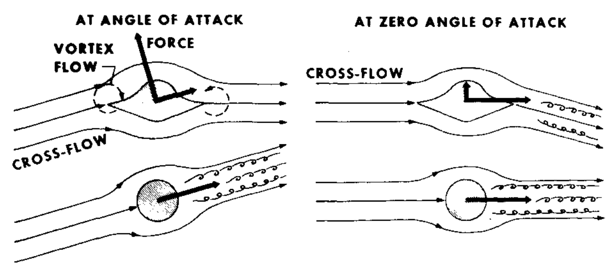

Fig. 9 Increase of favorable sideforce on forebody due to chine.

The trimmed maximum lift to drag ratio is shown in Fig. 6 as a function of Mach number. The net result is an aircraft with a trimmed maximum lift to drag ratio of 6.5 at Mach number 3.0 and above. For subsonic flight, the trimmed maximum lift-to-drag ratio is approximately 11.5.

Figure 7 illustrates the aeroelastic effects on pitching moment. The long slender fuselage and aerodynamic load distribution of the F-12 series aircraft results in significant aeroelastic effects in pitch and roll. The flexible aerodynamic characteristics were obtained using both digital and analog network analyzer techniques in conjunction with flight test data when it became available.

The chine also strongly affects directional stability. The long slender forebody without the chine shows a marked decrease in directional stability with increasing angle of attack as shown in Fig. 8. The addition of the chine results in increasing directional stability with increasing angle of attack. Wind-tunnel tests show that this is true with the vertical tails on and off and that the forebody effects are therefore significant.

The forebody cross-flow mechanism is illustrated in Fig. 9. The addition of the chine elongates the fuselage cross

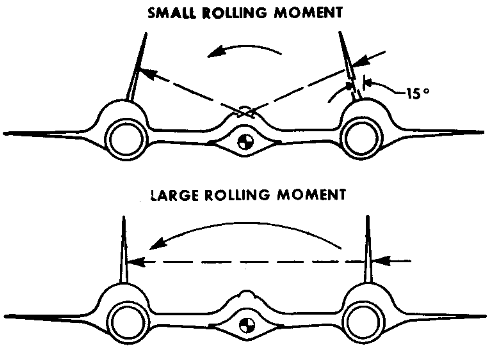

Fig. 10 Effect on vertical stabilizer cant on rolling moments.

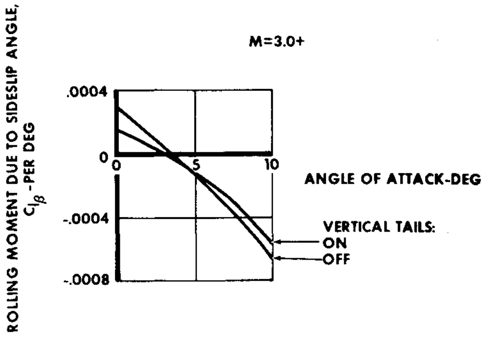

Fig. 11 Effect of twin vertical tails on rolling moment due to sideslip angle.

section and, at angle of attack, introduces strong vortex flow at the chine edges. The mass flow due to sideslip interacts with the vortices and the pressure distribution on the fuselage is affected. As in the case of a wing, resultant forces are produced which are favorable to directional stability. The resultant force on the circular body without vortex flow is unfavorable to directional stability.

At zero lift near zero angle of attack there is no significant vortex flow at the chine edges, the blended and round bodies develop unfavorable resultant side forces of equal magnitude, and there is no directional stability benefit due to the blended body. Vertical forces developed on the blended body because of its shape do not contribute to directional stability at zero angle of attack. Slender body theory applied to the YF-12C fuselage, considering its cross-sectional shape to be elliptical, substantiate the development of a resultant side force equal to that of the fuselage without chines, in the absence of chine vortex flow. The beneficial effects on directional stability of forebody "strakes" has been reported in the literature since the 1950's. Reference 4 is an example which also shows that the beneficial effect does not exist at zero angle of attack of the forebody and increases with angle until a relatively high value is reached.

The increasing directional stability of the YF-12C with angle of attack reduces the size of the verticals required for minimum stability and/or eliminates the need for central fins. The effectiveness of the YF-12C chine (Fig. 1) is demonstrated dramatically in comparison with the YF-12A (Fig. 2) which has the chine cut back to the canopy and requires a large folding centerline ventral and twin ventrals on the nacelles.

All-Movable Verticals

The verticals were sized for a minimum acceptable level of directional stability at design cruise Mach number. Conventional rudders were initially investigated, but were considered inadequate because extremely large deflections were required to control the engine-out condition. In addition, because of the high sustained operating temperatures encountered at high cruise Mach number, the rudder hinge line stagnation temperature would cause local heating problems. The rudders were changed early in the design to all-movable verticals above stub fins, and the change proved advantageous in several areas. Control effectiveness increased two and a half times. Engine-out control, therefore, required lower deflections and lower directional trim drag. The twin vertical tails are also canted 15° inboard at the tip, as shown in Fig. 10 to decrease the rolling moment due to sideslip and vertical deflection. Since the side load on the twin verticals act normal to the surface, the resulting moment arm at supersonic speeds is reduced by a function of the sine of the cant angle. No vertical tail effectiveness losses were encountered by canting the verticals. Also supersonically, since the aircraft center-of-gravity is forward of the verticals, the rolling moments due to sideslip and vertical stabilizer deflection measured in the stability axis system are further reduced as angle of attack increases as shown in Fig. 11.

Airport Performance

The chines and canted verticals also improve airport performance by reducing rolling moment due to yaw at high angles of attack in the landing approach configuration; thereby reducing the pilot workload required to keep wings level on landing approach. High $Cl\beta$, in the landing approach configuration is a normal characteristic of delta wing aircraft. In addition to effective engine-out control on takeoff or go-around, the all-movable verticals provide crosswind landing capability up to 35 knots at 90° to the flight path. This makes the aircraft operational in most normal weather conditions.

As mentioned earlier, conical camber was incorporated into the outboard wing leading edge primarily to move the center of lift inboard and therefore relieve the loading on the nacelle ring carry-through structure. This effect was proven in the wind tunnel through a reduction in rolling moment due to sideslip which is beneficial. A low rolling moment due to sideslip improves the Dutch roll characteristics and helps prevent roll-yaw coupling. The conical camber also improves the maximum lift characteristics of the outboard wing at high angles of attack. It also enhances the aircraft's cross-wind landing capability.

As the aircraft approaches the runway for touchdown, the close proximity of the wing to the ground produces additional lift called ground effect, as shown in Fig. 12. At normal approach speeds, this additional lift allows the aircraft to slow down from approach spped to touchdown speed without increasing angle of attack. This reduces pilot workload at a critical time in landing sequence. This also makes it almost impossible to make a hard landing. Evaluation of flight test landing data indicate landing sink rates of 1 to 1.5 fps.

Because of the high takeoff and landing speeds, it is essential that the aircraft have good handling qualities during these phases of flight. For a typical takeoff weight, the liftoff speed is approximately 200 knots, with a round roll of approximately 5400 ft. During a typical landing, the touchdown speed is approximately 150 knots and landing ground roll is 3600 ft as shown in Fig. 13.

SAS Integrated into Control System

The F-12 series of aircraft, as noted before, were designed to cruise at high altitudes and high Mach numbers. The low static margins required for minimum trim drag and maximum performance, coupled with low aerodynamic damping at these altitudes, necessitated the use of arti-

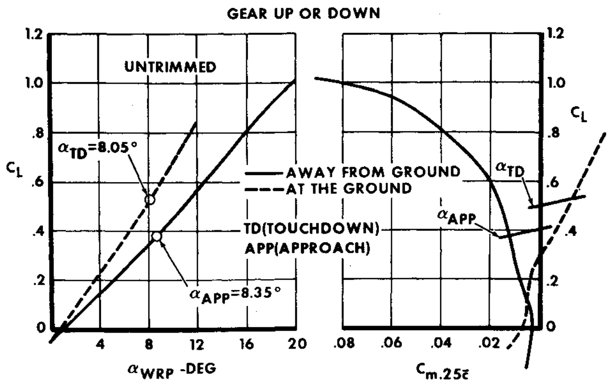

Fig. 12 Low speed lift and pitching moment.

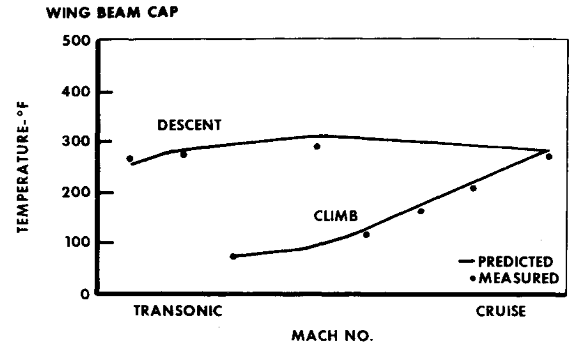

Fig. 14 Typical transient temperature profile.

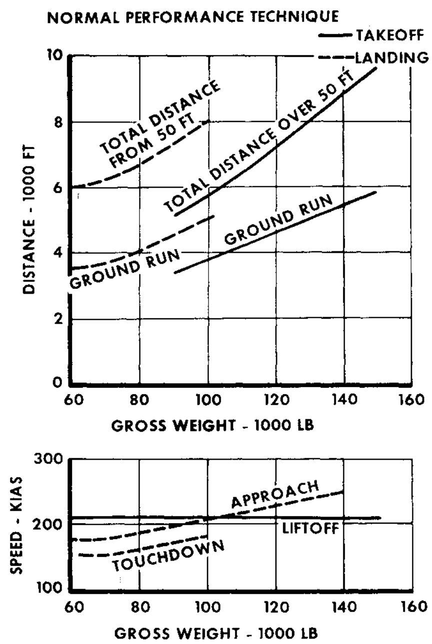

Fig. 13 Takeoff and landing performance.

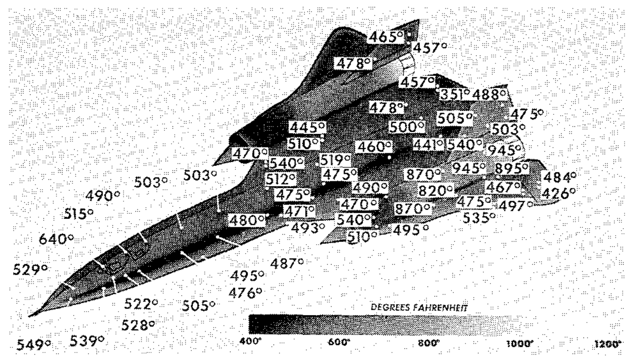

Fig. 15 SR-71 surface temperature cruise Mach.

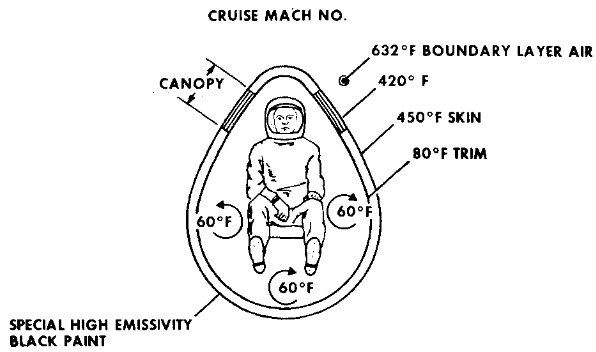

Fig. 16 Cockpit temperature environment.

ficial stability augmentation to satisfy the handling quality requirements of the mission. The automatic flight control system (AFCS) was an integral part of the aircraft design, and operates the basic flight controls to provide stability augmentation about all three axis, automatic pilot operation, and artificial speed stability in the transonic Mach number range. The description and development of the flight control system is given in Ref. 2.

Thermodynamics

The most important heat transfer problem for a supersonic cruise aircraft is the determination of the steady-state and transient temperatures. The heat balance equation is well known and will not be repeated. The two principal heat inputs are convective or aerodynamic heating and solar heating; the heat reduction is provided by the radiative component.

Since convective heating decreases with increasing altitude, and radiation is independent of altitude, an aircraft that cruises above 70,000 ft can take advantage of the radiation component and therefore requires the use of a high surface emissivity. Consequently, the F-12 series aircraft were all painted with a high-emissivity black paint that has an emissivity of 0.93 as compared to 0.38 for an unpainted titanium surface. This resulted in a surface temperature reduction of between 25 and 50°F at cruising altitudes. This surface temperature reduction was well worth adding 60 lb of paint to the takeoff weight. The equations used are given in the Appendix.

The entire aircraft surface temperature distribution for both steady-state and transient were predicted to within 20°F. A transient comparison is presented in Fig. 14. The skin reaches steady-state temperature approximately 11 min after the aircraft reaches cruise speed; the major structure takes about 35 min.

Figure 15 shows the typical Blackbird temperature distribution during cruise. Note the temperatures of the leading edges and inside the inlet, approximately 800°F, hotter than the average soldering iron. The wing and fuselage are between 450 and 500°F, hotter than the maximum household oven! The external skin temperatures in the afterburner and ejector section are between 900 and 1100°F. The tailpipes are white hot. The aircraft, flying in formation at night, use the tailpipe for reference.

The only heat sink available for the Blackbirds was the fuel. Consequently, the fuel was used to precool the hot compressor bleed air for the air conditioning system, and then the hot fuel was fed to the engine. No hot fuel was stored. Figure 16 shows the cockpit temperature distribution. To keep the pilot cool, it was necessary to feed −40°F air into the cockpit. The total aircraft heat load was over 40,000 Btu/min, about 1000 HP.

Ambient Temperature

One of the interesting ambient phenomena encountered by the aircraft was running into another jet stream at the top of the tropopause. The jet velocities and turbulence between 70,000 and 80,000 ft are very similar to those found at the bottom of the tropopause between 30,000 and 40,000 ft. The turbulence at the top of the tropopause however, is milder due to the low density; at 80,000 ft the density is one thirty-second that at sea level.

Another phenomena was the large variations of ambient temperature. For example, on January 16 and 29, 1963, respectively, the ambient temperature at 30 millibars (approximately 80,000 ft) over the same area of the United States varied from −85°C to −25°C.†

The standard day temperature is −56°C. Remember, the total temperature at M = 3.0+ is multiplied by a factor of three, so when you are 20°C hot, the steady-state surface temperature is approximately 60°C or 100°F hotter. The F-12 experience in the Northern hemisphere has shown a majority of cold days between 45,000 and 60,000 feet, and hot days above 70,000 ft. Near the equator, cold days extend to altitudes above 70,000 ft. Many of the pilots have reported clouds at 70,000 ft. Icing has been experienced on U-2's at 60,000 ft.

The ambient temperature variation not only affects the surface temperature, but seriously affects the inlet and engine operation. For example, every 1°C rise in ambient temperature results in a one percent reduction in range. An extremely hot day such as we have seen in the area of the North Pole, called the Polar Vortex, could seriously affect the range of a supersonic transport. This variation in ambient temperature causes a speed and altitude excursion resulting from the excitation of the longitudinal phugoid oscillation mode. This is discussed in detail in Refs. 2, 5, and 6.

Sonic Boom

The Blackbirds generate at cruise a sonic boom overpressure of approximately 1.5 psf.[7] The 1.5 psf is equivalent to the pressure of climbing up a two story building. It is the rate of change, of course, that is the difference. Early in our program, the Blackbirds refrained from flying over dams, National Parks, major population centers, and so forth. Flight experience showed that the clearer the day, the stronger the sonic boom.

Miscellaneous Items

One of the hazards encountered in the flight program was weather balloons. On numerous occasions the F-12's have barely missed balloons, their large cables or the large instrument package.

†Data obtained from the Institute for Meteorology and Geophysics, University of Berlin, Berlin, F.R. Germany, performed under a USAF contract.

Two items that have not been problems are ozone and cosmic radiation. Although the F-12's fly through the major ozone layer, the high stagnation temperature decomposes the ozone and presents no problems. None of the Blackbird pilots, civilian or military, have had any problems with cosmic radiation. They have hundreds of hours of flight time in this regime and are given frequent medical checkups with no ill effects noted on any pilot.

Flying in formation at Mach 3 speeds has been no different than formation flying at subsonic speeds. Two aircraft have flown within 500 ft of each other in all positions except directly in the engine exhaust wake with no difficulty.

In conclusion, the F-12 series aircraft are all equipped with aerial refueling provisions. Refueling has been quite routine between the F-12's and the KC-135's. Some aircraft have made as many as five refuelings in one flight. No attempt has ever been made on buddy or supersonic refueling.

Appendix

For the convective heating component, the following heat transfer coefficients were used to predict the surface temperatures for laminar flow:

$$h_c = 0.179\left(\frac{p_L V_L}{x}\right)^{1/2} \frac{(T_{\text{ref}})^{0.25}}{(T_{\text{ref}} + 200)^{1/2}}(c_p)_{\text{ref}}$$

for turbulent flow:

$$h_c = 41.7\, C_f \frac{p_L V_L}{T_{\text{ref}}}(c_p)_{\text{ref}}$$

where

$$T_{\text{ref}} = T_L\left[0.5\left(\frac{T_w}{T_L} + 1\right) + 0.22\left(\frac{T_{aw}}{T_L} - 1\right)\right]$$

for the turbulent case:

$$C_f = \frac{0.585\, \bar{C}_f}{0.557 + 2(\bar{C}_f)^{1/2}}$$

where

$$\bar{C}_f = \left[\frac{0.242}{\log_{10}(Re_{\text{ref}}\bar{C}_f)}\right]^2 \text{ (iterative solution required)}$$

$$Re_{\text{ref}} = 2.56 \times 10^4 \left[\frac{p_L V_L x\, (T_{\text{ref}} + 200)}{T_{\text{ref}}^{\,2.5}}\right]$$

References

[1]Johnson, C. L., "Some Development Aspects of the YF-12A Interceptor Aircraft," *Journal of Aircraft,* Vol. 7, No. 4, July–Aug. 1970, pp. 355–359.

[2]McMaster, J. R. and Schenk, F. L., "The Development of the F-12 Manual and Automatic Flight Control," *Journal of Aircraft,* Vol. 11, No. 4, April 1974, pp. 225–231.

[3]Campbell, D. H., "F-12 Propulsion System, Performance and Development," AIAA Paper 73-821, St. Louis, Mo., 1973.

[4]Jorgensen, L. H., "Inclined Bodies of Various Cross Sections at Supersonic Speeds," Memo 10-3-58A, Nov. 1958, NASA.

[5]Gilyard, G., Berry, D., and Belte, D., "Analysis of a Lateral-Directional Airframe/Propulsion System Interaction of a Mach 3.0 Cruise Aircraft," AIAA Paper 72-961, Palo Alto, Calif., 1972.

[6]Berry, D. and Gilyard, G., "Airframe/Propulsion System Interactions-An Important Factor in Supersonic Aircraft Flight Control," AIAA Paper 73-831, Key Biscayne, Fla., 1973.

[7]Maglieri, D. and Huckel, V., "Sonic Boom Measurements for SR-71 Aircraft Operating at Mach Numbers to 3.0 and Altitudes to 24, 384 Meters," TN D-6823, Sept. 1972, NASA.