

Design and Development of the Blackbird: Challenges and Lessons Learned

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The Lockheed Blackbirds hold a unique place in the development of aeronautics. In their day, the A-12, YF-12, M-21, D-21, and SR-71 variants outperformed all other jet airplanes in terms of altitude and speed. Now retired, they remain the only production aircraft capable of sustained Mach 3 cruise and operational altitudes above 80,000 feet. In this paper the author describes the design evolution of the Blackbird from Lockheed's early Archangel studies for the Central Intelligence Agency through Senior Crown, production of the Air Force's SR-71. He describes the construction and materials challenges faced by Lockheed, the Blackbird's performance characteristics and capabilities, and the National Aeronautics and Space Administration's role in using the aircraft as a flying laboratory to collect data on materials, structures, loads, heating, aerodynamics, and performance for high-speed aircraft.

Nomenclature

AFCS	=	Automatic Flight Control System
AOA	=	angle of attack
ASARS	=	Advanced Synthetic Aperture Radar
C	=	Centigrade
CAPRE	=	Capability Reconnaissance
c.g.	=	center of gravity
CIA	=	Central Intelligence Agency
F	=	Fahrenheit
FATOLA	=	Flexible Aircraft Takeoff and Landing Analysis
FCO	=	Fire Control Officer
FRC	=	Flight Research Center
g	=	acceleration due to the force of gravity
HTLL	=	High Temperature Loads Laboratory
IR	=	infrared
KEAS	=	knots equivalent air speed
LCO	=	Launch Control Officer
MOU	=	memorandum of understanding
NASA	=	National Aeronautics and Space Administration
OBC	=	Optical Bar Camera
RCS	=	radar cross-section
RSO	=	Reconnaissance Systems Operator
SST	=	Supersonic Transport
TEB	=	triethylborane

I. Introduction

THE Lockheed Blackbirds hold a unique place in the development of aeronautics. In their day, they outperformed all other jet airplanes in terms of altitude and speed. Now retired, the Blackbirds remain the only production aircraft capable of sustained Mach 3 cruise and cruising altitudes above 80,000 feet.

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Conceived as airborne reconnaissance platforms, the family of aircraft known collectively as the Blackbirds included the A-12, YF-12, M-21, and SR-71. Designed by Clarence L. “Kelly” Johnson under the nickname “Archangel,” the A-12 resulted from a series of designs for a successor to Lockheed’s earlier U-2 spy plane. The twelfth design in Johnson’s Archangel series was a sleek aircraft built almost entirely of titanium. With powerful turbo-ramjets, the A-12 was capable of attaining a cruise speed of Mach 3.2 and an operational altitude of 90,000 feet.

In August 1959, the Central Intelligence Agency (CIA) approved funding for construction of the A-12 as Project OXCART. Between 1960 and 1962, Lockheed engineers tested a scale model of the A-12 in NASA Ames Research Center’s 8’ by 7’ Unitary Plan High-Speed Wind-Tunnel at Moffett Field, Calif. (Fig. 1). The tests included evaluation of various inlet designs, control of cowl bleed, design performance at Mach 3.2, and off-design performance of an optimum configuration at speeds of up to Mach 3.5.

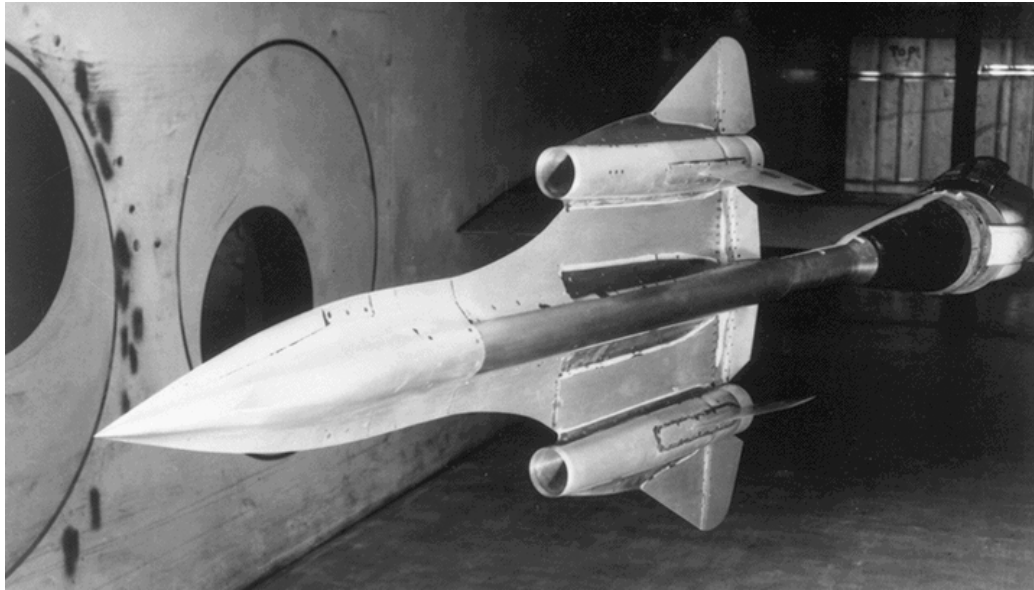


Figure 1. Lockheed engineers tested a scale model of the A-12 in NASA’s 8’ by 7’ Unitary Plan High-Speed Wind-Tunnel at Ames Research Center, Moffett Field, Calif. (Lockheed Martin)

As a reconnaissance platform, the A-12 was flown exclusively by the CIA. It accommodated a single pilot in a full pressure suit. The first airframe was delivered in February 1962 and made its maiden flight two months later. Test flights and operational missions continued until the airplanes were retired in June 1968.

In March 1960, even before delivery of the first A-12 prototype, Lockheed and Air Force officials discussed development of an interceptor version of the A-12. Designed as the AF-12 under project KEDLOCK, the interceptor featured a pulse-Doppler radar system and launch bays for three air-to-air missiles. A second crew position, located just behind the pilot’s cockpit, accommodated a Fire Control Officer (FCO) to operate the missile launch system. With the assistance of the CIA, the Air Force entered into an agreement with Lockheed to build three prototypes, eventually designated YF-12A, and the maiden flight took place in August 1963.

The public first became aware of the aircraft on 29 February 1964, when President Lyndon B. Johnson announced its existence. By agreement with Kelly Johnson, the president intentionally misidentified the aircraft as an “A-11.” With the YF-12A now public knowledge, the flight-test program was moved to Edwards Air Force Base, in the Mojave Desert northeast of Los Angeles. The Air Force soon began testing the aircraft’s weapons system and resolving troublesome issues with transonic acceleration and various subsystems.

The year 1964 also marked the debut of two more Blackbird variants, designated M-21 and SR-71. The M-21, a two-seat variant of the A-12, was built expressly as a launch aircraft for the secret D-21 reconnaissance drone as Project TAGBOARD. A fatal accident during the fourth launch resulted in the death of the launch control officer and destruction of both drone and M-21. The second new Blackbird, the SR-71, became the most familiar member of the family. Operated by the U.S. Air Force under Project SENIOR CROWN, the SR-71 served as an aerial reconnaissance workhorse around the world for more than 25 years.

The A-12 fleet (Fig. 2) operated in secret for six years, during which time several were lost in crashes. By June 1968 all surviving airframes had ended their service lives and been sent to Lockheed's facility in Palmdale, Calif., for permanent storage. Their operational mission had been assumed by the SR-71A, operated solely by the Air Force. A planned operational version of the YF-12A interceptor, designated F-12B, failed to materialize as Secretary of Defense Robert McNamara ultimately cancelled the program in a cost-cutting measure. As a consequence, on 29 December 1967, Air Force officials instructed Lockheed to terminate F-12B development. The YF-12A program ended in February 1968, and the aircraft joined the A-12 fleet in storage. There they remained until the National Aeronautics and Space Administration (NASA) reached an agreement with the Air Force for a joint research program. Beginning in 1969, NASA operated two YF-12A aircraft and one SR-71A (temporarily designated YF-12C for political reasons). The joint NASA-Air Force program continued for ten years.



Figure 2. In early 1964, the fleet had not yet received the characteristic paint scheme that later earned the aircraft its nickname, “Blackbird.” (Lockheed Martin)

The Air Force retired the SR-71 fleet in 1990, but two airframes were reactivated for operational service in 1995. They were retired again in 1997. NASA operated the SR-71 between July 1991 and October 1999 for research purposes and to support the Air Force reactivation program. After retirement from NASA service, all remaining Blackbird airframes were allocated to museums and former operating agencies for permanent display.

Over the years, numerous books and articles have been written about the Blackbirds. Previous authors have provided brief overviews of the technological aspects while concentrating on the developmental and operational history of these incredible airplanes. This paper will explore the technological aspects of the Blackbird family and the lessons learned through the process of designing, building, and operating them.

II. Design Evolution

Development of the Lockheed Blackbirds began with a requirement for a successor to the U-2, a reconnaissance airplane capable of high-altitude (but low-speed) flight that first flew in 1955. It was built by Lockheed's Advanced Development Projects division (known as the “Skunk Works”) under the CIA's Project AQUATONE under the direction of Lockheed chief engineer Kelly Johnson.

CIA and Air Force analysts concluded the U-2 would have a relatively short operational lifespan before hostile anti-aircraft technology rendered it obsolete. As early as 1956, just as the U-2 was becoming operational, Johnson

proposed a Mach 2.5 hydrogen-fueled airplane capable of cruising above 99,000 feet. Only 25 people were cleared into this special access program, code-named SUNTAN.¹

Lockheed's initial SUNTAN studies evolved into a vehicle nearly 300 feet long with a gross takeoff weight of 358,500 pounds. Johnson's CL-400 (Fig. 3) design posed numerous technical challenges involving materials, manufacturing, airframe/powerplant integration, and fuel production, storage and handling. As technological problems began to overwhelm the project, Johnson began to have serious doubts about its viability.

CL-400 GENERAL ARRANGEMENT

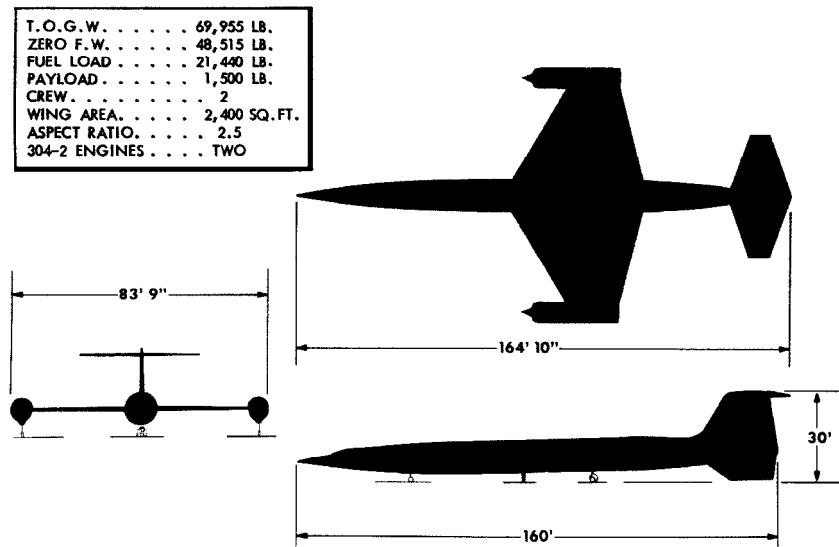


Figure 3. The SUNTAN studies produced a design that posed numerous technical challenges. (Lockheed Martin)

After further analysis of the SUNTAN design and proposed mission requirements he determined the CL-400 had severe range limitations that could not be overcome with available technology. During a 1957 meeting with the secretary of the Air Force, Johnson recommended terminating the program in favor of one focused on an airplane with a more conventional propulsion system. He advocated a smaller, lighter airframe powered by two Pratt & Whitney J58 engines. In February 1959, SUNTAN was finally terminated at Johnson's request and his final design, the hydro-carbon-fueled CL-400-15JP, served as a steppingstone to the Archangel project that eventually yielded the A-12.²

In the fall of 1957 the CIA commissioned a study to determine the probability of detecting an airplane by radar with respect to its speed, altitude, and radar cross-section (RCS). This analysis indicated that supersonic speed significantly reduced the ability of conventional radar systems to detect an aircraft. Subsequently the CIA, under Project GUSTO, solicited design proposals from Lockheed and the Convair Division of General Dynamics. The U.S. Navy also submitted an in-house concept, but it had insurmountable design flaws.³

Lockheed's most serious competition came from Convair's proposed ramjet-powered vehicle, codenamed FISH, which was to be carried aloft beneath a B-58 supersonic bomber. In order to survive extreme aerodynamic heating and also have a minimal radar signature, the vehicle was to be constructed using PyroCeram (a ceramic glass having virtually zero thermal expansion under extreme heating conditions) and other heat-resistant, radar-attenuating

¹ Crickmore, Paul F., *Lockheed Blackbird – Beyond the Secret Missions*, Osprey Publishing, Oxford, U.K., 2004.

² Goodall, James and Jay Miller, *Lockheed's SR-71 'Blackbird' Family*, Midland Publishing, Hinckley, England, 2002.

³ Johnson, Clarence L., *History of the Oxcart Program*, (SP-1362), Lockheed Aircraft Corporation, Advanced Development Projects, Burbank, Calif., 1968.

materials. Following a Mach 2.0 launch from a lengthened B-58 with uprated engines, two Marquardt ramjets would propel FISH during the Mach 4.25 cruise portion of its mission. The pilot would then deploy two pop-out General Electric J85 turbojet engines for maneuvering during the landing phase. The Convair team, however, ultimately concluded the vehicle's size, propulsion system, and logistics were impractical. Subsequently FISH was scrapped in favor of a larger vehicle that could function autonomously, without the need for a launch aircraft.

Built around two Pratt & Whitney JTD11D-20 (J58) engines, the new craft was called KINGFISH. It was to be capable of a top cruise speed of approximately Mach 3.25 at an altitude of 125,000 feet. The vehicle's wing edges were to be built in a complex pattern of interlocking wedges, every other one made of radar-absorbent material to reduce the RCS. Convair built a model of the KINGFISH airframe for radar signature tests, but never produced a flyable airframe.

Meanwhile Lockheed struggled to produce a viable design. Tentatively called the U-3 in early Skunk Works studies, the airplane had to meet stringent RCS requirements to make it more survivable than the U-2 was to hostile anti-aircraft defenses. Kelly Johnson developed and discarded numerous designs in an attempt to meet the CIA's specifications. While he could design an airplane capable of attaining high speeds and altitudes, he found it difficult to significantly reduce the radar signature. For a while it appeared likely that the contract would go to General Dynamics/Convair.

By August 1959 Johnson had offered the CIA a total of 11 high-speed proposals and two low-speed, low-RCS concepts. Just when it looked as if KINGFISH would be the winner, the CIA agreed to accept an airplane with a lower cruising-altitude capability if it had the desired RCS and speed. Johnson was able to modify his design and the 12th Lockheed concept was selected for production.⁴

A. Archangel Design Series

Johnson's Archangel concepts, numbered A-1 through A-11, were driven by the need for speed and altitude, but customer requirements for survivability ultimately led to a revolutionary design with a small radar signature. Along the path that eventually led to the A-12, Johnson explored an eclectic collection of alternative design concepts.

His first rough pencil sketch, made on 23 April 1958, for a Mach 3.0 airplane (then still called U-3) featured a slender, tapered airframe with a cross-section that was cylindrical up to the point where two engine pods nestled tightly against the aft fuselage. The high-mounted wing featured a diamond shape with squared tips. Two widely spaced, outwardly canted vertical stabilizers and two variable-position horizontal surfaces provided longitudinal and lateral control. At this point the CIA's stated design objectives included a 500-pound reconnaissance payload capability, unrefueled mission radius of 2,000 nautical miles and a 90,000-foot cruising altitude.⁵

In order to make his paper airplane a reality, Johnson and his team of engineers had to draw on available enabling technologies and design tools. Routine calculations were made using slide rules. More complex calculations, such as stress analysis, required Friden mechanical calculators. The most advanced computer available at the time was the IBM mainframe. With the era of computational fluid dynamics still far in the future, aerodynamic and loads testing was limited to that performed using wind-tunnel models.

Balancing the need for a lightweight structure against resistance to aerodynamic heating, the Skunk Works team focused on B120-VCA titanium alloy as the primary structural material. For propulsion Pratt & Whitney's J58 turbojet engine offered the best performance at high-Mach cruise conditions while mixed-compression, variable-geometry inlets maximized inlet recovery across the flight envelope. Engineers initially felt separate ramjets might be used to enhance high-altitude performance at cruise Mach numbers. The most promising available fuel was JP-150, with low vapor pressure and stability over a wide temperature range. High-energy fuels such as pentaborane and ethyldecaborane were considered and rejected. They offered a 35 percent increase in energy content per unit mass versus JP-150, but their high toxicity presented logistical difficulties.⁶

By July 1958 the U-3 had evolved into Archangel 1 (Fig. 4). The earliest version of the A-1 design featured a conventional fuselage, 166.67 feet long with a sharply pointed nose. The wing, spanning 49.6 feet, was mounted at the top of the airframe and featured a sharply swept leading edge and gently swept trailing edge. Two J58 engines occupied engine pods below the wing roots. The cruciform tail assembly featured conventional vertical and horizontal surfaces with a relatively large surface area.

⁴ Goodall and Miller, *Lockheed's SR-71 'Blackbird' Family*.

⁵ Whittenbury, John R., "From Archangel to Oxcart: Design Evolution of the Lockheed A-12, First of the Blackbirds," unpublished briefing slides, Lockheed Martin Aeronautics Company, Palmdale, Calif., 2003.

⁶ Ibid.

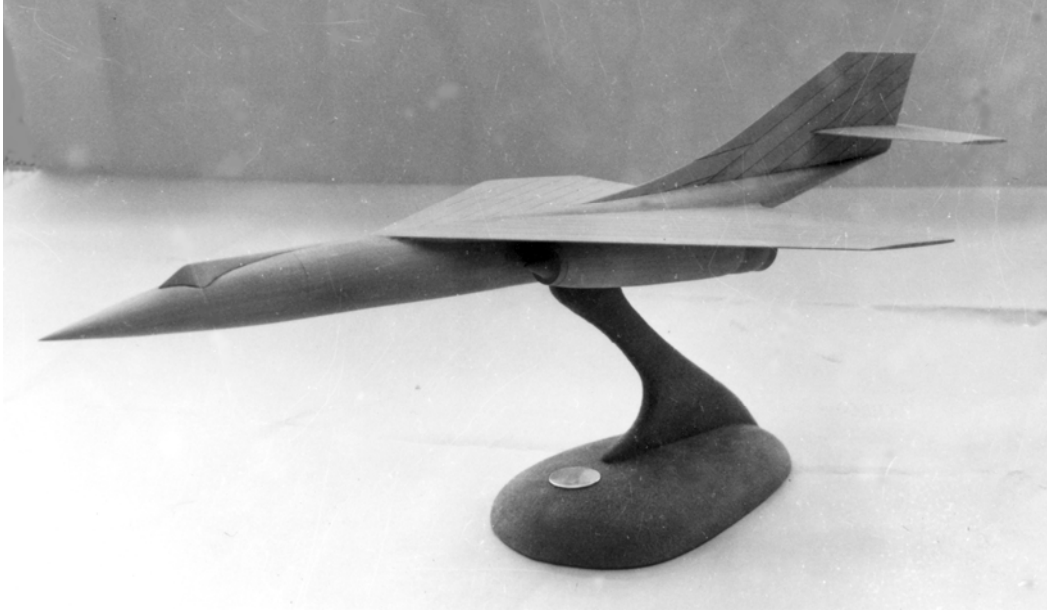


Figure 4. Archangel 1, or A-1, featured a fairly conventional configuration. (Lockheed Martin)

The aircraft's empty weight was estimated at 41,000 pounds. With a capacity for 61,000 pounds of stored fuel, it would have had a gross weight of 102,000 pounds at takeoff. The A-1 was designed to cruise at a speed of Mach 3.0 and altitudes between 83,000 and 93,000 feet with a mission radius of 2,000 nautical miles. Later versions of the A-1 explored such options as canards mounted on the forward fuselage, a double-delta wing configuration, and winglets.⁷

Next, Johnson worked on several versions of the A-2, including a four-engine vehicle with two J58 turbojets beneath the wing at mid-span to provide bending relief and ethyldecaborane-fueled, 75-inch-diameter ramjets at each wingtip. In addition the wing sweep angle was substantially reduced and the cruciform tail enlarged. With a length of 129.17 feet and a wing span of 76.68 feet the A-2 was expected to cruise at Mach 3.2 and altitudes of 94,000 to 105,000 feet. It was projected to have a gross takeoff weight of 135,000 pounds, assuming a fuel capacity of 81,000 pounds. The ramjets would be ignited at Mach 0.95 and 36,000 feet altitude.

Both the A-1 and A-2 were rejected due to excessive gross weight and the still-unaddressed RCS issue. Johnson responded by designing a scaled-down vehicle with smaller, modified Pratt & Whitney JT-12 engines. Because the JT-12 was a low-pressure-ratio engine it was well suited to high-Mach-number operation.⁸

The A-3's two JT-12 powerplants were mounted at mid-span with the engine nacelle centered in the wing structure. These turbojets looked insignificant compared to the 40-inch-diameter ramjets on the wingtips. The turbojets would provide thrust for takeoff, climb, and acceleration while the ramjets would be used only during the cruise portion of the flight. The A-3 (Fig. 5) of November 1958 was Johnson's smallest design to date, just over 62 feet long with a wingspan of 33.8 feet. It had a gross takeoff weight of just 34,600 pounds and was expected to meet all performance requirements. A semi-tailless configuration (no horizontal stabilizer) reduced both weight and RCS.

⁷ Ibid.

⁸ Johnson, Clarence L., "Archangel Log," Lockheed Corporation, Burbank, Calif., released in abridged form, April 1993.

A-3 NOVEMBER 1958

Length:	62.3 ft	Zero Fuel Weight:	12,000 lbs	Cruise Mach:	3.2
Span:	33.8 ft	Fuel Weight:	22,600 lbs	Cruise Alt:	95 kft
Height:	14.6 ft	Takeoff Gross:	34,600 lbs	Radius:	2,000 NM

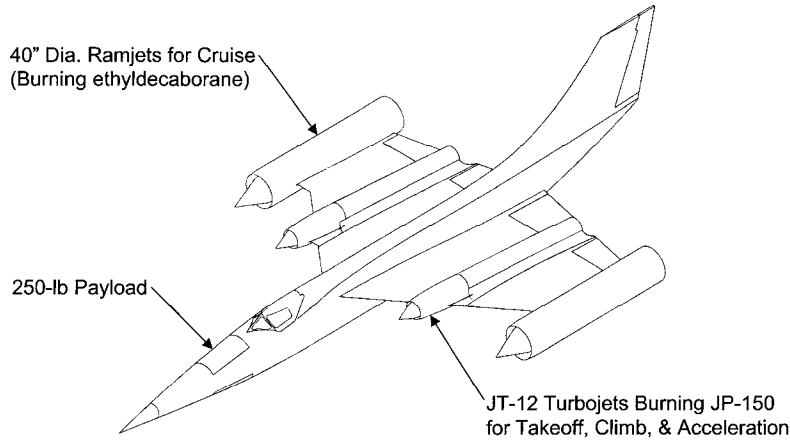


Figure 5. The semi-tailless A-3 featured reduced weight and a lower radar cross-section than earlier designs. (John Whittenbury via Lockheed Martin)

Johnson's A-4 was relatively small at 58 feet long with a 35-foot span. Its blended wing-fuselage configuration significantly reduced the RCS. The vertical stabilizer resembled a shark's dorsal fin running the length of the upper fuselage. A single J58 served as the main powerplant while two 34-inch-diameter ramjets on the wingtips provided cruise power. Maximum gross takeoff weight was estimated at 57,900 pounds.

In an attempt to further reduce size and weight, Johnson proposed the A-5. At a length of 46 feet and span of 32.5 feet, it came in at a gross weight of just 50,320 pounds but featured the most complex mix of powerplants yet. Two JT-12 turbojets buried in blended side fairings provided thrust for takeoff, climb, and landing. A centrally located 83-inch-diameter ramjet with a ventral intake provided cruise power while additional takeoff thrust came from a 10,000-pounds-thrust liquid-fueled rocket at the base of the vertical fin. In all other respects the A-5 resembled a scaled-down A-4. Design integration was extremely challenging, particularly with respect to fuel accommodation.

For the A-6 (Fig. 6), Johnson proposed a configuration with a blended triangular forebody and delta wings with squared tips. Inwardly canted vertical fins were located about two-thirds of the way out from the wing roots. The powerplants included a single J58 and two 34-inch-diameter ramjets buried in the fuselage. With a length of 64 feet and a span of 47 feet the airplane had a gross weight of 62,950 pounds. Weight penalties were reduced by equipping the airplane with lightweight landing gear. A detachable set of heavy-duty gear would be used for takeoff and drop away as soon as the craft lifted off the ground.

By January 1959 a number of things had become clear. Maximum performance and minimum RCS seemed to be mutually exclusive. The A-4 through A-6 designs lacked the necessary operational range. Skunk Works engineers noted that ramjet technology was not sufficiently mature for use in long-range cruise conditions. Two-stage systems, such as those involving a B-58 launch aircraft, were operationally impractical for multiple reasons including logistics and safety. Additionally, the customer was understandably anxious by this point to see a finished product. Johnson began to focus on a maximum-performance turbojet aircraft design with no performance concessions for the sake of improved RCS.

This effort resulted in the A-7, a configuration similar to the A-1 and A-2 but scaled down to just less than 98 feet long with a 47-foot wingspan. It was powered by a single J58 in the fuselage and two 34-inch-diameter Marquardt XPJ-59 ramjets on the wingtips. All engines would burn only JP-150 fuel. It had a projected maximum gross takeoff weight of 70,900 pounds.

A-6-5 JANUARY 1959

Length:	64.0 ft	Zero Fuel Weight:	29,200 lbs	Cruise Mach:	3.2
Span:	47.2 ft	Fuel Weight:	33,750 lbs	Cruise Alt:	90 kft
Height:	22.85 ft	Takeoff Gross:	62,950 lbs	Radius:	1,287 NM

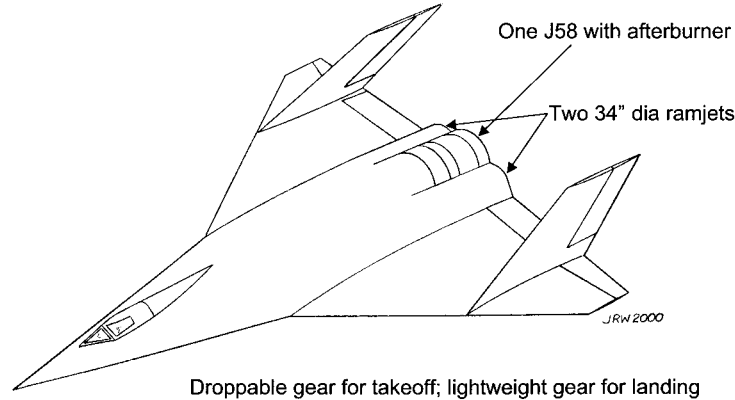


Figure 6. The A-6 was to be equipped with detachable heavy-duty gear for takeoff and lightweight, fixed gear for landing. (John Whittenbury via Lockheed Martin)

Johnson continued to refine the concept with the A-8 and A-9 designs but results were disappointing. Mission radius continued to hover around 1,637 nautical miles with a cruise altitude of slightly more than 91,000 feet, considerably less than the A-2 despite the weight reduction.

In February 1959 Johnson submitted the A-10 concept, an elegantly simple design. The 109-foot-long cylindrical fuselage featured a long forebody and was sharply tapered at each end. The semi-double-delta wings had squared tips and spanned 46 feet. A vertical tail fin with conventional rudder provided lateral stability. Two General Electric J93-3 turbojets would propel the airplane to speeds of Mach 3.2 at a 90,000-foot cruise altitude. At a takeoff weight of 86,000 pounds, the A-10 demonstrated a significant weight reduction (18,000 pounds) relative to the A-1 that allowed it to reach higher altitudes. Mission radius was estimated at 2,000 miles. RCS was still a problem, but Johnson was more concerned with performance.

The following month he refined the design further. The A-11 (Fig. 7) featured true double-delta wings spanning 56.67 feet. Fuselage length increased to 116.67 feet and the J93 engines were replaced with J58s. The A-11 was designed to take off from a home base, cruise at Mach 3.2 at 93,500 feet, and complete an eight-hour, 13,340-nautical-mile mission with two aerial refuelings.⁹

Johnson pitched his A-11 concept to the CIA and reported the results of six months of radar studies. He emphasized that expected improvements to radar systems would enable detection of any airplane that might conceivably fly within the next three to five years. He specifically noted that the probability of detection of the A-11 was practically 100 percent. It was subsequently agreed the airplane might make such a strong radar target that it could be mistaken for a bomber. This was unacceptable for an airplane that was intended for use in clandestine reconnaissance missions. In July 1959, Johnson was surprised to learn that the CIA had offered to extend Lockheed's program and accept lower cruising altitudes in exchange for incorporation of RCS reduction techniques.

Johnson subsequently proposed the A-12 with the J58 engines in a mid-wing arrangement to reduce the airplane's side profile. chines along the forebody reduced fuselage sloping while providing additional lift and stability. The single vertical stabilizer was replaced with two all-moving vertical fins, one on top of each engine nacelle. These were canted inward for further RCS reduction. Serrations on the wing edges incorporated radar-absorbent materials. Johnson noted in his project diary, "This airplane weighs about 110,000 to 115,000 pounds and, by being optimistic on fuel consumption and drag, can do a pretty good mission."¹⁰

⁹ Whittenbury, "From Archangel to Oxcart."

¹⁰ Johnson, "Archangel Log."

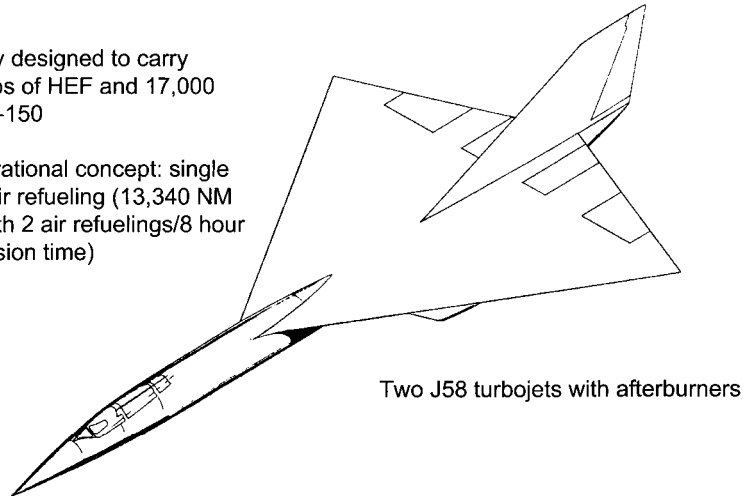
A-11

MARCH 1959

Length: 116.67 ft	Zero Fuel Weight: 36,800 lbs	Cruise Mach: 3.2
Span: 56.67 ft	Fuel Weight: 55,330 lbs	Cruise Alt: 93.5 kft
Height: 21.03 ft	Takeoff Gross: 92,130 lbs	Radius: 2,000 NM

Originally designed to carry
31,000 lbs of HEF and 17,000
lbs of JP-150

Key operational concept: single
base + air refueling (13,340 NM
range with 2 air refuelings/8 hour
total mission time)



Two J58 turbojets with afterburners

Figure 7. The A-11, although an elegant design, had an unacceptably high RCS. (John Whittenbury via Lockheed Martin)

Lockheed and Convair submitted final proposals to the CIA on 20 August 1959. Although Convair's KINGFISH promised better overall performance, the evaluation panel considered it to be technologically riskier. Subsequently, Lockheed was awarded a four-month initial contract with the admonition that it must prove the viability of its anti-radar approach by 1 January 1960, before receiving full go-ahead. At this point Project GUSTO was terminated. The new airplane would be built under Project OXCART.¹¹

B. A-12 Configuration

The A-12 design (Fig. 8) incorporated features to maximize performance, survivability, and mission capability while minimizing weight, detectability, and (to the extent possible) cost. The fuselage contained no wasted space or extraneous material, and even the fuel did double duty as a coolant.

The airplane's fuselage consisted of a titanium structure of semi-monocoque construction with a circular cross-section. The sides flared out into sharply blended chines, assembled as interlocking saw-toothed wedges. On all A-12 airframes except those of the prototype and trainer variant, the outward-pointing teeth were fashioned from titanium while the interlocking, inward-pointing, teeth were made from radar-absorbent composites.

The sharply tapered nose section was pressurized and contained navigational and communications equipment, a remote compass transmitter, periscope optics, air inlet computer and angle transducer, and other radio equipment. A combination pitot-static and alpha-beta probe was installed at the forward tip to capture airspeed and altitude data.

The pilot's station (cockpit) featured a V-shaped windscreen and was enclosed by an aft-hinged clamshell canopy. Both the windscreen and canopy featured windows with dual glass assemblies. The outer monolithic glass panels were separated from inner laminated glass panels by air gaps. An internal heated-air defrosting/defogging system, a deicing system, and an external rain-removal system insured good visibility in all weather conditions. The pilot's station was outfitted with conventional aircraft controls and instruments.¹²

The crew cabin pressure could be set to 10,000- or 26,000-foot equivalent altitude pressurization. At altitudes below the pressure altitude selection, the cabin was essentially unpressurized. In theory, the pressurized cockpit allowed the pilot to operate in a standard flight suit with oxygen mask at altitudes below 50,000 feet but a full

¹¹ Whittenbury, "From Archangel to Oxcart."

¹² *A-12 Technical Manual MA12-2-1 – Airframe*, February 1966.

pressure suit was normally worn to ensure crew safety under normal as well as emergency conditions. In an emergency the pilot could jettison the canopy and egress using a rocket-propelled ejection seat at any altitude and Mach number within the flight envelope. A drogue chute stabilized the seat during descent until man-seat separation occurred automatically at a barometric altitude of 15,000 feet.¹³

A-12 KEY FEATURES

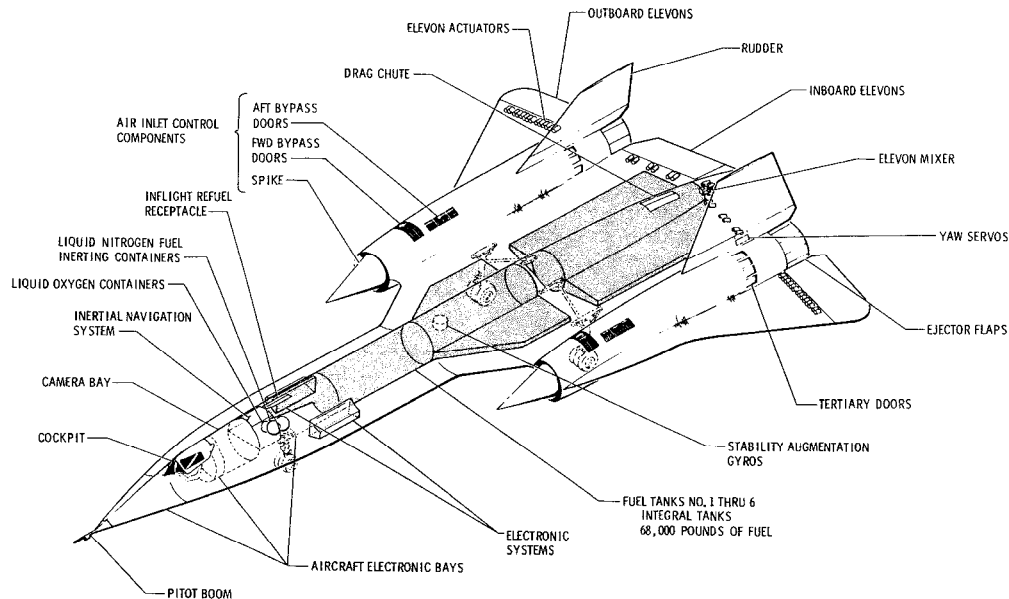


Figure 8. The A-12 was designed for performance and functionality. There was no wasted space or excess weight. (Lockheed Martin)

The electronic compartment (E-bay) was located just aft of the pilot's station. This pressurized and air-conditioned space contained most of the communication and navigation equipment as well as the stability augmentation system, autopilot, flight reference, Mach trim, and other electronic systems.

The mission equipment bay (Q-bay) was located immediately aft of the E-bay and could be pressurized or unpressurized depending on specific equipment needs. This compartment provided space for installation of cameras and sensors, test packages, and/or ballast as dictated by mission requirements.

Air-conditioning equipment was located in the AC-bay, just aft of the Q-bay. This compartment housed most of the environmental control system equipment and the inertial navigation system. It also provided access to various circuit breakers and miscellaneous electrical components.

An in-flight refueling receptacle was located on top of the fuselage, just aft of the AC-bay. When de-energized, the receptacle doors formed the upper fuselage contour. When opened, the doors revealed a trough to accept the aerial tanker's refueling probe.

Another set of doors on the upper side of the aft fuselage provided a cover for the drag chute compartment. The drag chute, along with the wheel-braking system, aided airplane deceleration during normal landings or aborted takeoffs.

The underside of the fuselage featured nose and main landing gear wheel wells with hydraulically and mechanically actuated flush doors. The main gear wells also included insulated buckets to protect the tires from overheating while retracted during cruise.

¹³ *Lockheed SR-71 Supersonic/Hypersonic Research Facility Researcher's Handbook*, Volume II, Technical Description, Lockheed Advanced Development Company, Palmdale, Calif., 1995.

Remaining internal spaces in the fuselage were occupied by six integral fuel tanks. These, along with the wing tanks, provided a fuel capacity of 69,800 pounds. The fuel was pressure-fed by two or more boost pumps in each tank. A cross-feed transfer system allowed the tank pumps to supply fuel to either engine. The airplane's tail cone assembly contained a mixer for elevon control and a fuel dump port for use in the event of an in-flight emergency.

The wing was a thin, modified double-delta with rounded tips. It was fully cantilevered, highly tapered and, in addition to the basic structure, incorporated inboard and outboard elevons to provide the combined aerodynamic functions of ailerons and elevators. Except where interrupted by the main gear well, the wing acted as an integral fuel cell between the leading edge and elevon support beams and spanwise between the fuselage and engine nacelle. The external surfaces of the upper and lower wing panels were beaded and corrugated to permit the skin and structure to expand and contract in response to temperature changes during flight.

At mid-span each wing supported an engine nacelle containing rings and carry-through structure to support the outer wing. Both inner and outer wings were of multi-spar construction with chordwise stiffened skin panels attached to spanwise beams. The outer nacelle half (with attached outer wing) was hinged to open for engine access and servicing.

The tail group consisted of two inwardly canted, all-moving rudders and the inboard and outboard elevons. Each rudder was mounted on a fixed stub fin atop the rear portion of the engine nacelle. Contained within each stub fin an electro-hydraulic actuator moved the rudder through 20 degrees of travel on each side of the neutral position. The hydraulically actuated elevons were secured to the aft wing beam.¹⁴

C. Blackbird Family Tree

The A-12 spawned a series of advanced airplanes based on a common airframe. All variants were known as Blackbirds and all but a few reached the prototype stage. Only the first and last variants, however, matured into operational systems.

The first A-12 derivative, developed for the Air Force under Project KEDLOCK, was a two-seat air defense interceptor variant capable of launching air-to-air missiles at targets of varying altitude. Johnson conceived the AF-12 as a modified A-12 airframe incorporating a fire control system coupled with the AN/ASG-18, the first U.S. coherent-pulse Doppler radar for long-range, look down/look up, and single-target attack.

The AF-12 design necessitated numerous changes to external configuration. A second crew position was added behind the cockpit to accommodate a fire control officer (FCO). Two infrared (IR) sensors, an integral part of the target tracking system, were placed on either side of the nose. The nose assembly itself was originally to be chined like that of the A-12 but was soon replaced by a radome with a circular cross-section.

The nose configuration, designed to accommodate the radar, significantly altered the Blackbird's aerodynamics and resulted in directional stability problems. Engineers resolved the problem by adding two small ventral fins to the engine nacelles and a large, hydraulically powered folding ventral fin on the centerline of the aft fuselage. Because of its size, the fuselage fin had to be folded to one side prior to takeoff and landing.¹⁵

In 1962, the Department of Defense instituted a common designation system for military aircraft, under which the AF-12 became the YF-12A. Lockheed built three prototypes, the first of which completed its maiden flight on 7 August 1963. Air Force crews tested the aircraft's weapon systems while attempting to resolve troublesome problems with transonic acceleration and various subsystems. In 1965 several official speed and altitude records were set in the aircraft. Plans to build an operational version of the interceptor, designated F-12B, were ultimately cancelled by Secretary of Defense Robert McNamara in a bitter feud with the Air Force over appropriation of defense funds.¹⁶

In early 1962 Kelly Johnson designed a drone aircraft capable of operating in the same speed and altitude range as the A-12. Under Project TAGBOARD, Kelly Johnson submitted a written proposal for a feasibility study regarding the Q-12, as he called the drone. It was accepted and Johnson drew up plans for a ramjet-powered vehicle that would be launched for a dorsal pylon atop the fuselage of a modified A-12-type aircraft. The major modification to the OXCART design included provisions for a launch control officer (LCO) seated in a compartment behind the cockpit. The drone rested on a pylon mounted on the aircraft's centerline between the twin vertical stabilizers.

On 28 February 1963, Johnson received approval to produce 20 drones and two launch aircraft. As construction began, Johnson saw the two vehicles as "mother" and "daughter." To avoid confusion with the single-seat

¹⁴ *A-12 Technical Manual MA12-2-1 – Airframe.*

¹⁵ Goodall and Miller, *Lockheed's SR-71 'Blackbird' Family*

¹⁶ Crickmore, *Lockheed Blackbird – Beyond the Secret Missions.*

reconnaissance jet, he designated the mothership M-21 (with “M” for “mother” and reversing the numerals). The drone became the D-21 and the mated combination was called MD-21.¹⁷

The M-21 (Fig. 9) had generally the same performance and handling characteristics as the A-12. To stay within the aircraft’s capabilities while maintaining optimal attachment loads on the D-21, maneuvering loads were limited to no more than 2.0g for the mated configuration. Most rolling maneuvers for the MD-21 were prohibited to prevent adverse side loads on the D-21. The only aileron maneuver allowed for the mated configuration consisted of a steady turn, performed within the airplane’s capabilities.¹⁸



Figure 9. To alleviate load problems, the D-21 was mounted so that it floated at zero-moment incidence when attached to the M-21. (Lockheed Martin)

The D-21 was almost 43 feet long with a nearly 20-foot wingspan, and about seven feet tall. As a result of shape and materials, it had a small RCS. Maximum gross takeoff weight was 11,000 pounds. Powered by an internally mounted Marquardt XRJ43-MA20S-4 ramjet engine, it had a design cruise speed of Mach 3.35 at 80,000 to 90,000 feet and a range of 1,439 miles.¹⁹

Initial drone separation trials began in March 1966. The flight profile required the M-21 pilot to attain a speed of Mach 3.12 at an altitude of 72,000 feet and commence a gentle pull-up before pushing the nose over to maintain a steady force of 0.9 g. With the drone’s ramjet operating, the LCO initiated pneumatic separation of the drone. On its second free flight, the drone attained a speed of Mach 3.3 and altitude of 90,000 feet. Although it demonstrated the planned performance characteristics, the D-21 still suffered a few technical problems. Additionally, the launch maneuver was risky for the flight crew.

On 29 April 1966, Johnson made a formal proposal to Strategic Air Command Headquarters for a modified drone (eventually designated D-21B) that would be launched from beneath the wing of a B-52H bomber. This, he said, would provide greater safety, reduced cost, and expanded deployment range. In order to propel the D-21B to ramjet ignition speeds (around Mach 3.0), the drone would require a rocket booster for the initial flight phase following launch.

On 31 July, however, Johnson’s worst fears were realized during the fourth launch attempt from the M-21. After the drone lifted off the pylon, its ramjet unstarted. The D-21 rolled over on its side and plunged into the mothership’s aft fuselage. The M-21 pitched up and broke apart, sending debris plummeting toward the Pacific Ocean. Although both crewmen ejected from the stricken craft, the LCO perished before rescue forces arrived.

¹⁷ *ibid.*

¹⁸ Angerman, G. J., *Structural Criteria and Design Loads, M-21 (SP-727)*, Lockheed Aircraft Corporation, Advanced Development Projects, Burbank, Calif., 1966.

¹⁹ Crickmore, *Lockheed Blackbird – Beyond the Secret Missions*.

As a result of the tragedy, Johnson cancelled further use of the MD-21. The remaining D-21 drones were modified to the D-21B configuration and two B-5H aircraft were configured as launch platforms under Project SENIOR BOWL.²⁰

On 14 September 1960, Johnson began work on a bomber version of the Blackbird that he called the RB-12. His proposal resulted from the reported development of small, high-yield nuclear warheads. He suggested that four hypothetical 400-pound bombs, or a single large bomb, could be carried inside the airplane's fuselage without compromising fuel load. No aerodynamic changes were required and the radar-attenuating features remained intact. Johnson pitched his proposal to the Air Force, emphasizing the airplane's performance and survivability characteristics. Although Johnson found the Department of Defense more interested in the bomber than the interceptor, the RB-12 never went beyond the mock-up stage. It was ultimately rejected because it was seen as a threat to North American Aviation's XB-70, the proposed replacement for the B-52.

During September 1962, Johnson began exploring what he called a "common market" version of the A-12. A single airframe configuration, known as the R-12 Universal airplane, would serve as the basis for a reconnaissance, recon/strike, or interceptor variant, depending on customer needs. This, he believed, would greatly simplify production.²¹

In February 1963, Lockheed was given pre-contractual authority to build six R-12 airframes with the understanding that an additional order of 24 was forthcoming. The details of the contract allowed the Air Force and CIA to share the financial burden.

Simultaneous development of the A-12 and R-12 fueled Pentagon debate as to the need for two similar reconnaissance platforms. The Air Force used the opportunity to press its case that it should have sole jurisdiction over such a mission. This eventually doomed the A-12 to cancellation.

As Lockheed pressed ahead with the R-12, the airplane's configuration diverged noticeably from that of the A-12. The most obvious difference was the addition of a second crew position, behind the cockpit, to accommodate the reconnaissance systems operator (RSO). The fuselage was lengthened slightly to make room for additional fuel capacity and the tail cone was extended slightly. The nose chines were broadened to improve cruise characteristics and compensate for loss of directional stability due to the change in length. There were numerous internal changes as well with regard to various subsystems.

Air Force officials showed interest in the RS-12 reconnaissance/strike variant. Consequently, Johnson worked on systems and structural issues related to weapons carriage. The RS-12 was eventually re-designated SR-71 (Fig. 10).



Figure 10. The SR-71 incorporated many common elements from the other Blackbird variants. (Lockheed Martin)

In 1964, SR-71 airframes began to roll off the assembly line (Fig. 11). By late 1967, a total of 31 airframes had been delivered to the Air Force. Two of these were SR-71B trainer models with a raised instructor's cockpit in place of the RSO position. After one of these crashed in January 1968, it was replaced with a trainer built from the aft fuselage of the first YF-12A and the forward section of a structural test article (with added instructor's position). The new trainer was called the SR-71C.

²⁰ *ibid.*

²¹ Goodall and Miller, *Lockheed's SR-71 'Blackbird' Family*.

During their service lives, 12 of the SR-71 airframes were lost to accidents. The operational fleet was retired twice, first in 1990. A few aircraft were reinstated into service, but were retired again in 1997. NASA used several as research platforms and became the final agency to fly the Blackbird. The last SR-71 flight took place on 9 October 1999. Most surviving airframes were placed on display in various museums around the U.S., and one in the United Kingdom.²²



Figure 11. Construction of the Blackbirds presented numerous technical challenges. (Lockheed Martin)

III. Building the Blackbirds

Lockheed engineers faced unique challenges in designing and building the Blackbirds. Aerodynamic friction and continuous engine operation during high-speed flight subjected some parts of the airplane to temperatures as high as 1,050 °F. Average surface temperatures ranged from 462 to 622 °F. This precluded the use of aluminum as a basic structural material. The Skunk Works team turned instead to titanium, stainless steel, and other advanced alloys, as well as to high-temperature plastics.²³

Only titanium and steel could withstand the expected operational temperatures, but steel was extremely heavy and Lockheed had little experience with lightweight stainless steel honeycomb structures. Skunk Works technicians realized aged B-120 titanium had nearly twice the strength/density ratio of stainless steel per cubic inch, but weighed approximately half as much. They also found they could manufacture titanium structures with fewer parts using conventional construction methods than were necessary with steel. High-strength composites were not available in 1960. While the Blackbirds featured an abundance of composite plastic laminates (Fig. 12) as anti-radar treatments, those substances were not used as primary structure.

Titanium rivets turned out to be among the most difficult items to manufacture. In the early days of the program it was nearly impossible to obtain pure enough samples of the metal in wire form. For this reason titanium rivets,

²² *ibid.*

²³ Johnson, Clarence L., "Development of the Lockheed SR-71 Blackbird," *Lockheed Horizons*, Issue 9, Winter 1981/82, Lockheed Corporation, Burbank, Calif., 1981.

bolts, and other fasteners were initially very expensive. The price gradually lessened as these items saw wider use throughout the aircraft manufacturing industry.²⁴

Titanium alloys presented numerous challenges because of adverse chemical reactions between the metal and various materials and compounds commonly used in aircraft construction and maintenance. To prevent corrosion and stress-corrosion cracking at high temperatures, it was imperative that titanium parts be prevented from contacting such materials as cadmium, mercury, fluorine, chlorine, bromine, astatine, and iodine. Certain common hand tools were cadmium-plated and some marking materials (pens and pencils) contained chemicals that caused corrosion. Contaminating elements also could be found in the composition of solvents, adhesive tapes, paints, packing materials, plastics, fire extinguishing agents, cleaning agents, and other materials commonly used in aircraft maintenance. Technicians and maintenance personnel were required to be vigilant, and use only compatible materials from approved lists.²⁵

Improved manufacturing techniques also were developed at the Skunk Works. To prevent parts from going undergauge while in the acid bath technicians devised a new series of metal gauges two-thousandths of an inch thicker than standard gages. Technicians also developed improved drill bits. When the first A-12 was built a high-speed drill could make only 17 holes before having to be discarded. By the end of the SR-71 program, bits developed at the Skunk Works could drill 100 holes and then be re-sharpened for further use.

Over the course of 20 years more than 13 million titanium parts were manufactured at Lockheed. The history of all but the first few can be effectively traced through detailed paperwork back to the original mill pour. For the last 10 million, even the direction of the grain in the sheet from which the part was cut had been recorded.²⁶

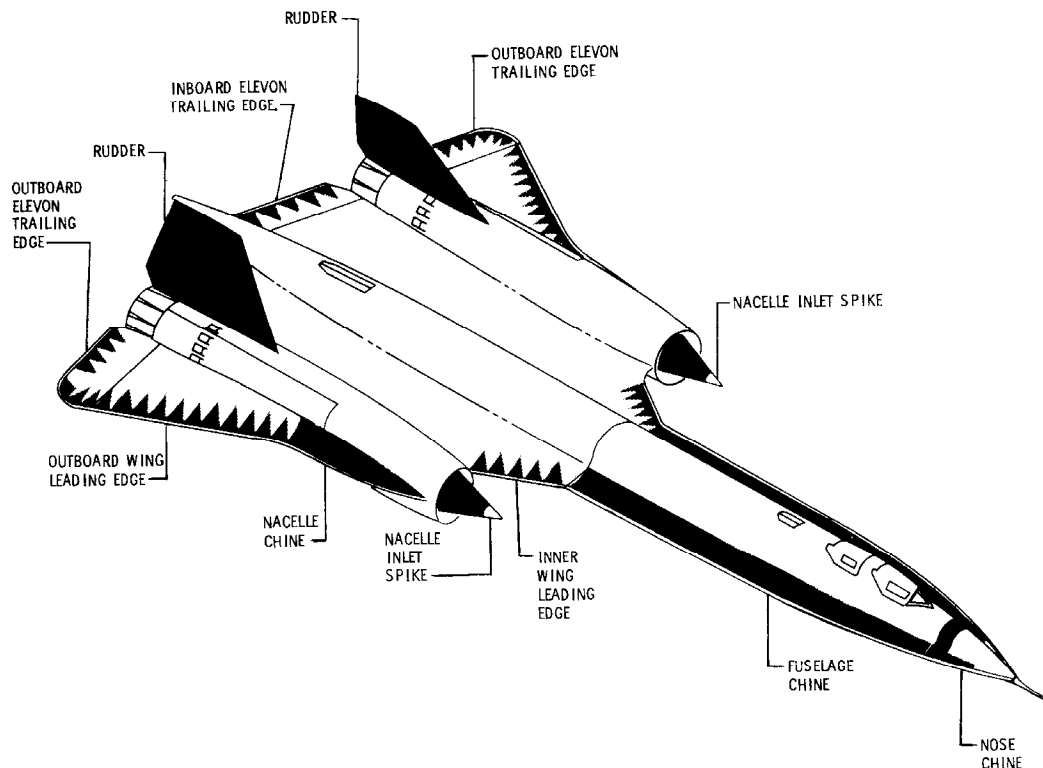


Figure 12. For RCS reduction, most peripheral assemblies of the A-12 and SR-71 were made of composite plastic laminates. (Lockheed Martin)

²⁴ Johnson, "Some Development Aspects of the YF-12A Interceptor Aircraft," *Journal of Aircraft*, Vol. 7, No. 4, American Institute of Aeronautics and Astronautics, July-August 1970.

²⁵ *Technical Manual SR-71-2-2, Organizational Maintenance – Airframe Group: SR-71, SR-71B, AND SR-71C Aircraft*, U.S. Air Force, 1987.

²⁶ Johnson, "Development of the Lockheed SR-71 Blackbird."

A. Exotic Materials

Fully 93 percent of the Blackbird's structural weight consisted of titanium alloys (Fig. 13). Since all-titanium construction had not yet become common, Lockheed engineers and technicians pioneered new inspection, test, quality control, and manufacturing techniques. Lockheed technicians found that the difficulty of machining titanium had a great effect on overall construction costs. The initial rate of metal removal from high-strength titanium alloys was only five percent of what the rate would be for aluminum. It was impossible to obtain die forgings to final dimensions or extrusions in finished form. Lockheed technicians had to invent new drills, cutting machinery, powerheads for profilers, and cutting lubricants to increase the rate of metal removal. On some large components, cut on tape-controlled profilers, approximately 90 percent of the forging weight had to be removed by machining. To save on structural weight, many assemblies contained large numbers of small parts. In similar aluminum assemblies, many of these parts would have been combined to reduce the parts count.

Moreover, large sections of the leading and trailing edges, vertical stabilizers, chines, and inlet spikes were made of "plastic" laminates of phenyl silane, silicone-asbestos, and fiberglass. These materials – featured primarily on the A-12 and SR-71 families – helped reduce the aircraft's radar signature.

The Blackbirds earned their nickname because they were coated with a high-emissivity black paint for improved heat radiation, thus reducing thermal stresses on the airframe. The first A-12 initially flew unpainted. Early models in the A-12 and YF-12A series were subsequently painted black only on the periphery of the airframe where heating was greatest: on chines, leading and trailing edges, and rudders.

Engineers soon realized it would be advantageous to take advantage of Kirchoff's law of Radiation that describes how a good heat absorber, such as a black body (any extremely dark object), is also an efficient heat emitter. Although convective heating decreases with increasing altitude, heat radiation occurs independently of altitude. Therefore, in late 1963, Skunk Works engineers decided to take advantage of the black-body radiation phenomenon by painting the A-12 fleet and subsequent variants entirely black.



Figure 13. Fully 93% of the Blackbird's structure was made of titanium alloys. (Lockheed Martin)

Titanium is characteristically light, strong, heat-resistant, and non-magnetic. Its strength compares closely with corrosion-resistant steel, but with just slightly over half the density. Three types of titanium alloys were used in the Blackbirds. The first, designated A-A110AT, contains approximately 5 percent aluminum and 2.5 percent tin. The

second, B-120VCA, contains approximately 13 percent vanadium, 11 percent chromium, and 3 percent aluminum. Finally, C-120AV contains approximately 6 percent aluminum and 4 percent vanadium. Most of the Blackbirds' titanium skin, ranging in thickness from 0.020-inch to 0.040-inch, consisted of B-120VCA fastened to the frame by riveting or spot-welding.

On the Blackbirds, titanium rivets were used in place of more commonly used Monel alloy fasteners that were specified by industry standards at the time. Rivets are cold-driven, and rivet holes require the maintenance of close tolerance to insure good gripping.

The Blackbirds also incorporated A-126 corrosion-resistant steel in some parts of the structure and surface panels. This heat-treatable alloy contains approximately 15 percent chromium, 26 percent nickel, 2 percent titanium, and 1 percent molybdenum. It was capable of withstanding 1,200 °F, well within the aircraft's performance envelope.

Areas subject to extremely high temperatures, such as the engine nacelle exhaust ejector section incorporated two types of nickel alloys. René 41 is a nickel base metal alloyed with chromium, iron, molybdenum, cobalt, titanium, and aluminum. It can withstand temperatures up to 1,600 °F. Hastelloy-X – nickel alloyed with chromium, iron, and molybdenum – can withstand approximately 2,200 °F.

Most of the peripheral assemblies of the A-12 and SR-71 series aircraft were comprised of so-called plastic parts, consisting of silicone-asbestos and phenyl silane glass laminates. Designers made extensive use of these materials in the forward fuselage chines, wing edges, inlet spike cone, tailcone, and vertical stabilizers to reduce the airplane's radar cross-section. Composite honeycomb sandwich skin panels, some more than one inch thick, were fastened to the underlying titanium framework and easily removed for maintenance or replacement. These were applied to areas that typically experienced 400 to 750 °F during high-speed cruise. Not all Blackbirds featured such extensive amounts of plastic components. On the A-12 prototype, A-12T trainer, M-21, and YF-12A models, silicone-asbestos panels were replaced with A-110AT titanium alloy skin supported by hat-section stiffeners.

B. Structural Features

The Blackbirds not only incorporated cutting-edge materials, but also some novel design concepts (Fig. 14). The Lockheed team developed a monocoque structure for the fuselage and nacelles, and a multispar/multirib wing structure with chordwise corrugations for stiffness and to prevent warping at high temperatures. This resulted in a failsafe redundant structure.

The presence of fuselage side-fairings, or chines, generated nearly 20 percent of the aircraft's total lift. Acting as fixed canards they produced a favorable effect on trim drag and minimized the aft shift of the aerodynamic center of pressure as the aircraft's speed increased from subsonic to supersonic. Additionally, vortices from the chines improved directional stability of the aircraft as angle of attack increased. The chines also provided a convenient housing for wires and plumbing on either side of the cylindrical center-body fuel tanks.

The A-12 series featured a fairly flat, sharply tapered, chined nose. The airplane was a single-sensor platform, capable of carrying a camera or radar in the Q-bay. The YF-12A had a large plastic-laminate radome with a circular cross-section to house the fire-control radar for the interceptor's missile launch system. Fuselage chines on the YF-12A ended abruptly at the nose break. The airplane carried no reconnaissance sensors, but was fitted with missile launch bays in the forebody chines. The SR-71 used three interchangeable chined noses for the Capability Reconnaissance (CAPRE) side-looking radar, Optical Bar Camera (OBC), and Advanced Synthetic Aperture Radar System (ASARS). The CAPRE and OBC nose sections had silicone-asbestos chine panels, while the ASARS nose had a one-piece quartz/polymide radome/chine section. The SR-71 was a multi-sensor platform, capable of carrying a variety of cameras, radar, and other mission equipment simultaneously in the nose and fuselage bays.

The forward fuselage primary structure had a circular cross-section incorporating rings comprised of aged B-120VCA titanium alloy. Tapered chines blended into the sides of the fuselage. The chine structure was not integral with the fuselage structure, but was attached to it as fairings. The chines were partitioned into compartments to house electronics and mission equipment. The fuselage portion was covered with titanium skin, while silicone-asbestos panels covered the chines. The chine support structure was made mostly of annealed B-120VCA. Equipment bay doors were constructed using A-110AT material with some extruded sections as stiffeners. Fuselage longerons, located at the top, bottom, and sides, consisted largely of C-120AV aged-titanium extrusions.

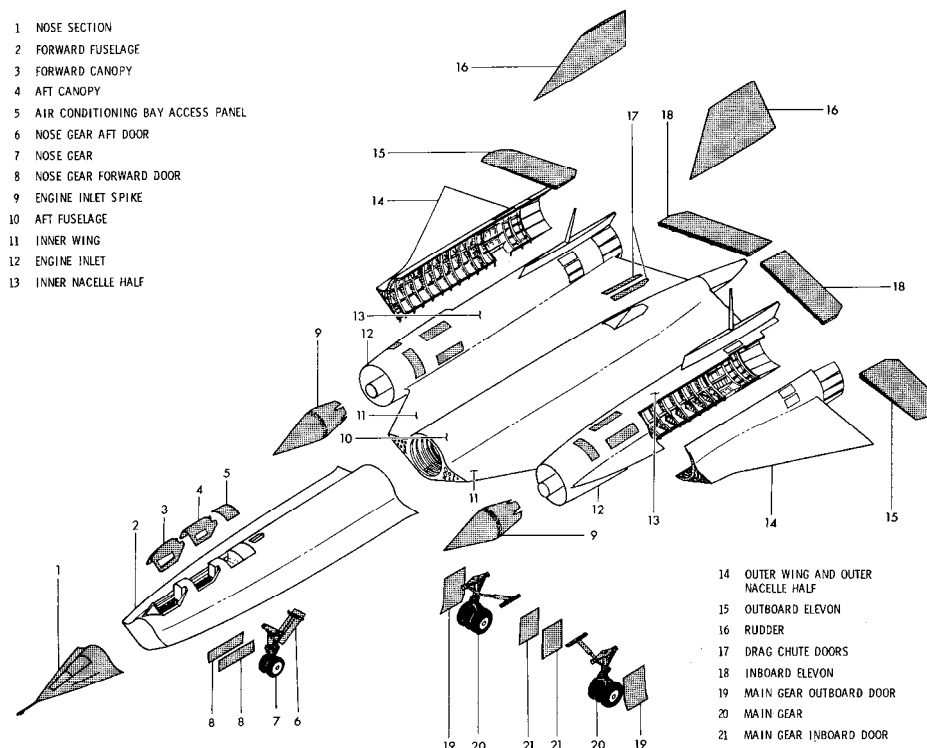


Figure 14. This diagram illustrates the major structural subassemblies of the SR-71. (Lockheed Martin)

Canopies enclosed each flight station. The A-12 was a single-seat aircraft. All other Blackbirds had two cockpits. The rear-seat position served different functions, depending on the aircraft model: reconnaissance (A-12, SR-71A), trainer (A-12T, SR-71B/C), interceptor (YF-12A), or mothership (M-21). Each canopy consisted of a titanium frame accommodating two side-glass window assemblies. Each window was comprised of two sealed glass panels separated by a 9/32-inch airspace acting as an insulating barrier against aerodynamic heating. Gaskets prevented excessive leakage of cockpit pressurization, but a small amount of air was allowed to bleed through between the panels to prevent fogging. An angular windscreen was provided only for the pilot's position, and for the instructor's cockpit on trainer models. It consisted of two glass assemblies, sealed and secured in a V-shaped titanium frame. The windscreen glass assemblies were similar to the side panels but were coated with magnesium fluoride to reduce glare. All windows were capable of withstanding high temperatures and high impact forces. The laminated inner window assembly consisted of a 1/4-inch-thick outer tempered glass panel, a 1/8-inch-thick silicon plastic layer, and a 3/16-inch-thick inner tempered glass panel. The outer window consisted of a 3/8-inch-thick glass panel. At cruise conditions temperatures reached 420 °F on the outer surface of the glass panels and 450 °F on the adjacent titanium skin. By comparison, boundary-layer air outside the cockpit reached 632 °F and the inner surface of the cockpit was about 80 °F. To keep the pilot cool, it was necessary to feed -40 °F air into the cockpit to maintain temperatures around 60 °F.

The aft fuselage main structure also had a circular cross-section and consisted of longerons, bulkheads, rig-frames, and stressed skins. This part of the fuselage was fastened onto the wing structure above and below wing beams extending through the fuselage. Longerons were constructed of titanium alloy and varied in cross-section according to load-capacity requirements. Bulkheads, separating fuel tanks and wheel well compartments, were of conventional web-and-stiffener design. The bulkheads were made primarily of titanium alloy sheet and formed sections, with the use of some extruded sections as stiffeners. Titanium ring frames in the aft fuselage consisted of Z-sections formed into quarter-circle segments attached to the longerons.

Titanium skin was spot-welded and riveted in place on the fuselage and panel assemblies. To prevent buckling, skin panels were attached to the wing spars with fasteners capable of sliding as the panels expanded and contracted with temperature changes. Fillet panels were used to blend the fuselage into the wing assemblies. The YF-12A and SR-71B/C trainer models had two small titanium ventral strakes mounted on the underside of each engine nacelle

for additional stability, to offset aerodynamic changes caused by their forward fuselage configurations. In addition, the YF-12A also had a titanium ventral fin near the aft end. The ventral fin was so large that it had to remain folded in a stowed position during takeoff and landing. During a NASA research mission in 1975 a YF-12A lost its main ventral fin during a sideslip maneuver. The incident gave researchers an opportunity to flight-test a new material. Technicians fitted a replacement ventral fin, made of Lockalloy, on the damaged YF-12A (Fig. 15). Lockalloy, developed by Lockheed California Company, consisted of 62 percent beryllium and 38 percent aluminum. Aircraft designers considered it a promising material for use in constructing high-temperature aircraft structures.



Figure 15. A ventral fin constructed of a Lockheed-designed beryllium-aluminum alloy was tested on a YF-12A.

The inner wing assemblies consisted of forward and aft wing boxes on either side of the main wheel well. A leading-edge section was attached to the front of the forward wing box and a trailing-edge section to the rear of the aft wing box. The wing box assemblies consisted mainly of titanium alloys, with some corrosion-resistant steel. To reduce the aircraft's RCS by reducing radar backscatter, the leading and trailing edges were characterized by triangular plastic panels interlocked with adjacent triangular titanium alloy panels. The inner wing surface panels consisted of multiple-layer titanium alloy formed-sheet construction. The lower surface panels were permanently installed and sealed to the wing structure for fuel retention in the integral fuel tanks while the upper panels were removable for maintenance access. The inside surfaces of the panels were formed into corrugations to alleviate effects of aerodynamic heating. Outer surfaces were beaded in the chordwise direction, with beads located between the inner surface corrugations. This type of construction, with the beaded and corrugated portions spot-welded together, allowed the panels to expand and contract with changes in temperature.

The outer wing assemblies were built onto the outer half of each engine nacelle. These consisted of titanium alloy machined forgings and formed parts. Interlocked triangular plastic and titanium panels made up the leading edge.

Inboard and outboard elevons served as the primary control surfaces, hinged at the trailing edge of the wings. The forward section of each elevon was a structural box of titanium alloy beams, ribs, and skin. The trailing edges were constructed of triangular-shaped titanium alloy panels alternated with plastic panels, as on the leading edge of the wing.

The two tails were canted inward and mounted atop the aft end of each engine nacelle. Each tail consisted of a stub fin and a rudder. The stub fin was fixed in place, extending approximately 21 inches above the nacelle surface. It was constructed of titanium alloy machined parts, plate, formed members, and sheet. The stub fin contained rudder servos and housed each rudder pivot post. One full rudder, having no fixed vertical stabilizer, was mounted on each stub fin. Each rudder extended approximately 75 inches above the stub fin. The left and right rudders were identical and interchangeable. The A-12 prototype, A-12T trainer, M-21 motherships, and YF-12A had rudders

made from titanium alloy. All others incorporated rudders made largely of plastic materials. The metal rudders were built with a central structural box section and attached leading- and trailing-edge assemblies. Plastic rudders incorporated basic frame members of titanium alloy. Subordinate members, including some of the ribs, spars, and exterior surface panels were made of bonded silicone-asbestos reinforced plastic materials. The plastic rudders weighed approximately 500 pounds and the metal rudders weighed somewhat less.

Each nacelle consisted of an engine inlet, inner and outer nacelle halves, and exhaust ejector. The engine inlet was a barrel-section structure attached to the front beam of the inner wing aft box section. The outboard side of the inlet supported a chine section that faired into the outer wing leading edge. The main body of each nacelle was split, with the inner half built as an integral part of the inner wing. The outer half was hinged for access to the engine. Nacelle ring frames on most of the Blackbirds were spot-welded, built-up, titanium alloy assemblies. Later SR-71 airframes incorporated machined titanium alloy forgings in place of most of the built-up ring frames. Longitudinal members of each nacelle half were built up of formed-sheet and extruded titanium alloy beams. The structure included various bypass doors and suck-in doors to control airflow within the inlet and engine compartment. Ejector flaps, operated by differences in air pressure on the outside and inside of each nacelle, were attached to the aft end. Because they were exposed to 1,200 °F temperatures, the inner surfaces of the ejector flaps consisted of Hastelloy-X. Tracks used to secure the flap sections together were constructed of René 41 alloy with titanium fillers between each flap.

The engine inlet spike assembly (Fig. 16) was a conical structure located in the center of each inlet. Moving the spike back and forth controlled the amount of air entering the engine. Spike position was governed by engine air requirements. The spike moved forward during subsonic flight and aft during supersonic cruise. The A-12 prototype, A-12T trainer, M-21, and YF-12A were equipped with titanium alloy spike assemblies. All other variants employed spike assemblies with a titanium tip and substructure, but external surfaces and some internal components were made from silicone-asbestos reinforced plastic materials.²⁷



Figure 16. A moveable cone, or spike, controlled the position of the shock wave and the Mach number of airflow within the inlet. (NASA)

The airplane was assembled in such a way as to alleviate structural loads. The wing bending moment was carried around the engine by frames within the nacelle, and through the fuselage by way of continuous spars. Wing surface panels were designed as a beaded (stiffened) structure to carry shear stress but not allow bending. The panels were assembled in such a way as to allow for thermal expansion relative to cooler spar caps. A chordwise corrugation under each skin bead was capable of carrying chordwise loads. Aerodynamic heating affected structural loading as

²⁷ Merlin, Peter W., "SR-71 Blackbird," *Advanced Processes & Materials*, Issue 161(5), ASM International, May 2003. Most of the material in this section was derived from the aforementioned article. Primary sources included: *A-12 Technical Manual MA12-2-2 – Airframe*, 1966, *Technical Manual SR-71-2-2, Organizational Maintenance – Airframe Group: SR-71, SR-71B, and SR-71C Aircraft*, 1987, and *Lockheed's SR-71 'Blackbird' Family* by James Goodall and Jay Miller, Aerofax/Midland Publishing, 2002.

the temperature difference between the top and bottom of the fuselage caused the nose section to droop significantly. Although most of the plastic parts in the chines and wing edges were considered secondary structure, they were required to conform to all local aerodynamic and thermal load limits.²⁸

Propulsion for the Blackbirds consisted of two Pratt & Whitney JTD-11B-20 (J58) afterburning turbojet engines (Fig. 17). Each had nine compressor and two turbine stages. A variable geometry inlet diffuser and a complex bleed bypass system allowed for high engine efficiency in the Mach 2.0 to Mach 3.2 flight regime by controlling the location of the shock wave inside the inlet and allowing air to bypass the turbine section and go directly to the afterburner. The forward compressor stages and inlet case were made of titanium alloys, including Ti-8-1-1 and Ti-5-2.5, because these have good creep (expansion and contraction) properties at temperatures up to 850 °F. The first-stage turbine vanes incorporated Mar-M-200DS, a nickel-base alloy cast with spanwise columnar crystal grains. Its granular structure reduced the risk of thermal shock cracking. Some first and second stage turbine blades, second-stage turbine vanes, and afterburner nozzle flaps were made from another nickel-base alloy, IN-100. The diffuser case was constructed using Inconel-718 nickel alloy, capable of withstanding 1,250 °F. Most J58 engine components were made of Waspalloy, an oxidation-resistant nickel-base alloy capable of withstanding 1,400 °F, but burner components were fashioned from Hastelloy-X. Turbine disks were made of Astralloy, a precipitation-hardened nickel-base alloy suitable for operations up to 1,500 °F. This extremely expensive material was available as a forging, and had creep and tensile strength qualities superior to Waspalloy. Parts with applications similar to those requiring the use of Hastelloy-X, but which required greater resistance to buckling and sliding wear, were made of L-605 (Haynes 25). A cobalt-base alloy, L-605 was easy to weld and form. This was later replaced with Haynes 188 and Haynes 230, both of which had improved oxidation resistance. The exhaust ejector on each engine was supported by streamlined struts and a ring of René 41 on which were hinged free-floating trailing edge flaps of Hastelloy X. During afterburner operation, these flaps experienced maximum temperatures of 1,400 °F on their inner surfaces and 1,600 °F on outer surfaces.



Figure 17. Technicians install a Pratt & Whitney J58 engine. (NASA)

²⁸ Alitzer, John, "SR-71 Structures and Materials," part of "Case Studies in Engineering: The SR-71 Blackbird," Course Ae107, Presented at the Graduate Aeronautical Laboratories, California Institute of Technology, Pasadena, Calif., April-May 1990.

By contrast with some of its other, more advanced concepts, the aircraft operated with fairly conventional flight controls. The inboard and outboard elevons provided pitch and roll and the two all-moving vertical fins provided lateral control. Because of thermal soak requirements, control cables were made of Elgiloy, a material used in watch springs.²⁹

Because it operated in an environment of high aerodynamic heating, the Blackbird required a special low-vapor-pressure, high-flash-point fuel, designated JP-7, one so difficult to ignite that a lit match thrown into a puddle of it is extinguished. Consequently, a pyrophoric igniter called triethylborane (TEB) was injected into the fuel for engine start and afterburner ignition. The fuel also served as a heat sink. Before entering the engine, cold fuel was used to pre-cool hot compressor-bleed air for use in the air conditioning system. The integral fuel tanks were coated with 10,000 linear feet of fluorosilicone sealant that leaked a considerable amount of fuel as a result of the provisions for tank expansion and contraction with changes in temperature ranging from minus-60 to more than 600 °F.³⁰

IV. Performance Characteristics

The defining performance characteristics of the Blackbirds included flight at high speeds and high altitudes as a result of a unique aerodynamic design and propulsion system. The aircraft operated within an exceptionally large Mach and altitude envelope (Fig. 18) but the equivalent airspeed, angle of attack (AOA), and load-factor envelope was relatively narrow. Takeoff and landing speeds were about 210 and 155 knots respectively. The airplane climbed at 400 to 450 knots equivalent airspeed (KEAS) and operated at normal supersonic cruise speeds between 310 and 400 KEAS. All Blackbird variants were designed to obtain maximum cruise performance around Mach 3.2 at altitudes from 74,000 to 85,000 feet. The external configuration, engine air inlet system, powerplant, and fuel sequencing were optimized at Mach 3.2 and the airplane attained true airspeeds near 1,850 knots.³¹

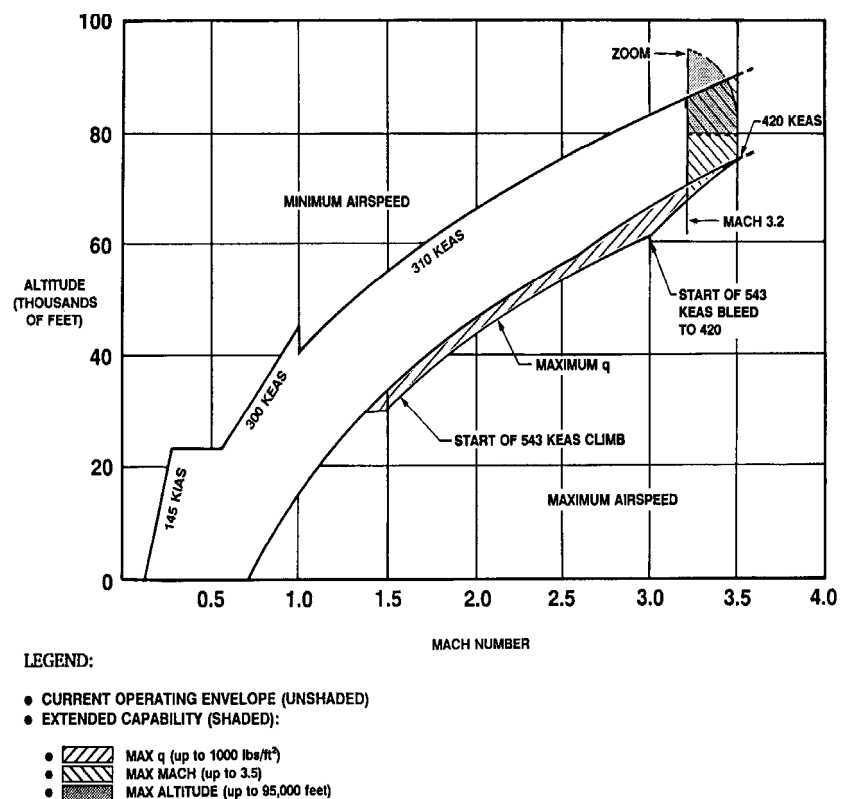


Figure 18. Standard flight envelope for the SR-71. (Lockheed Martin)

²⁹ Merlin, Peter W., "SR-71 Blackbird," *Advanced Processes & Materials*.

³⁰ *ibid.*

³¹ SR-71A *Flight Manual*, T.O. SR-71A-1, Section 6, "Flight Characteristics," October 1986.

A. Aerodynamics

The distinctive shape of the Blackbirds contributed to their performance capabilities. External configuration features affecting flight characteristics included delta wings, fuselage chines, and location of the engine nacelles.

The Blackbird was configured with very thin delta wings with rounded tips and a twist to the leading edge. The airplane had normal delta-wing flight characteristics including a large increase in drag as the airplane approached its AOA limit. This resulted in very high sink rates at slow speeds. The wings had a positive dihedral effect (i.e. a right yaw produces right roll and vice versa) that diminished at higher Mach numbers, and the airplane had low roll-damping qualities over the entire speed range. The Blackbird was equipped with a stability augmentation system (SAS) to compensate for poor lateral-directional stability. The outboard portion of the wing's leading edge had a negative conical camber that moved the center of lift inboard, to relieve loading on the nacelle carry-through structure. This also improved the maximum lift characteristics of the outboard wing at high AOA, and enhanced the airplane's performance during crosswind landings.

Except on the YF-12A, which had a different nose configuration, the Blackbirds had a pronounced chine (blended forward wing-body) extending from the leading edge of the wing to the nose. This chined forebody, accounting for approximately 40 percent of total aircraft length, improved directional stability with increasing AOA at all speeds, especially in the subsonic range. At supersonic speeds the chines also provided a substantial portion of the total lift and eliminated the need for canard surfaces or special nose-up trimming devices.³²

Automatic fuel tank sequencing shifted the center of gravity (c.g.) aft during acceleration, corresponding with the aft shift of center of lift with increasing Mach number. The system then maintained the c.g. at a relatively constant optimum location during cruise. This had the negative impact of reducing the static longitudinal stability margin, but the SAS compensated to provide satisfactory handling qualities. Additionally, the airplane's thermodynamic heating characteristics dictated that fuel in the wing tanks had to be used first because of the high surface-area-to-volume ratio.

Engineers also discovered an interesting effect as fuel depletion caused differential heating between the upper fuselage and the cooler lower surfaces where fuel remained. Differential expansion of upper and lower fuselage panels caused the chines to be deflected downward, marginally changing their aerodynamic characteristics.

The mid-span location of the engines minimized fuselage drag and interference effects. The inboard cant and droop of the nacelles allowed maximum pressure recovery at the engine inlets at normal AOA for high-altitude supersonic cruise. This configuration, however, rendered the aircraft sensitive to asymmetric thrust conditions.³³

B. Handling Qualities

The Blackbird's handling qualities evolved from wind-tunnel model tests that verified the lift-to-drag ratios necessary to achieve mission performance, and established the airplane's stability and control characteristics. In order to meet performance requirements, Lockheed designers had to accept a compromise affecting the airplane's inherent stability and control. In exchange for low drag in cruise, the engineers accepted low stability margins. If they had designed the airplane for high pitch-stability, large control deflections would have been required for trim, and the resulting trim drag would have compromised mission performance.³⁴

Low stability margins and aerodynamic damping inherent at high mission altitudes adversely affected the airplane's dynamic response and handling qualities. Lift (from the fuselage chines) forward of the c.g. destabilized the airplane in pitch. The chines, acting as fixed canards, also adversely affected handling in sideslip maneuvers at cruise AOA. To make up for these deficiencies, Lockheed designers incorporated an automatic flight control system (AFCS) consisting of a triple-redundant SAS, autopilot, and automatic pitch trim control (Mach-trim) system.³⁵

Overall, the Blackbird's handling characteristics were satisfactory. Although stick forces were extremely high at design cruise speed and low lift coefficients, the airplane was usually flown on autopilot under those conditions so the pilot was unaware of the high forces. The airplane had marginal lateral or directional stability under some conditions but the SAS compensated to allow safe maneuvering.³⁶

³² *ibid.*

³³ *A-12 Utility Flight Manual*, T.O. A12-1, Section 6, "Flight Characteristics," September 1965.

³⁴ Meyer, J.E., J.R. McMaster, and R.L. Moody, *Handling Qualities of the SR-71*, SP-508, Lockheed Advanced development Company, Burbank, Calif., October 1964, revised July 1967.

³⁵ Crickmore, *Lockheed Blackbird: Beyond the Secret Missions*.

³⁶ Abrams, Richard, William A. Lusby Jr., Mervin L. Evenson, and William L. Skliar, *SR-71A Category II Performance Tests*, 69-AFFTC-39459, Air Force Flight Test Center, Edwards, Calif., March 1970.

C. Propulsion System

The JT11D-20 (J58) afterburning turbojet engines had a unique variable-geometry inlet diffuser and a complex air-bleed bypass system that allowed air to bypass the turbine section and go directly to the afterburner, thus acting as a turbo-ramjet (Fig. 19). During high-speed flight, the inlet and exhaust ejector generated more than 80 percent of the total motive force while the engine itself provided less than 20 percent. The Blackbirds had a design cruise speed of Mach 3.2 (about 2,100 mph), limited primarily by structural temperature restrictions.

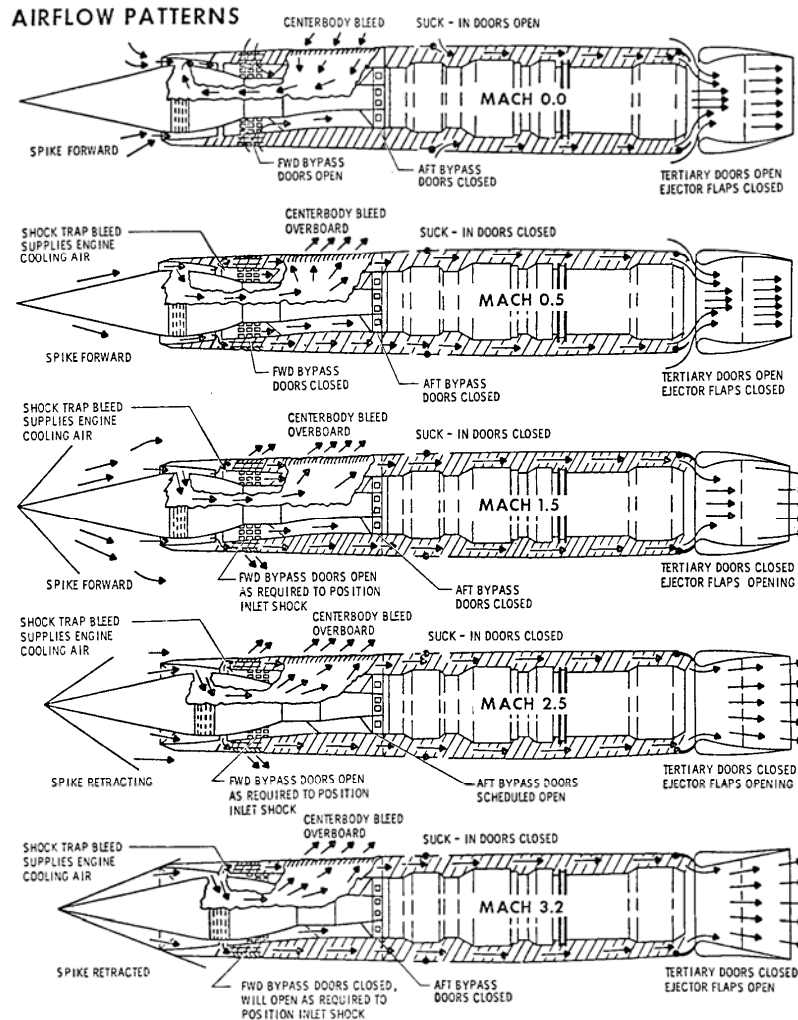


Figure 19. Engine operation from zero to cruise Mach number.
(U.S. Air Force)

The J58 engines had a maximum afterburner thrust rating of 34,000 pounds each at sea-level, standard-day conditions. The Blackbird's propulsion system included a mixed compression inlet in which air entered at supersonic speeds and slowed to subsonic speeds before reaching the engine. Air velocity had to be reduced because no existing engines could run on supersonic flow. Several devices moderated airflow into the engine. A movable cone, or spike, in the inlet translated forward and aft to control the position of the shock wave and inlet Mach number. Forward bypass doors opened and closed to maintain proper shock-wave position. The doors operated automatically as a function of pressures measured in the ducts. Aft bypass doors, operated by the pilot as a function of Mach number and forward-door position, controlled airflow at the engine turbine face. Designers also devised a system to bleed off low-energy boundary-layer air that formed along the surface of the inlet spike. This practice

improved inlet efficiency by rendering the entire main inlet flow passage available to the high-energy, high-velocity airflow.³⁷

During high-speed flight in the Blackbird, compression of air in the inlets generated most of the vehicle's thrust. At Mach 2.2 the inlet produced 13 percent of the overall thrust with the engine and exhaust ejector accounting for 73 and 14 percent, respectively. At Mach 3 cruising speeds the inlet provided 54 percent of the thrust and the exhaust ejector 29 percent. At this point the turbojet continued to operate but provided only 17 percent of the total motive force. The inlet had a compression ratio of 40:1 at cruise conditions where each inlet swallowed approximately 100,000 cubic feet of air per second.³⁸

A significant percentage of air entering the inlet bypassed the engine through ducts and traveled directly to the afterburner. At cruise Mach conditions, fuel burned more advantageously in the afterburner than in the main burner section. Hence, engineers described the powerplant as a turbo-ramjet.³⁹

Shock waves created by the inlet spikes presented a unique challenge. If designers failed to properly match airflow to the inlet, the shock wave created drag. Normally the shock wave would be expected to occur slightly behind the throat and supersonic diffuser for stability. But in this case, the spike and bypass doors functioned together to retain the shock wave inside the inlet. Sometimes, however, large airflow disturbances or improper inlet control system operation caused the inlet to expel the shock wave. This resulted in an inlet unstart, the byproduct of insufficient pressure and air for normal engine operation. This sudden loss of thrust produced violent yawing, pitching, and rolling motions.⁴⁰

D. Speed and Altitude

The Blackbirds are best known for their speed and altitude performance. The airplanes set numerous records, both official and unofficial. Some of the latter remained unknown to the public for many years.

In May 1965, Air Force crews set several official speed and altitude records in the YF-12A, including a closed-course speed of Mach 3.14 (2,070.101 mph) and a sustained altitude of 80,257.65 feet. Although impressive to the public at large, these feats did not represent the Blackbird's maximum capabilities. Just one week later, a CIA pilot flew an A-12 to a maximum speed of Mach 3.29 (2,171 mph), but this fact remained classified for more than 30 years.⁴¹

The maximum design cruise speed for all Blackbird variants was Mach 3.2. According to the SR-71 pilot's handbook (flight manual), Mach 3.17 was the maximum recommended cruise speed for normal operations. The pilot, however, could increase speed to Mach 3.3 as long as the engine CIT did not exceed 427 °C. Speeds exceeding Mach 3.3 were occasionally recorded during test flights, but these operations put excessive thermal stress on the airframe.

Maximum speed was limited by structural temperature restrictions, a part of the flight envelope known as the "heat barrier." In July 1976, relatively cool outside air temperatures allowed an Air Force crew to set an official speed record in the SR-71A, accelerating to Mach 3.32 (2,193 mph). This record stood even after the airplane's official retirement flight, in March 1990, set a 1,998-mile straight-course speed record between Los Angeles and Washington, D.C., of just over 64 minutes at an average speed of 2,144 mph. Although it might have been possible to better the speed of the 1976 flight, the crew on the retirement sortie did not want to take that record away from another SR-71 crew.⁴²

Designed to fly as high as 90,000 feet, the Blackbirds typically operated between 70,000 and 85,000 feet, altitudes at which they could carry a useful sensor payload and fuel supply. An Air Force crew set an official world altitude record in the SR-71A in July 1976, cruising at 85,069 feet. This record, however, already had been broken unofficially during Category II (Performance) testing when the fourth SR-71A, with a gross weight of

³⁷ Allender, James R., Ernest L. Pyne, Mervin L. Evenson, and William L. Skliar, *SR-71A Category II Stability and Control Tests*, Air Force Flight Test Center, Edwards, Calif., July 1970.

³⁸ Urie, David, "Case Studies in Engineering: The SR-71 Blackbird," Course Ae107, Presented at the Graduate Aeronautical Laboratories, California Institute of Technology, Pasadena, Calif., April-May 1990.

³⁹ Matraga, Gene, and William J. Fox, "YF-12A Development and Operational Experience," unpublished paper presented at the Supercruiser Conference, Wright-Patterson AFB, Ohio, February 17-20, 1976, p. 3. NASA Dryden Historical Reference Collection.

⁴⁰ Merlin, Peter W., *Mach 3+: NASA/USAF YF-12 Flight Research, 1969-1979*, NASA SP-2001-4525, NASA Headquarters, Washington, D.C., 2002.

⁴¹ "OXCART A-12 Aircraft Experience Data and Systems Reliability," BYE-8725-68, Central Intelligence Agency, Washington, D.C., 15 January 1968.

⁴² Crickmore, *Lockheed Blackbird – Beyond the Secret Missions*.

80,000 pounds, reached a cruising altitude of 86,700 feet. Engineers had predicted the maximum cruising altitude at that weight would be just 85,000 feet.⁴³

During another Category II flight, the test crew pushed the same airplane to the upper right-hand (maximum) corner of its performance envelope. After setting up an optimum climb profile, the pilot accelerated the airplane to Mach 3.22 and achieved an altitude of 89,650 feet.⁴⁴

The A-12, a lighter airplane due to its single crew station, was capable of attaining higher operating altitudes than the SR-71. In August 1965, a CIA pilot flew an A-12 to a maximum cruising altitude of 90,000 feet during a test flight.⁴⁵

The SR-71 was approximately 20,000 pounds heavier than the A-12. This meant it would attain altitudes about 3,000 feet lower than those attained by the A-12 at any given point in a flight profile for missions of the same range.⁴⁶

In 1975 Lockheed attempted to determine the feasibility of extending the Blackbird's speed and altitude capabilities. The results of several studies concluded the airplane's maximum speed limit could be extended to Mach 3.5 for short periods of time. The only structural limit to speeds above Mach 3.5 was a KEAS limit of 420, set by inlet duct pressures and temperatures that exceeded acceptable values. Limited inlet-capture area and excessive engine compressor inlet temperatures also limited operations at higher Mach numbers.

Similar studies addressed the possibility of achieving flight in the SR-71 well above 85,000 feet. Results indicated the SR-71 could briefly reach an altitude of about 95,000 feet in a zoom climb profile. The proposed mission could have been accomplished with an airplane at a gross weight of 85,000 pounds. According to the flight profile, the pilot would accelerate from Mach 3.2 to Mach 3.5 at an altitude of 80,000 feet, then zoom to 95,000 feet as speed decreased to normal cruise Mach numbers. The airplane would subsequently settle back down to an altitude of about 84,000 feet. Sustained flight at altitudes above 85,000 feet was limited by wing surface area and engine thrust capabilities.⁴⁷

E. Cruise and Climb Performance

In conventional jet aircraft, flying faster meant using more fuel. In the Blackbird, however, increased speed resulted in reduced fuel consumption at cruise conditions. For example, the SR-71 flight manual provided Specific Range charts indicating that an aircraft operating at a gross weight of 100,000 pounds in standard-day temperatures (-69 °F) would burn 38,000 pounds of fuel per hour at Mach 3.0. If the pilot accelerated to Mach 3.15, total fuel flow would drop to 36,000 pounds per hour.

Deviations from standard-day temperatures could significantly affect performance, especially during climb and acceleration. As outside air temperature increased above standard-day values the pilot could feel the Blackbird slow down. The inlets didn't function as efficiently because the forward bypass doors opened more, slowing climb rates during acceleration and requiring more thrust during cruise.

Lower-than-standard temperatures improved performance. A fully fueled SR-71 with a 135,000-pound gross weight, accelerating from Mach 1.25 at 30,000 feet to Mach 3.0 at 70,000 feet could burn about 28,000 pounds of fuel if the temperature were 10 °C above standard. With a temperature deviation of 10 °C (5.6 °F) below standard-day conditions, the same airplane would burn only 16,000 pounds of fuel. At cruise conditions a 100,000-pound aircraft could burn 44,000 pounds of fuel per hour if temperatures were 10 °C above standard. At 10 °C below standard, it would only consume 35,000 pounds per hour.

Because outside air temperature fluctuated along the flight path, the Blackbird pilot had to constantly monitor his CIT indicator and fuel consumption. A chart on his checklist compared CIT with Mach number and ambient air temperature, allowing the pilot to recognize temperature deviations as they were encountered (Fig. 20). Although the maximum design speed of the airplane was Mach 3.2, the pilot was authorized to accelerate to Mach 3.3 as long as CIT remained at or below 427 °C.⁴⁸

⁴³ Abrams, *et al.*

⁴⁴ Byrnes, Donn A. and Kenneth D. Hurley, *Blackbird Rising: Birth of an Aviation Legend*, Sage Mesa Publications, Los Lunas, NM, 1999.

⁴⁵ "OXCART Development Summary and Progress (1 October 1966 – 31 December 1966)," Tab A, Section 2, p.3, Central Intelligence Agency, Langley, VA, n.d.

⁴⁶ Memorandum for Director of Special Activities from Assistant for Programs, Research and Development (Special Activities), regarding "Comments to W.R. Thomas III Memorandum to the Director, Bureau of Budget," Central Intelligence Agency, 27 July 1966.

⁴⁷ *Lockheed SR-71 Supersonic/Hypersonic Research Facility Researcher's Handbook*, Volume II.

⁴⁸ Graham, Richard H., *SR-71 Revealed: The Inside Story*, Motorbooks International, Osceola, WI, 1996.

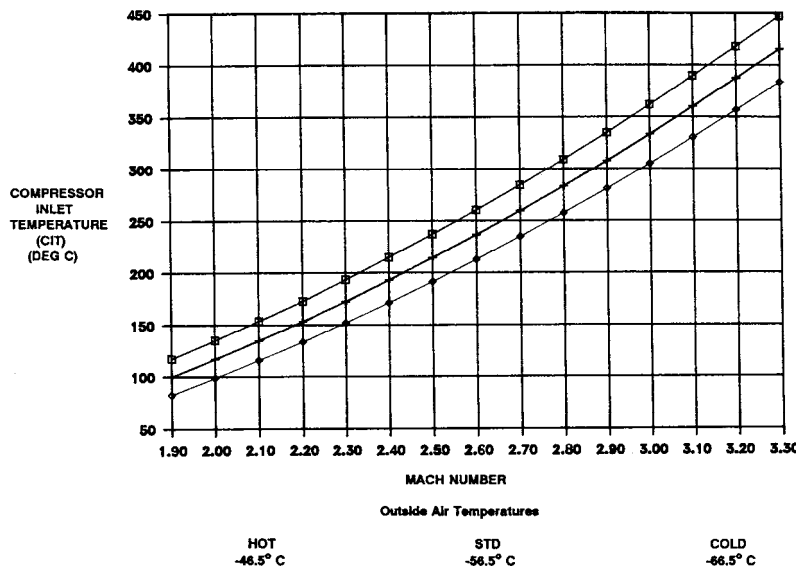


Figure 20. The relationship between engine compressor inlet temperature and Mach number. (Lockheed Martin)

F. Range and Endurance

According to a Lockheed design study the A-12 had a planned maximum range of 4,351 nautical miles, using 60 percent afterburner, at altitudes between 77,500 and 89,500 feet. The range for a maximum altitude profile (85,500 to 97,000 feet) at 100 percent afterburner was estimated to be 3,706. During flight-testing the A-12 demonstrated a maximum un-refueled range of 2,800 nautical miles at altitudes between 75,400 and 81,300 feet. A model specification for the SR-71 described the aircraft's maximum range as 3,800 nautical miles, using 60 percent afterburner and an altitude profile from 74,000 to 85,000 feet. Range for a maximum altitude profile of 80,000 to 91,000 feet was 3,048 nautical miles.⁴⁹

Operationally, the Blackbirds demonstrated an average range of 2,800 nautical miles and could be flown for extended missions with aerial refueling, limited only by usage of life-support consumables. At a cruise speed of Mach 3.2 and standard-day temperatures, the airplane had a maximum specific range of 54.1 nautical miles per 1,000 pounds of fuel.⁵⁰

The range of the airplane was largely dependent on the pilot's ability to endure the claustrophobic conditions of the Blackbird's cockpit for long periods of time. On 18 October 1966, an A-12 demonstrated a maximum endurance flight of 7.67 hours. The mission included subsonic and supersonic cruise and four aerial refuelings. This paved the way for operational sorties and ferry flights to forward deployment areas.⁵¹

Two months later, a Lockheed test pilot performed an A-12 proof-of-range sortie with a non-stop 10,200-mile flight in just over six hours. Most A-12 and SR-71 sorties lasted between two and five hours. In April 1971, an Air Force SR-71 crew earned the Mackay Trophy and Harmon Trophy for flying a record-setting 15,000 miles in 10.5 hours. The longest SR-71 operational missions took place during 1987 for the purpose of monitoring the war between Iran and Iraq. Each 11-hour sortie was flown from Kadena, Japan, to the Persian Gulf and back. The longest lasted 11.2 hours.⁵²

⁴⁹ Memorandum for Director of Special Activities from Assistant for Programs, Research and Development (Special Activities), regarding "Comments to W.R. Thomas III Memorandum to the Director, Bureau of Budget," Central Intelligence Agency, 27 July 1966.

⁵⁰ Graham, Richard H., *SR-71 Revealed: The Inside Story*.

⁵¹ "OXCART Development Summary and Progress (1 October 1966 – 31 December 1966)."

⁵² Crickmore, *Lockheed Blackbird – Beyond the Secret Missions*.

V. NASA's Mach 3 Flying Laboratory

NASA was involved with development of the Blackbirds from the very beginning. Wind-tunnel tests at Ames Research Center were critical to development of the Blackbird airframe and its unique engine inlet system. During developmental testing at Edwards Air Force Base, the Air Force allowed NASA technicians to install instrumentation on the SR-71 to collect data, but the agency was unable to obtain a Blackbird of its own until 1969.

The first major NASA project involving the Blackbirds was conducted with the Air Force as a partner. The joint NASA-Air Force YF-12 research program lasted 10 years and produced a wealth of data on materials, structures, loads, heating, aerodynamics, and performance for high-speed aircraft (Fig. 21). A second NASA effort in the 1990s employed several SR-71 aircraft as high-speed, high-altitude laboratories to conduct a variety of scientific experiments.

Within a year of the public debut of the YF-12A, NASA expressed an interest in the aircraft for use as a research platform. In an overview of active and proposed research programs for 1965, planners at the NASA Flight Research Center (FRC, later renamed Dryden Flight Research Center) noted that the YF-12A had “significant features of the configuration and operation of the aircraft that are of vital research interest,” and which would complement research being conducted with the XB-70, F-111, and X-15.

NASA engineers regarded the YF-12A, with its capacity to sustain Mach 3 cruise speeds, as a potential source of data for developing advanced supersonic and hypersonic aircraft. Initially, the FRC program consisted of analyzing results of the Air Force-Lockheed test program in hopes of a better understanding of:

- 1) High-altitude hypersonic handling qualities
- 2) Techniques to determine the structural integrity of hypersonic aircraft in flight
- 3) Performance of hypersonic air-breathing propulsion systems
- 4) The interrelationships between the aerodynamics of air propulsion systems and the aerodynamics of hypersonic cruise configurations.⁵³

In 1969, the Air Force agreed to make two YF-12A aircraft available to NASA researchers. A Memorandum of Understanding for a joint Air Force-NASA research program stipulated that the Air Force would provide the airplanes, personnel, ground support equipment, and facilities. NASA, in turn, agreed to pay operational expenses for the program, using funding that became available following termination of other research programs involving the XB-70 and X-15.

The MOU outlined the general provisions of a joint NASA/Air Force YF-12 research program consisting of Phases I and II. The Air Force Phase I, conducted to explore the tactical performance and support requirements of an advanced interceptor, included tactical tests of command, control, and communications; test intercepts of flying targets; and tests of the ASG-18 fire control system. The program also encompassed an examination of post-attack escape maneuvers, a demonstration of a semi-autonomous operational concept for a Mach 3 interceptor, and an assessment of the feasibility of a visual identification maneuver against an SST-type target.⁵⁴

NASA YF-12 research represented a cooperative effort by researchers from every NASA aeronautical center. Engineers from Langley Research Center in Virginia concentrated primarily on aerodynamics and structures. Lewis Research Center (now Glenn Research Center), Ohio, had an interest in propulsion aspects. Engineers from Ames Research Center focused on inlet dynamics and the correlation between wind tunnel and flight data. Researchers at the FRC organized these various interests into a single, unified investigation.⁵⁵

⁵³ “Project Programs – Part II,” briefing material from the center director’s monthly Projects Review meeting, NASA Flight Research Center, Edwards, Calif., March 1965, NASA DFRC Historical Reference Collection.

⁵⁴ “Memorandum of Understanding, USAF-NASA Research and Development Program,” June 5, 1969, NASA DFRC Historical reference Collection.

⁵⁵ Hallion, Richard P., *On The Frontier: Flight Research at Dryden, 1946-1981*, Washington, D.C., NASA SP-4303, 1984, p.191.



Figure 21. NASA employed several Blackbirds in a joint research program with the Air Force from 1969 to 1979. (NASA)

A. Heating and Loads Research

Initially, NASA researchers planned for the YF-12 program to focus on propulsion technology, especially inlet performance. Since the YF-12 featured a mixed-compression inlet, engineers planned to investigate drag, compressor face distortion, unstart margins, control parameters, air data requirements, and bleed system effects.

But problems associated with high-temperature instrumentation delayed the propulsion investigation. This postponement gave NASA engineers time to develop a second initiative: a structures research program involving thermal stresses and aerodynamic loads. The overall effort relied on wind-tunnel data, analytical prediction, and flight research.

Since supersonic aircraft undergo aerodynamic as well as thermal loads, the NASA team planned a series of experiments to measure both types of loads, combined and separately. Strain gauges placed in several locations within the fuselage measured aerodynamic loads. At the same time, instruments on the left side of the aircraft recorded skin temperatures.

The airplane enjoyed ideal qualities for thermal research. Previous research aircraft, such as the X-15, had experienced high temperatures but only for short periods of time. The YF-12, however, could sustain high-speed thermal loads for relatively long periods during cruise, enabling temperatures to stabilize.

After collecting flight research data over most of the YF-12 performance envelope, researchers compared it to data collected during ground testing in the High Temperature Loads Laboratory (HTLL) at the FRC during 1972 and 1973. The process of comparison involved several steps. Flight research data provided measurements of the combined effects of temperature and loads. Once this information had been gathered, technicians put the aircraft into the HTLL and heated the entire structure to the same temperatures it had experienced in flight. By measuring the strain outputs from temperature alone, NASA engineers could then separate the thermal effects from the flight data to obtain accurate measurement of aerodynamic loads.⁵⁶

Results of the heating experiments showed that the predictions largely agreed with the laboratory results. Data obtained during flight, however, indicated temperatures as much as 20 degrees higher than anticipated because of the differences in the process of heat transfer. The rate of radiant heating is lower than that for aerodynamic heating in areas of higher structural mass. Moreover, the dry fuel tanks used in the ground tests also influenced the results. In flight, the aircraft's fuel acted as a heat sink. Given the absence of fuel in the aircraft during ground-based heating tests, the fuel tank skin temperatures exceeded those obtained in flight. The simulation and flight measurements converged as the flight test aircraft depleted its fuel supply. Once these values converged, researchers established a correction for in-flight strain gauge measurements.⁵⁷

⁵⁶ Jenkins, Jerauld M. and Robert D. Quinn, "A Historical Perspective of the YF-12A Thermal Loads and Structures Program," NASA Dryden Flight Research Center, Edwards, Calif., NASA TM-104317, May 1996, pp. 8-11.

⁵⁷ Ibid., p.13.

B. Propulsion Research

With the YF-12, NASA researchers hoped to establish a technology base for the design of an efficient propulsion system for supersonic cruise aircraft, such as a Supersonic Transport (SST). Primary areas under investigation included inlet design analysis, propulsion system steady-state and dynamic performance, inlet engine control systems, and airframe/propulsion interactions (Fig. 22).

During the YF-12 research program, unscheduled unstarts were common on any given mission. Researchers studied the phenomenon of unstarts by inducing them intentionally and then using manual techniques and automatic systems to restart the engine. As a result of these important investigations into spike schedule refinements (coordinating spike position to retain the shock wave in the inlet) and hardware improvements, unstarts became a rare occurrence.⁵⁸

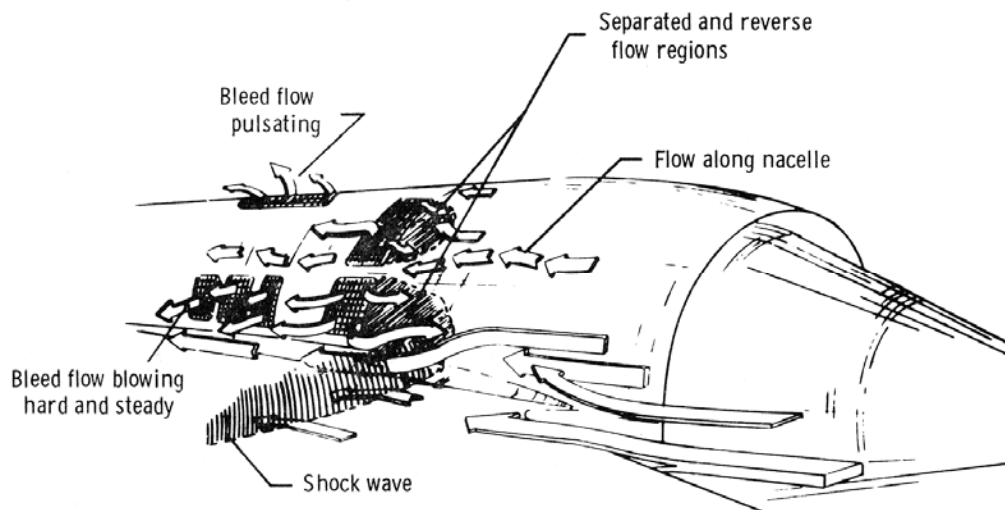


Figure 22. Researchers studied the characteristics of airflow in the engine inlets and nacelles. (NASA)

After entreaties from NASA officials, Air Force representatives agreed to loan NASA an SR-71A. For political reasons the aircraft's identity was hidden under the fictitious designation "YF-12C." By May 1971, Lockheed technicians undertook an inspection of the YF-12C in preparation for its addition to the NASA research program. They completed their work on the airplane by the middle of June, and prepared it to join the YF-12A aircraft already in NASA service.⁵⁹

In June 1971, the program suffered a setback when one of the YF-12A aircraft was lost in a non-fatal accident. After the airplane caught fire due to a leaking fuel line, the crew ejected safely but the airplane plunged into the desert and was completely destroyed. While the remaining YF-12A continued to serve as a loads testbed, the YF-12C arrived at the FRC in July 1971. Propulsion research flights did not begin, however, until June 1972.⁶⁰

⁵⁸ Albers, James A., *Status of the NASA YF-12 Propulsion Research Program*, NASA TM X-56039, March 1976.

⁵⁹ "Project Activity Guide (Accomplishments)," dated 2 June 1971 and 17 June 1971 list all three aircraft indicating that the YF-12C was not simply a replacement for the airplane that crashed on 24 June 1971. NASA Dryden Historical Reference Collection.

⁶⁰ Albers, James A., *Status of the NASA YF-12 Propulsion Research Program*.

Propulsion research using the YF-12C included airspeed calibrations, collection of baseline data, and data collection at numerous flight conditions. To gather data on propulsion system performance, pilots performed such maneuvers as level accelerations and decelerations, constant power turns, and airspeed lag calibration roller coaster maneuvers. They also gathered data on engine bypass door and inlet spike performance and established speed-power points. Finally, they performed constant-speed climbs and descents at specific KEAS or Mach numbers and constant-power turns. As the crews operated the engine inlet controls in manual and automatic modes, instruments measured oscillations known as phugoids.⁶¹

C. Landing Studies

In something of a departure for Blackbird researchers, NASA and Lockheed engineers investigated space shuttle landing dynamics using the YF-12C. Several flights, conducted in April and June 1973, demonstrated shuttle-type flight characteristics during low lift-to-drag approaches. The descent profile maximized engine negative thrust-inlet drag, and also allowed for the lowest possible lift coefficient.

In 1974, NASA engineers used the YF-12 aircraft to study the landing dynamics of a low-aspect-ratio supersonic aircraft. The data validated the Flexible Aircraft Takeoff and Landing Analysis (FATOLA) computer program developed by NASA Langley, one that offered a six-degree-of-freedom rigid body simulation. Technicians from McDonnell Douglas Astronautics Corporation programmed FATOLA with the YF-12 structural mode data and computed the airplane response to taxi, landing, and takeoff using a measured runway profile.

The program coordinated the research efforts of the NASA Langley Structures and Dynamics Division in developing an active landing gear control system for proposed SST aircraft. FRC researchers obtained experimental response data from flight tests to correlate with the response calculated using the FATOLA program. The validated FATOLA program defined the interactive characteristics of active-control landing gear systems with other aircraft characteristics and systems such as engine thrust, ground effect and crosswind aerodynamics, unsymmetrical touchdown conditions, airframe structural elasticity, and anti-skid braking.⁶²

A second landing project took place in 1977. This research demonstrated a dual-mode adaptive landing gear system to reduce the dynamic response of an airplane during ground taxi. An adaptive landing gear system can increase the lifespan of an airframe by reducing vibration stress incurred during taxi, takeoff, and landing.

Lockheed engineers designed a dual-mode adaptive landing gear system for the YF-12A (Fig. 23). The configuration included a strut with an optimized air load-stroke curve during landing, and an automatic switch-over system to allow for a flatter air load-stroke curve during taxi. The study demonstrated the effectiveness of a dual-mode adaptive landing gear system in reducing the dynamic response of an airplane during taxi. It also provided a database to aid in determining the degree of correlation between analytically predicted responses and actual test results with a full-scale YF-12A.⁶³

A final YF-12 landing study took place in March 1978. Dryden engineers scheduled three space shuttle orbiter landing approach simulation flights in the YF-12A. Researchers compared data collected from the YF-12 flights with that accumulated by simulated shuttle approaches flown in the F-8 Digital Fly-By-Wire aircraft and the NC-131H Total In-Flight Simulator. These simulations paved the way for the Approach and Landing Test (ALT) program using the space shuttle Enterprise.⁶⁴

⁶¹ A phugoid oscillation occurs when an aircraft's airspeed or pitch attitude is disturbed from its trimmed equilibrium condition by pilot input or natural air turbulence. The oscillations tend to die out after a few cycles and the aircraft returns to its trimmed condition.

⁶² "YF-12 Runway Response," Jim McKay notebook. NASA Dryden Historical Reference Collection. The original program, designed by NASA Langley for use with rigid bodies, was called Takeoff and Landing Analysis (TOLA). After McDonnell Douglas Astronautics Corporation programmers modified it with a flexible-body option it was renamed Flexible Aircraft Takeoff and Landing Analysis (FATOLA). Jim McKay refers to it simply as TOLA throughout his notes, but it is more properly called FATOLA as used for the YF-12.

⁶³ Gamon, Max A., "Testing and Analysis of Dual-Mode Adaptive Landing Gear, Taxi Mode Test System for YF-12A," Lockheed, September 1979, NASA CR-144884.

⁶⁴ Thompson, Milton O., "DFRC Orbiter Landing Investigation Team – Final Presentation," briefing at NASA Dryden Flight Research Center, Edwards, California on August 17, 1978. NASA DFRC Historical Reference Collection.



Figure 23. The YF-12A was used for several landing studies. (NASA)

Engineers compared data from the YF-12 shuttle simulations and the ALT flights. They found that the YF-12 pilots could correct the vehicle's flight path quickly and smoothly while maintaining desired altitude. By contrast, orbiter pilots in the Enterprise experienced significant oscillations in attitude and altitude. The comparative analysis of the two vehicles identified such critical orbiter flight control characteristics as excessive time delay in the attitude response to pilot control inputs and degraded flight path response to attitude changes associated with an unfavorable orbiter pilot location in the cockpit. The study determined that moving the pilot location forward improved the pilot's ability to control the vehicle's sink rate and landing performance.⁶⁵

D. Flying Laboratory

With their unique capabilities, Blackbirds were ideally suited to serving as flying laboratories, subjecting a wide range of experiments to conditions of high-altitude flight at Mach 3 speeds. NASA researchers used the aircraft to study boundary-layer flow effects, digital integrated controls, heat transfer, and drag effects. Other experiments included evaluation of a maintenance monitoring and recording system, measurement of engine effluents for pollution studies, noise suppression tests, sonic boom effects, and testing of a series of structural wing panels designed by NASA Langley and fabricated by Lockheed.

In July 1973, following ground tests in NASA's High Temperature Loads Laboratory a YF-12A was instrumented for boundary-layer measurements along the lower fuselage. Engineers typically use a number of empirical theories to predict compressible turbulent-boundary-layer parameters. Since these theories produce substantially different values, they require additional data from flight and wind-tunnel experiments. NASA researchers fitted the YF-12A with boundary-layer rakes to collect such data during flight.

The YF-12A also carried an aft-facing step experiment to determine the drag penalty caused by aft-facing surface discontinuities in a thick boundary-layer region. Such discontinuities caused drag and shock wave propagation at supersonic speeds. The experiment provided designers with data for predicting the drag associated with lap joints and shingle structures on large aircraft at high Mach numbers.⁶⁶

In early November 1974, the YF-12A underwent an experiment known as Coldwall (Fig. 24) to study the effects of compressible turbulent boundary layer and heat transfer coefficient at high speed. The test apparatus consisted of a 13-foot-long stainless steel tube mounted on a ventral pylon below the forward fuselage. The tube, equipped with thermocouples and pressure sensors, required cooling by liquid nitrogen and a covering made of insulating material. Planners intended the insulator to be pyrotechnically removed at Mach 3, exposing the tube to aerodynamic heating.

⁶⁵ Teper, Gary L., Richard J. DiMarco and Irving L. Ashkenas, "Analysis of Shuttle Orbiter Approach and Landing Conditions"; Hawthorne, Calif., Systems Technology, Inc., Technical Report TR-1137-1, January 1980, pp. 17 – 26.

⁶⁶ *Basic Research Review for the NASA OAST Research Council*; RTOP-761-74-01, Robert D. Quinn, August 1971, pp. 15; RTOP-501-06-05, RTOP-501-06-08, RTOP-770-18-10, RTOP 501-06-05, Edwin J. Salzmann, 7 August 1972 and 20 August 1974, pp .9 – 10; RTOP-505-06-31. Sheryll Goecke Powers, 20 October 1975, p. 9.

Researchers also conducted wind-tunnel tests of a similar tube for comparison with data obtained in flight in order to validate ground research methods.



Figure 24. The Coldwall experiment provided heat transfer data. (NASA)

Actual Coldwall project data flights did not begin until August 1976, beginning with a series of baseline “hot wall” flights without the liquid nitrogen coolant or insulation. The first true Coldwall flights took place in 1976 and 1977.⁶⁷

At the time, several theories existed regarding the nature of turbulent heat transfer, but they yielded conflicting results when compared with wind-tunnel data. The competing schools of thought included Edward R. van Driest’s equations for estimating turbulent heat transfer, E. R. G. Eckert’s reference enthalpy method, and the Spalding-and-Chi method for determining skin friction coefficients. Researchers used the Coldwall experiment data to validate Van Driest’s theory.

Following the in-flight loss of a ventral fin in February 1975, researchers tested a new material. Technicians fitted a replacement fin, made of Lockalloy skin panels over titanium framing, on the damaged YF-12A. Lockalloy, a metal alloy developed by Lockheed, consisted of 62 percent beryllium and 38 percent aluminum. Aircraft designers considered it a promising material for constructing high-temperature aircraft structures.

The YF-12 also served as a testbed for advanced structural panels. A number of structural-configuration and material concepts showed promise in terms of reducing aircraft structural weight. These panel tests were initiated at NASA Langley under the Supersonic Cruise Aircraft Research (SCAR) program. Each panel type underwent ground testing by Lockheed before the actual flight test. In 1977, a SCAR panel was fitted to the YF-12C wing surface and flown regularly on a non-interference basis. Engineers assessed its structural integrity after each flight.⁶⁸

In 1978, engineers tested a Loads Alleviation and Mode Suppression (LAMS) system on a YF-12A. The design involved the use of small canards (or shaker vanes) on the aircraft forebody to excite the airplane’s structural modes using controlled dynamic inputs at selected flight conditions. Such a system allowed a pilot to use feedback control techniques to suppress the aircraft’s aeroelastic contributions to local acceleration and to develop techniques to reduce aircraft damage from air turbulence. The resulting flight test data could then be compared with calculated aeroelastic response data, thus validating analytical techniques.⁶⁹

Meanwhile, the YF-12C was used for cooperative controls research. This program focused on digital integrated control of the aircraft’s inlets, autopilot, auto-throttle, air data system, and navigation system.

⁶⁷ “Aeronautical Projects Update - June 1977,” Memorandum from Director of Aeronautical Projects and Director of Research to the Director of NASA Hugh L. Dryden Flight Research Center, dated 5 July 1977. NASA DFRC Historical Reference Collection.

⁶⁸ Carter, Alan L., *Basic Research Review for the NASA OAST Research Council*, RTOP-743-32-23, pp. 43 – 45, 20 August 1974.

⁶⁹ Edinger, Lester D., Frederick L. Schenk, and Alan R. Curtis. *Study of Load Alleviation and Mode Suppression System (LAMS) on the YF-12 Airplane* (Washington, D.C.: NASA CR-2158, December 1972), p. 2.

As a result, a Cooperative Airframe/Propulsion Control System (CAPCS) digital computer went into the YF-12C. This system incorporated the air data, inlet, and autopilot systems into a single computer to improve overall aircraft flight control. The CAPCS system exceeded designers' goals. Flight-path-control precision improved by a factor of 10. Additionally, aircraft range increased by seven percent, and inlet unstarts became almost unknown. Ultimately, Lockheed installed the system in the entire operational SR-71 fleet.⁷⁰

E. NASA SR-71 Research Program

In 1990, after the Air Force formally retired the Blackbirds, NASA arranged to acquire two SR-71A models and the sole remaining SR-71B trainer for use as research aircraft. The following year, the SR-71B was used in tests of the Navy Radar Surveillance Technology Experimental Radar (RSTER) during a sortie over the Atlantic Ocean. The RSTER was an ultrahigh frequency sensor designed to detect high-flying missiles despite a high degree of radar clutter and jamming interference. In another project, an SR-71A carried an Orbital Sciences Corporation frequency scanning experiment and the OSC F3SAT backup satellite, carried in passive mode to check pre-launch conditions.

At extremely high altitudes, the airplane was an ideal platform for remote sensing technology experiments. Between October 1993 and October 1994, the aircraft carried several such packages. In the spring of 1993, the SR-71A carried the Southwest Research Institute Ultraviolet Imaging System. The UV-sensitive charge-coupled device, combined with a telescope, was a prototype for a miniature astronomical lab designed for use on the space shuttle. That summer the airplane's nose was equipped with a near-ultraviolet spectrometer for observation of volcanic gases in the UV spectrum. An upward-looking UV-sensitive video camera recorded a variety of celestial objects in wavelengths blocked from the view of ground-based astronomers. The Low Earth Orbit Experiment validated technology for ozone mapping sensors to be carried on the Russian Meteor-3 satellite. Finally, a Dynamic Auroral Viewing Experiment provided data for the U.S. Navy.

The SR-71 also served as a testbed for an Optical Air Data System (OADS), a fiber optic device using laser technology to replace the pitot tube (airspeed probe) on high-performance aircraft. It used laser light instead of air pressure to produce airspeed and attitude reference data such as angle of attack and sideslip normally obtained with small tubes and vanes extending into the air stream or from tubes with flush openings on an aircraft's outer skin. The flights provided information on the presence of atmospheric particles at altitudes above 80,000 feet, where future hypersonic aircraft might be expected to operate. The system, known as a sheet-pair laser anemometer, projected six sheets of laser light from the underside of the airplane. As microscopic atmospheric particles passed between the beams, direction and speed were measured and processed into standard speed and attitude references. An earlier OADS data collection system was successfully tested at Dryden on an F-104 testbed.

Under NASA's commercialization assistance program the SR-71 was used in the development of Motorola's commercial satellite-based, instant wireless personal communications network, called IRIDIUM. During IRIDIUM development tests, the SR-71 acted as a surrogate satellite for transmitters and receivers on the ground. The SR-71 also was used in a project for University of California-Los Angeles researchers investigating the ability of charged chlorine atoms to protect and rebuild Earth's ozone layer.

In 1995, NASA crews flew a number of sonic boom research flights in support of the High-Speed Research Program. This was a NASA-wide program to develop technology for a supersonic passenger aircraft called the High-Speed Civil Transport. Researchers used the SR-71 to study ways of reducing sonic boom overpressures in the hope that such data could eventually lead to aircraft designs that would reduce peak overpressures and minimize the startling effect they produce on the ground.⁷¹

The final major project for NASA's SR-71 involved the Linear Aerospike SR-71 Experiment (Fig. 25). Technicians mounted a 41-foot-long flight test fixture, dubbed the "canoe" and capable of containing liquid rocket propellants, on top of the aircraft. It supported a 12-percent-scale, half-span model of an X-33 research vehicle – a prototype of a proposed space shuttle replacement – complete with a working linear aerospike engine with eight thrust cells. In this way the SR-71 served as a flying wind tunnel to validate ground-based wind-tunnel data and computer-generated predictions. Although the X-33 project was cancelled in 1998, the experiment provided researchers with information that may help predict how operation of aerospike engines at altitude will affect the aerodynamics of a future reusable launch vehicle.⁷²

⁷⁰ "NASA YF-12 Cooperative Control Program" briefing, 1983. NASA Dryden Historical Reference Collection.

⁷¹ Merlin, Peter W., "Lockheed SR-71 Flight Log," September 2002. NASA Dryden Historical Reference Collection.

⁷² Hallion, Richard P. and Michael H. Gorn, *On the Frontier: Experimental Flight at NASA Dryden*, Smithsonian Books, Washington, D.C., 2003.



Figure 25. A half-span scale model of the X-33 was dorsally mounted on the SR-71 to test a linear aerospike propulsion system. (NASA)

VI. Lessons Learned

The Blackbirds provided numerous valuable lessons to designers, builders, and users of these remarkable aircraft. These lessons include results of the Lockheed Advanced Development Projects Division's "Skunk Works Principles" of management, innovative design and manufacturing techniques, and data from numerous experimental research programs.

A. Kelly's Way – The Skunk Works Approach

Since the early 1940s, the Lockheed (now Lockheed Martin) Skunk Works has become synonymous with innovative aerospace design and manufacturing techniques. This is due in large part to a management approach pioneered by Skunk Works founder Clarence "Kelly" Johnson. Designed to foster creativity and innovation, his method established principles for development and production of highly complex aircraft in a relatively short time and at relatively low cost. Although not easily applied in the corporate world of the early 21st century, it is worthwhile to study this innovative business model.

Johnson often summed up his method in just seven words: "Be quick. Be quiet. Be on time." Eventually, however, he wrote a set of 14 rules addressing program management, organization, contractor/customer relationships, documentation, customer reporting, specifications, engineering drawings, funding, cost control, subcontractor inspection, testing, security, and management compensation. This management approach offers a proven, efficient method for developing new technologies, executing engineering and manufacturing development programs, procuring limited production systems at low rates, and upgrading current systems.⁷³

In the modern corporate structure, however, serious disconnects between acquisition policies and procedures have created an environment not typically conducive to true Skunk Works operations. The longer a program lasts, the harder it becomes to maintain a small organization. While the Skunk Works approach is not universally applicable, it may be beneficial, in certain situations, for the government to allow a contractor to operate in this manner.⁷⁴

B. Technological Achievement

The process of designing, building, and operating the unique family of aircraft known as the Blackbirds provided numerous technological lessons. Perhaps the most impressive characteristic of the Blackbirds is the fact that they were designed before the advent of supercomputing technology. A small team of talented engineers, using slide-rules and know-how, built a family of operational airplanes capable of flying faster and higher than any air-breathing craft before or since. In addition, they had to invent new methods for parts fabrication, tooling assembly, construction, and testing.⁷⁵

⁷³ Miller, *Lockheed Skunk Works: The First Fifty Years*, Aerofax, Arlington, TX, 1993.

⁷⁴ Aronstein, David C. and Albert C. Piccirillo, *Have Blue and the F-117A: Evolution of the Stealth Fighter*, American Institute of Aeronautics and Astronautics, Reston, VA, 1997.

⁷⁵ Merlin, Peter W., "SR-71 Blackbird," *Advanced Processes & Materials*, Issue 161(5), ASM International, May 2003.

To meet customer requirements for RCS reduction as well as for high speed, Lockheed spent a great deal of time and money investigating high-temperature radar-absorbing materials. These included pioneering work with first-generation composites and high-temperature plastics. Lockheed's innovative methods of reducing total and incidental RCS became the basis for virtually all U.S. low-observables studies and hardware to follow, eventually leading to development of true "stealth" aircraft that would be virtually invisible to radar.

The Blackbirds' hostile operating environment necessitated the development of fuels, lubricants, and sealants that could withstand high temperatures. Other specialized materials, such as seals for the hydraulic system and high-temperature window glass, had to be developed as well. For operational missions, it was necessary to solve the problem of how to take clear pictures through hot, turbulent airflow across the camera windows.⁷⁶

Because the A-12 went from limited go-ahead to first flight in just 30 months, the manufacturing process required a total overlap in all design and construction phases. Consequently, there was not enough time to do things progressively and in sequence. Design actions had to be taken based on the best available estimates. Extensive component testing was accomplished as early as possible to validate the overall design as the airplane was being built. If testing dictated a change, it was accomplished as a progressive modification before the first flight.

Lack of advanced computer modeling capability necessitated reducing problems to their lowest common denominator before making calculations. This simplified the airplane's design and forced engineers to rely on their expertise. According to Lockheed engineer John Alitzer, "The most valuable design engineer is the engineer with the ability to ballpark a design based on raw data and then have it prove to be close to correct when all supporting information is fed to the computers."⁷⁷

Creating a powerplant for the Blackbirds also resulted in significant lessons for engine manufacturer Pratt & Whitney as the company embarked on an intensive design and development effort. The propulsion integration phase involved determining aerodynamic compatibility, installation and structural technology advances, and development of a unique mechanical power-drive mechanism and tailored fuel system. Engine designers had to explore uncharted territory and discover, identify, and address numerous challenges arising from such areas as engine cooling and airflow. It quickly became apparent that a straight turbojet cycle provided a poor match for the inlet and did not produce the required net thrust at cruise Mach conditions. To overcome these difficulties, Pratt & Whitney designers invented a bleed-air bypass cycle to match engine/inlet airflow requirements.

Engine materials and fabrication technology presented some of the greatest challenges. The manufacturer had to learn how to form sheet metal from materials previously used only to forge turbine blades, and devise methods for welding it successfully. Turbine disks, shafts, and other components also had to be fabricated from high-strength, temperature-resistant materials. Accessory drives, pumps, and other auxiliary equipment had to be designed to withstand the temperatures and stresses encountered in routine operation. Parts of the afterburner had to withstand as much as 3,200 °F.

Although Pratt & Whitney had a very large computer system for its day, it was no more sophisticated than some of the hand-held calculators that became available within two decades. Consequently, like the Blackbirds it powered, the J58 was essentially designed by slide-rule. Pratt & Whitney's success was primarily the result of compatible conceptual designs, diligent application of engineering fundamentals, freedom to change the engine and aircraft design with minimal contractual paperwork, and exceptional teamwork.⁷⁸

Matching the powerplant to the airframe was a significant challenge that centered on development of the inlet system. The Blackbird inlet was a triumph of engineering that required extensive development work prior to finalizing the design. In order to arrive at a usable inlet configuration, Lockheed technicians collected approximately two million data points in the wind tunnel. At least that much data was later collected during flight-testing for the purpose of validating predictive methods.⁷⁹

C. Results of the NASA Research

Use of the Blackbirds as flying laboratories provided important lessons for researchers. The joint NASA/Air Force YF-12 research program of the 1970s and later SR-71 projects produced a wealth of data, derived from flight and ground research as well as from simulation and modeling. Collectively, these investigations made important

⁷⁶ Goodall and Miller, *Lockheed's SR-71 'Blackbird' Family*.

⁷⁷ Alitzer, John, "SR-71 Structures and Materials," part of "Case Studies in Engineering: The SR-71 Blackbird," Course Ae107, Presented at the Graduate Aeronautical Laboratories, California Institute of Technology, Pasadena, Calif., April-May 1990.

⁷⁸ Brown, William H., "J58/SR-71 Propulsion Integration or The Great Adventure Into the Technical Unknown," *Lockheed Horizons*, Issue 9, Winter 1981/82, Lockheed Corporation, Burbank, Calif., 1981.

⁷⁹ Johnson, *History of the Oxcart Program*.

contributions to the advancement of aerodynamics and thermodynamics. Among other achievements, the comparison of flight data to wind-tunnel data and predictions helped researchers develop more accurate modeling techniques for flexible, supersonic aircraft designs.

Because the high speeds of the YF-12 generated sustained aerodynamic heating, the YF-12 team needed to devise data-recording techniques suited to these conditions. To begin with, researchers compared heating measurements in the High Temperature Loads Laboratory to in-flight heating. The results allowed them to more accurately calibrate instrumentation for loads measurement on high-speed aircraft by separating thermal loads from aerodynamic loads.

The YF-12 aircraft likewise provided a wide range of propulsion data on variable-cycle engine operation and mixed-compression inlet operation. Flight research demonstrated that an inlet could be designed using small-scale models and also showed that YF-12 inlet dynamics had a profound effect on stability and control. Ultimately, NASA developed a computer control system for the bypass doors to improve efficiency. It increased aircraft range and performance and eventually became incorporated into the operational SR-71 fleet.⁸⁰

Wind-tunnel model data provided an opportunity to validate scale and wind-tunnel effects against the flight data. It also enabled engineers to determine more precisely the placement of instruments in the airplane inlet. Inlet-flow system interaction studies helped researchers define the inlet operating envelope and yielded information about unstart/restart boundaries. Engineers compared data from the NASA Ames and NASA Lewis wind tunnels to data obtained during research flights to better evaluate scaling and tunnel effects.

During a series of landing studies, a mixed-volume dual-mode gear system reduced airplane dynamic response during high-speed taxi. Overall, the dual-mode system provided significant dynamic response reductions, yielding a smoother ride. Analytical results generated by a digital computer program provided excellent correlation with the flight test data at most areas, except the cockpit.

During handling-qualities investigations made during the YF-12 program, researchers concentrated on characteristics associated with longitudinal control during high-speed supersonic cruise, with possible application to the development of a supersonic passenger transport aircraft. Flight research on the YF-12 also included certain propulsion and aerodynamics problems encountered during the Blackbird's operational life.

The YF-12 team also employed the aircraft as a platform for studying human factors in a high-altitude supersonic cruise environment. Researchers first identified sets of aircraft and physiological parameters most sensitive to pilot workload. Next, they isolated and quantified physical and non-physical workload effects. Finally, they gathered and reduced flight data for comparison with findings from a clinical study to develop a pilot workload model from which predictions could be made.

NASA engineers conducted extensive studies of the boundary layer, using instrumented rakes. They found significant discrepancies between wind-tunnel model data and flight test results. These apparently resulted from surface imperfections on the full-scale aircraft, so researchers developed predictive methods to compensate for these differences.⁸¹

Another benefit of the YF-12 program arose from the extreme altitude range at which the aircraft flew. The YF-12 contributed valuable sonic boom information and showed that mild turbulence could be encountered even at the highest altitudes at which the aircraft cruised.⁸²

Finally, NASA and Air Force researchers gained valuable information concerning loads suppression and mode alleviation for flexible aircraft using a nose-mounted canard (shaker vane) system. This apparatus allowed them to make direct comparisons with calculated aeroelastic response data, and thereby validate available analysis techniques.

Thus, over its 10-year lifespan, the program made significant contributions to high-speed aeronautical research. Perhaps most important, it left a legacy of structural, aerodynamics, propulsion, and atmospheric physics data likely to serve as the basis for future high-speed aircraft designs and analytical model evaluation.⁸³

In the 1990s, NASA again employed Blackbirds in a variety of projects. With the ability to fly at altitudes above 80,000 feet and at speeds in excess of Mach 3, the Blackbird was a unique asset for high-speed, high-altitude

⁸⁰ Merlin, Peter W., *Mach 3+: NASA/USAF YF-12 Flight Research, 1969-1979*, NASA SP-2001-4525, NASA Headquarters, Washington, D.C., 2002.

⁸¹ Merlin, *Mach 3+: NASA/USAF YF-12 Flight Research, 1969-1979*.

⁸² Matranga, Gene J., "The Realities of Manned Supersonic and Hypersonic Flight – Lessons Learned" presentation at NASA Lewis Research Center Hypersonic Propulsion Symposium August 1988. Matranga's personal collection.

⁸³ Merlin, *Mach 3+: NASA/USAF YF-12 Flight Research, 1969-1979*.

research. Additionally, the various fuselage bays designed to hold reconnaissance equipment were ideal for carrying research instrumentation, remote sensing technology experiments, and experiment packages.⁸⁴

Shortly after completing this research program, the Blackbird was retired for the last time. Its legacy, however, will live on in future designs of high-performance aircraft and advanced aerospace vehicles.

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Apologies to anyone I missed. Any factual errors are the author's responsibility. I made an attempt in good faith to get the facts straight by using the best available source material.

⁸⁴ Merlin, "Storied SR-71 is Dryden's newest display."