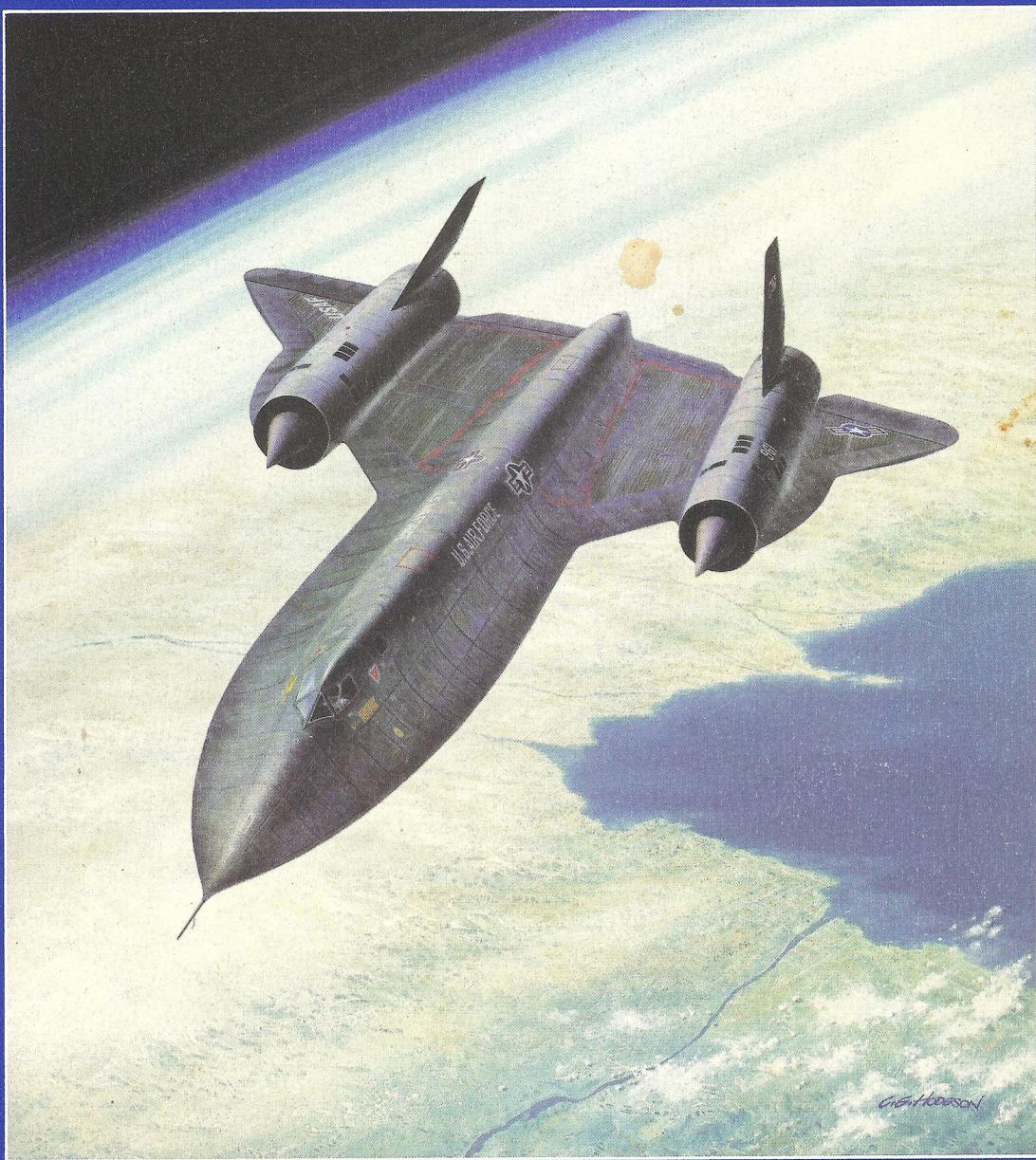


LOCKHEED HORIZONS



Winter 1981/82

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Lockheed SR-71 at Altitude

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This paper has been prepared by the writer to record the development history of the Lockheed SR-71 reconnaissance airplane. In my capacity as manager of Lockheed's Advanced Development Division (more commonly known as the "Skunk Works") I supervised the design, testing, and construction of the aircraft referred to until my partial retirement five years ago. Because of the very tight security on all phases of the program, there are very few people who were ever aware of all aspects of the so-called "Blackbird" program. Fortunately, I kept as complete a log on the subject as one individual could on a program that involved thousands of people, over three hundred subcontractors and partners, plus a very select group of Air Force and Central Intelligence Agency people. There are still many classified aspects of the design and operation of the Blackbirds but by my avoiding these, I have been informed that I can still publish many interesting things about the program.

In order to tell the SR-71 story, I must draw heavily on the data derived on

two prior Skunk Works programs—the first Mach 3-plus reconnaissance type, known by our design number as the A-12, and the YF-12A interceptor, which President Lyndon Johnson announced publicly 1 March 1964. He announced the SR-71 on 24 July of the same year.

BACKGROUND FOR DEVELOPMENT

The Lockheed U-2 subsonic, high-altitude reconnaissance plane first flew in 1955. It went operational a year later and continued to make overflights of the Soviet Union until 1 May 1960. In this five-year period, it became obvious to those of us who were involved in the U-2 program that Russian developments in the radar and missile fields would shortly make the U-Bird too vulnerable to continue overflights of Soviet territory, as indeed happened when Francis Gary Powers was shot down on May Day of 1960.

Starting in 1956, we made many studies and tests to improve the survivability of the U-2 by attempting to fly higher and faster as well as reduc-

DEVELOPMENT OF THE LOCKHEED SR-71 BLACKBIRD

Clarence L. Johnson
Senior Advisor
Lockheed Corporation

ing its radar cross-section and providing both infrared and radar jamming gear. Very little gains were forthcoming except in cruise altitude so we took up studies of other designs. We studied the use of new fuels such as boron slurries and liquid hydrogen. The latter was carried into the early manufacturing phase because it was possible to produce an aircraft with cruising altitudes well over 100,000 feet at a Mach number of 2.5. This design was scrapped, however, because of the terrible logistic problems of providing fuel in the field.

Continuing concern for having a balanced reconnaissance force made it apparent that we still would need a manned reconnaissance aircraft that could be dispatched on worldwide missions when required. From vulnerability studies, we derived certain design requirements for this craft. These were a cruising speed well over Mach 3, cruising altitude over 80,000 feet, and a very low radar cross-section over a wide band of frequencies. Electronic countermeasures and advanced communica-

tions gear were mandatory. The craft should have at least two engines for safety reasons.

GETTING A GRASP ON THE PROBLEM

Our analysis of these requirements rapidly showed the very formidable problems which had to be solved to get an acceptable design.

The first of these was the effect of operating at ram-air temperatures of over 800°F, Figure 1. This immediately ruled out aluminum as a basic structural material, leaving only various alloys of titanium and stainless steel to build the aircraft. It meant the development of high-temperature plastics for radomes and other structures, as well



The Author About
to Fly in an Early
A-12 Flight Test

as a new hydraulic fluid, greases, electric wiring and plugs, and a whole host of other equipment. The fuel to be used by the engine had to be stable under temperatures as low as minus 90°F in subsonic cruising flight during aerial refueling, and to over 350°F at high cruising speeds when it would be fed into the engine fuel system. There it would first be used as hydraulic fluid at 600°F to control the afterburner exit

flap before being fed into the burner cans of the powerplant and the afterburner itself.

Cooling the cockpit and crew turned out to be seven times as difficult as on the X-15 research airplane which flew as much as twice as fast as the SR-71 but only for a few minutes per flight. The wheels and tires of the landing gear had to be protected from the heat by burying them in the fuselage fuel tanks

for radiation cooling to save the rubber and other systems attached thereto.

Special attention had to be given to the crew escape system to allow safe ejection from the aircraft over a speed and altitude range of zero miles per hour at sea level to Mach numbers up to 4.0 at over 100,000 feet. New pilots' pressure suits (Figure 2), gloves, dual oxygen systems, high-temperature ejection seat catapults, and parachutes would have to be developed and tested.

The problems of taking pictures through windows subjected to a hot turbulent airflow on the fuselage also had to be solved.

HOW THE BLACKBIRD PROGRAM GOT STARTED

In the time period of 21 April 1958 through 1 September 1959, I made a series of proposals for Mach 3-plus reconnaissance aircraft to Mr. Richard Bissell of the CIA and to the U.S. Air Force. These airplanes were designated in the Skunk Works by design numbers of A-1 through A-12.

We were evaluated against some very interesting designs by the General Dynamics Corporation and a Navy in-house design. This latter concept was proposed as a ramjet-powered rubber inflatable machine, initially carried to altitude by a balloon and then rocket boosted to a speed where the ramjets could produce thrust. Our studies on this aircraft rapidly proved it to be totally unfeasible. The carrying balloon had to be a mile in diameter to lift the unit, which had a proposed wing area of $\frac{1}{2}$ th of an acre!

Convair's proposals were much more serious, starting out with a ramjet-powered Mach 4 aircraft to be carried aloft by a B-58 and launched at supersonic speeds. Unfortunately, the B-58 couldn't go supersonic with the bird in place, and even if it could, the survivability of the piloted vehicle would be very questionable due to the probability of ramjet blow-out in maneuvers. At the time of this proposal the total flight operating time for the Marquardt ramjet was not over 7 hours, and this time was obtained mainly on a ramjet test vehicle for the Boeing Bomarc missile. Known as the X-7, this test vehicle was

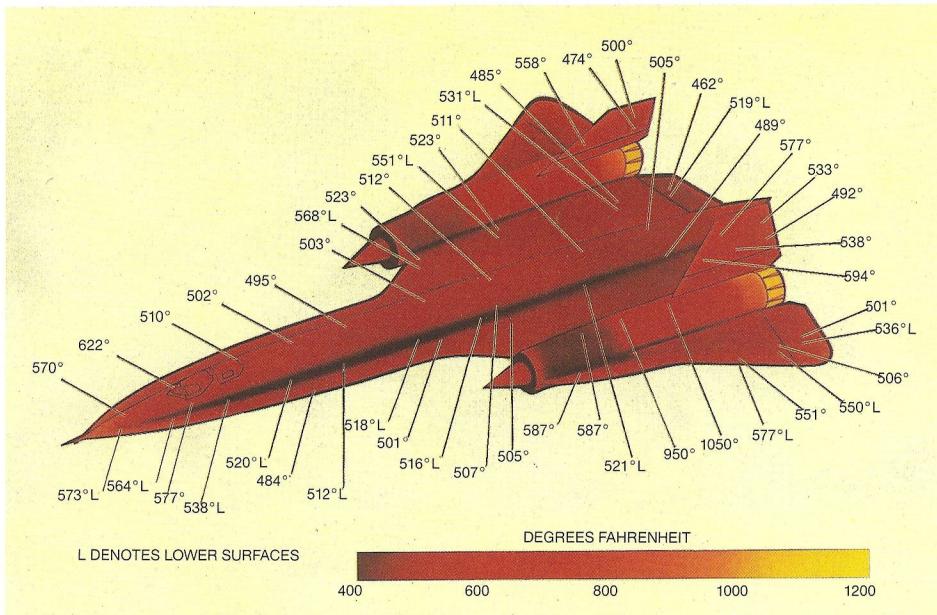


FIGURE 1 Surface Temperatures at Design Cruising Speed and Altitude



FIGURE 2 YF-12A Test Pilot in Full Pressure Suit with Walk-around Oxygen Kit

built and operated by the Lockheed Skunk Works!

The final Convair proposal, known as the Kingfisher, was eliminated by Air Force and Department of Defense technical experts, who were given the job of evaluating all designs.

On 29 August 1959 our A-12 design was declared the winner and Mr. Bissell gave us a limited go-ahead for a four-month period to conduct tests on certain models and to build a full-scale mock-up. On 30 January 1960 we were given a full go-ahead on the design, manufacturing, and testing of 12 aircraft. The first one flew 26 April 1962.

The next version of the aircraft, an Air Defense long-range fighter, was discussed with General Hal Estes in Washington, D.C. on 16 and 17 March 1960. He and Air Force Secretary for Research and Development, Dr. Courtlandt Perkins, were very pleased with our proposal so they passed me on for further discussions with General Marvin Demler at Wright Field. He directed us to use the Hughes ASG 18 radar and the GAR-9 missiles which were in the early development stages for the North American F-108 interceptor. This we did, and when the F-108 was eventually cancelled Lockheed worked with Hughes in the development and flight testing of that armament system. The first YF-12A flew 7 August 1963.

In early January 1961 I made the first proposal for a strategic reconnaissance bomber to Dr. Joseph Charyk, Secretary of the Air Force; Colonel Leo Geary,



our Pentagon project officer on the YF-12; and Mr. Lew Meyer, a high financial officer in the Air Force. We were encouraged to continue our company-funded studies on the aircraft. As we progressed in the development, we encountered very strong opposition in certain Air Force quarters on the part of those trying to save the North American B-70 program, which was in considerable trouble. Life became very interesting in that we were competing the SR-71 with an airplane five times its weight and size. On 4 June 1962 the Air Force evaluation team reviewed our design and the mock-up—and we were

given good grades.

Our discussions continued with the Department of Defense and also, in this period, with General Curtis LeMay and his Strategic Air Command officers. It was on 27 and 28 December 1962 that we were finally put on contract to build the first group of six SR-71 aircraft.

One of our major problems during the next few years was in adapting our Skunk Works operating methods to provide SAC with proper support, training, spare parts, and data required for their special operational needs. I have always believed that our Strategic Air Command is the most sophis-



Palmdale, California Production Test Facility



A-12 Test Aircraft Fleet in Storage After Development Testing

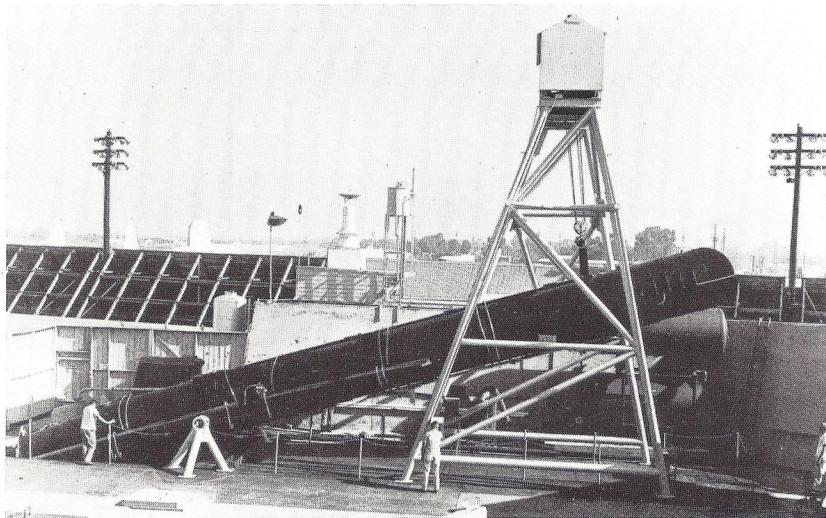


FIGURE 3 Full-Scale Fuel System Test Rig to Test Various Angles of Climb and Descent on Fuel Feed Capability



FIGURE 4
Engine Nacelle Leakage Test Model. Tested to Over 50 psi

ticated and demanding customer for aircraft in the world. The fact that we have been able to support them so well for many years is one of the most satisfying aspects of my career.

Without the total support of such people as General Leo Geary in the Pentagon and a long series of extremely competent and helpful commanding officers at Beale Air Force Base, we could never have jointly put the Blackbirds into service successfully.

BASIC DESIGN FEATURES

Having chosen the required performance in speed, altitude, and range, it was immediately evident that a thin delta-wing planform was required with a very moderate wing loading to allow flight at very high altitude. A long, slender fuselage was necessary to contain most of the fuel as well as the landing gear and payloads. To reduce the wing trim drag, the fuselage was fitted with lateral surfaces called chines, which actually converted the forward fuselage into a fixed canard which developed lift.

The hardest design problem on the airplane was making the engine air inlet

and ejector work properly. The inlet cone moves almost three feet to keep the shock wave where we want it. A hydraulic actuator, computer controlled, has to provide operating forces of up to 31,000 pounds under certain flow conditions in the nacelles. To account for the effect of the fuselage chine air flow, the inlets are pointed down and in toward the fuselage.

The use of dual vertical tails canted inward on the engine nacelles took advantage of the chine vortex in such a way that the directional stability improves as the angle of attack of the aircraft increases.

AERODYNAMIC TESTING

All the usual low-speed and high-speed wind tunnel tests were run on the various configurations of the A-12 and YF-12A, and continued on the SR-71. Substantial efforts went into optimizing chine design and conical camber of the wing leading edge. No useful lift increase effect was found from the use of wing flaps of any type so we depend entirely on our low wing-loading and powerful ground effect to get satisfactory takeoff and landing characteristics.

Correlation of wind tunnel data on fuselage trim effects was found to be of marginal value because of two factors: structural deflection due to fuselage weight distribution; and the effect of fuel quantity and temperature. The latter was caused by fuel on the bottom of the tanks, keeping that section of the fuselage cool, while the top of the fuselage became increasingly hotter as fuel was burned, tending to push the chines downward due to differential expansion of the top and bottom of the fuselage. A full-scale fuel system test rig was used to test fuel feed capability for various flight attitudes, Figure 3.

By far the most tunnel time was spent optimizing the nacelle inlets, bleed designs, and the ejector. A quarter-scale model was built on which over 250,000 pressure readings were taken. We knew nacelle air leakage would cause high drag so an actual full-size nacelle was fitted with end plugs and air leakage carefully measured. Proper sealing paid off well in flight testing. Figure 4 shows the nacelle test set-up.

With the engines located half way out on the wing span, we were very concerned with the very high yawing

moment that would develop should an inlet stall. We therefore installed accelerometers in the fuselage that immediately sensed the yaw rate and commanded the rudder booster to apply 9 degrees of correction within a time period of 0.15 seconds. This device worked so well that our test pilots very

often couldn't tell whether the right or left engine blew out. They knew they had a blowout, of course, by the bad buffeting that occurred with a "popped shock." Subsequently, an automatic restart device was developed which keeps this engine-out time to a very short period.

POWERPLANT DEVELOPMENT

Mr. Bill Brown of Pratt & Whitney presented a fine paper on this subject 13 May 1981 to the American Institute of Aeronautics and Astronautics in Long Beach, California. Mr. Brown's paper is reproduced herewith.

J58/SR-71 PROPULSION INTEGRATION OR THE GREAT ADVENTURE INTO THE TECHNICAL UNKNOWN

William H. Brown

Retired Engineering Manager, Government Product Division

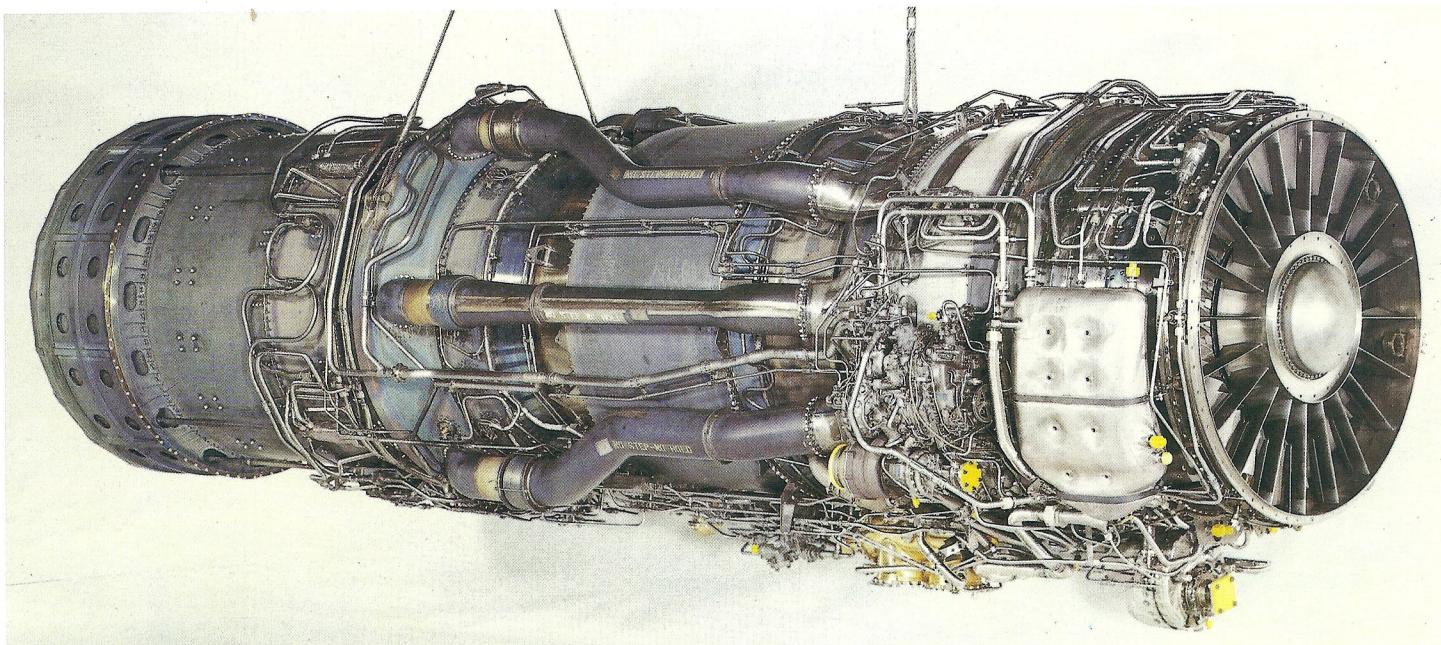
Pratt & Whitney Aircraft Group
United Technologies Corporation

Successful integration of the J58 engine with the SR-71 aircraft was achieved by:

- Inherently compatible engine cycle, size and characteristics.
- Intensive and extensive design/development effort.
- Propulsion integration involved aero-

dynamic compatibility, installation and structural technology advances, development of a unique mechanical power takeoff drive, and fuel system tailoring. All four areas plowed new ground and uncovered unknowns that were identified, addressed, and resolved. Interacting airframe systems, such as the

variable mixed compression inlet, exhaust nozzle, and fuel system were ground tested with the J58 engine prior to and coincident with flight testing. Numerous iterative redesign-retest-resolution cycles were required to accommodate the extreme operating conditions.



Pratt & Whitney J58 (JT11D-20) Engine



Successful propulsion operation was primarily the result of

- Compatible conceptual designs.
- Diligent application of engineering fundamentals.
- Freedom to change the engine and/or aircraft with a minimum of contractual paperwork.
- A maximum of trust and team effort with engineer-to-engineer interchange.

The centerline of the basic J58 engine was laid down in late 1956. It was to be an afterburning turbojet rated at 26,000-lb maximum takeoff thrust and was to power a Navy attack aircraft

which would have a dash capability of up to Mach 3 for several seconds. By the time Pratt & Whitney Aircraft, along with Lockheed and others, began to study the SR-71 "Blackbird" requirements several years later, we had completed approximately 700 hours of full-scale engine testing on the J58.

In the "Blackbird" joint studies, the attitude of open cooperation between Lockheed and Pratt & Whitney Aircraft personnel seemed to produce better results than if a more "arms-length" attitude were adopted. This open cooperation resulted in a more com-

plete study which identified the enormous advances in the state-of-the-art and the significant amount of knowledge which had to be acquired to achieve a successful engine/airframe integration. The completeness of this study was probably instrumental in Lockheed and Pratt & Whitney Aircraft winning the competition. The Government stated that the need for the "Blackbird" was so great that the program had to be conducted despite the risks and the technological challenge. Furthermore, the Government expected the risks to be reduced by fallout from the X-15 and B-70 programs. Unfortunately, there was no meaningful fallout.

Figures A and B indicate some of the increased requirements of the "Blackbird" engine compared to the requirements for the previous J75 engine. As it turned out, even these requirements didn't hold throughout the "Blackbird's" actual mission. For example, the engine inlet air temperature exceeded 800°F under certain conditions. The fuel inlet temperature increased to 350°F at times and the fuel temperature ranged from 600°F to 700°F at the main and afterburner fuel nozzles. Lubricant temperatures rose to 700°F and even to 1000°F in some localized parts of the engine.

Because of these extremely hostile environmental conditions, the only design parameters that could be retained from the Navy J58-P2 engine were the basic size and the compressor and turbine aerodynamics. Even these were modified at a later date.

The extreme environment presented a severe cooling problem. It was vital to cool the pilot and aircraft electronics; but this left little or no heat sink in the fuel available to cool the rest of the aircraft or the engine. Because of this, the only electronics on the engine was a fuel-cooled solenoid which was added later and a trim motor buried inside the engine fuel control. To keep cooling requirements to a minimum, we even had to provide a chemical ignition system using tetraethyl borane (T.E.B.) for starting both the main engine and the afterburner. A new fuel and a chemical lubricant had to be developed to meet the temperature requirements. Pratt & Whitney Aircraft together with

	J57 AND J75	JT11D-20
MACH NUMBER	2.0 FOR 15 MIN (J75 ONLY)	3.2 (CONTINUOUS)
ALTITUDE	55,000 FT	100,000 FT
COMPRESSOR INLET TEMPERATURE	250°F (J75 ONLY)	800°F
TURBINE INLET TEMPERATURE	1750°F (TAKEOFF) 1550°F (CRUISE)	2000°F
MAXIMUM FUEL INLET TEMPERATURE	110–130°F	300°F
MAXIMUM OIL INLET TEMPERATURE	250°F	550°F
THRUST/WEIGHT RATIO	4.0	5.2
MILITARY OPERATION	30-MIN TIME LIMIT	CONTINUOUS
AFTERSURNER OPERATION	INTERMITTENT	CONTINUOUS

FIGURE A Comparison of J58 Development Objectives with Then-Current Production Engines

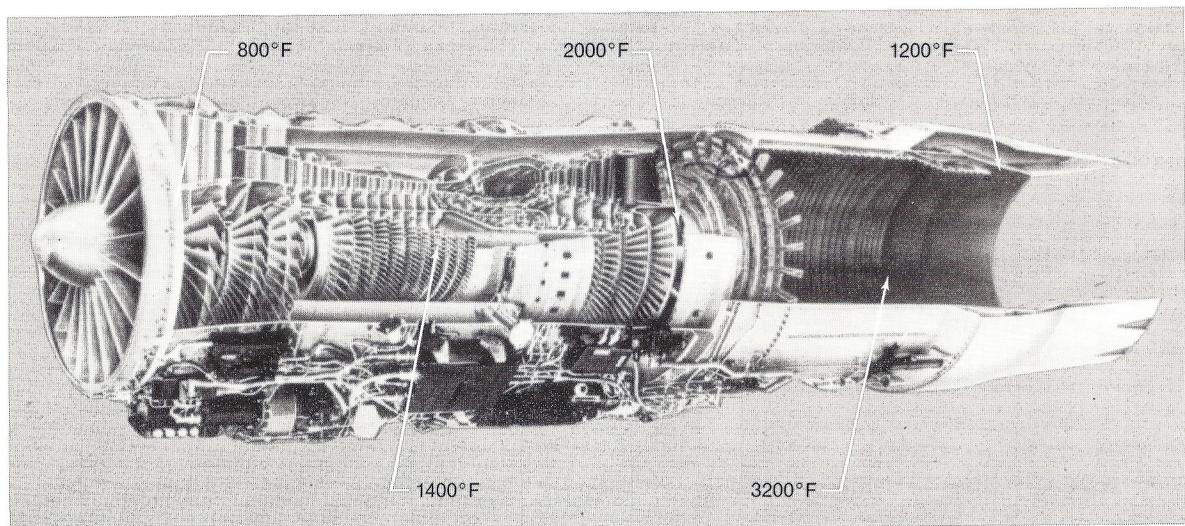


FIGURE B
J58 Flight Temperatures

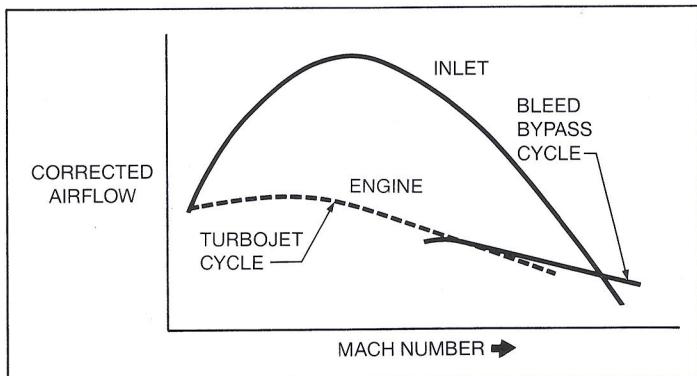


FIGURE C Inlet and Engine Air-Flow Match

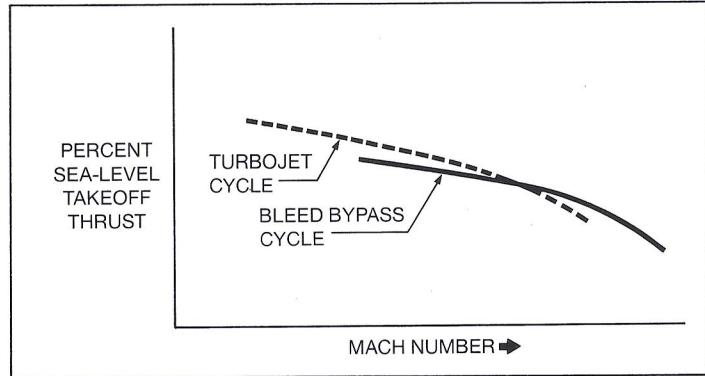


FIGURE D Net Thrust Comparison—Bleed Bypass Cycle versus Turbojet Cycle

the Ashland, Shell, and Monsanto Companies took on the task of developing these fluids.

Early in the development, we found that a straight turbojet cycle did not provide a good match for the inlet nor the required net thrust at high Mach number operating conditions. To overcome these problems, we invented the bleed bypass cycle with which we could match the inlet airflow requirements, as shown in Figure C. Another advantage of this cycle was that above Mach 2, the corrected airflow could be held constant at a given Mach number regardless of the throttle position. The bleed bypass cycle also provided more than 20-percent additional thrust during high Mach number operation, Figure D.

Fabrication and materials technology presented one of the greatest challenges. We had to learn how to form sheet metal from materials which previously had been used only for forging

turbine blades. Once we had achieved this, we had to learn how to weld it successfully. Disks, shafts, and other components also had to be fabricated from high-strength, temperature-resistant turbine-blade-like materials to withstand temperatures and stresses encountered. I do not know of a single part, down to the last cotter key, that could be made from the same materials as used on previous engines. Even the lubrication pump was a major development. The newly developed special fuel was not only hot, but it had no lubricity. A small amount of fluorocarbon finally had to be added to allow the airframe and engine pumps and servos to work.

Fuel was used as the engine hydraulic fluid to actuate the bleeds, afterburner nozzle, etc. Because there was nothing to cool the fuel, it just made one pass through the hydraulic system and then was burned.

If the foregoing were not enough, developmental testing problems also had to be overcome. There were no test facilities which had the capabilities to provide steady-state temperature and pressure conditions required for testing at maximum operating conditions nor could they provide for performing transients. A partial solution is shown in Figure E. On this test stand, the exhaust of a J75 engine was run through and around the J58 to simulate transients of the temperature environment.

In addition, there was essentially no instrumentation rugged enough to obtain accurate real-time measurements. As Pratt & Whitney Aircraft developed more rugged instrumentation and better calibration facilities, improved data were gradually obtained. Lockheed, of course, was kept up-to-date as we obtained better data. A good part of the time Lockheed and Pratt & Whitney Aircraft jointly ran fuel sys-

tem rigs, inlet distortion rigs, etc., as well as some engine calibration tests and wind tunnel testing of the ejector.

It's important to remember that this all started nearly a quarter of a century ago. Although Pratt & Whitney Aircraft had a very large computer system for its day (the IBM 710), it was no more sophisticated than some of the hand held calculators now available. Consequently, the J58 engine, in effect, was a slide-rule design. Despite all of the testing and faired curves, we knew we had to solve many of our mutual integration problems through flight test.

Approximately three months before Pratt & Whitney finished the Pre Flight Rating Test which was 3 years and 4 months after go-ahead (the Model Qualification Test was completed 14 months later), the first "Blackbird" took to the air. It was powered by two afterburning J75 turbojet engines to wring out the aircraft subsonically. As soon as Lockheed felt comfortable with the aircraft, a J58 was installed in one side. After several months of subsonic flight tests, J58 engines were installed in both sides, and we started flight testing for real.

Naturally there were problems. Here are a few notable ones and the solutions.

The first problem happened very early—the engine wouldn't start! The small inlet wind tunnel model did not show the inlet being so depressed at the starting J58 airflows. In fact, instead of air flowing out of the compressor 4th-stage through the bleed ducts into the afterburner, it flowed the other way! As a temporary fix, Lockheed removed an inlet access panel for ground starts. They later added two suck-in doors (see Figure F) and Pratt & Whitney Aircraft added an engine bleed to the nacelle. These two changes eliminated the ground starting problem.

Originally, the blow-in door ejector or convergent-divergent nozzle was built as part of the engine. It was subsequently decided jointly by Lockheed and Pratt & Whitney Aircraft that it would save weight if it was built as part of the airframe structure. This was deemed appropriate, particularly as the main wing spar structure had to go around the throat of the ejector. Pratt

& Whitney Aircraft, however, would still be responsible for nozzle performance in conjunction with the engine primary nozzle. In addition, we would perform all of the wind tunnel testing. In exchange, Pratt & Whitney Aircraft would build the remote gearbox because Lockheed's gearbox vendor had no experience with gear materials or bearings and seals that would withstand the temperatures required. As a matter of fact neither did we, but we were already committed to learn.

A problem partially related to the ejector was that the airplane burned too much fuel going transonic. To help solve the problem, thrust measurements were taken in flight, movies of ejector operation in flight were made, local Mach numbers were measured, etc. Two fundamental mistakes were uncovered. The back end of the nacelle (the ejector) went supersonic long before the airplane did, and the fairing of the aircraft transonic wind tunnel drag data was not accurate. While we were puzzling out the solution, some pilot decided to go transonic at a lower altitude and higher Keas. This for all intents and purposes solved the problem. From this we learned not to run nacelle wind tunnel tests unless the model contains at least a simulation of the adjacent

aircraft surfaces. We also learned to take enough data points so that transonic drag wind tunnel data does not have to be faired.

As flight testing increased to the higher Mach numbers, new problems arose. One, which today may be considered simple with our modern computer techniques, concerned the remote gearbox. The gearbox mounts started to exhibit heavy wear and cracks, and the long drive shaft between the engine and the gearbox started to show twisting and heavy spline wear. After much slide-ruling, we finally decided that the location of the gearbox relative to the engine was unknown during high Mach number transients. We resorted to the simple test of putting styluses on the engine and mounted a scratch plate on the gearbox. We found, to our astonishment, that the gearbox moved about 4 inches relative to the engine. This was much more than the shaft between the engine and the gearbox could take. The problem was solved by providing a new shaft containing a double universal joint.

Another problem arose when the aircraft fuel system plumbing immediately ahead of the engine started to show fatigue and distortion. Measurements with a fast recorder showed that

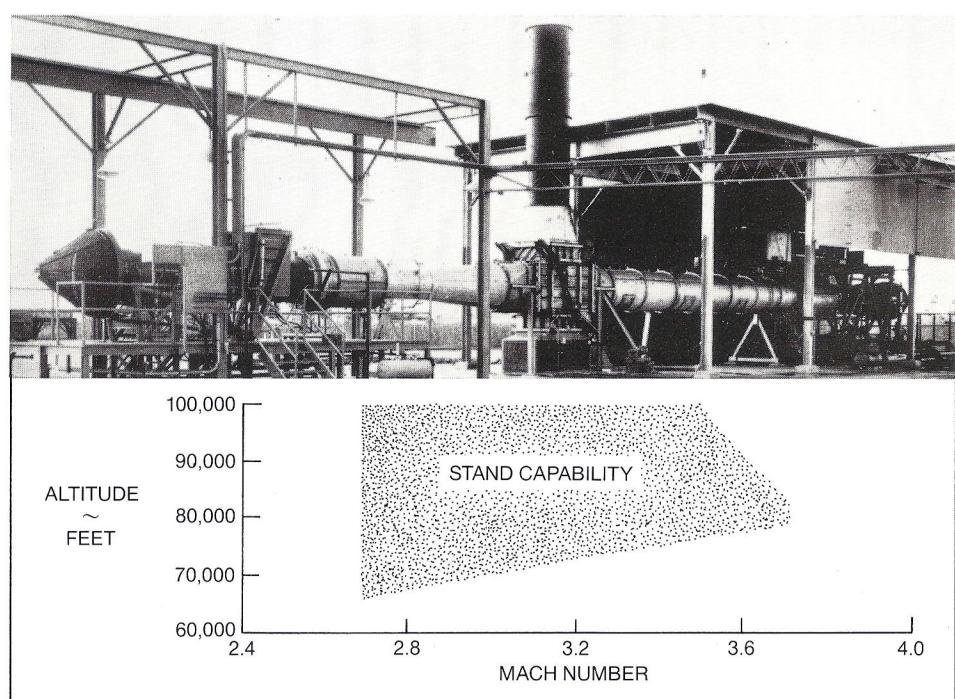


FIGURE E Heated Environment Test Stand

pressure spikes at the engine fuel inlet were going off scale. This overpressurizing was found to be caused by feedback from the engine hydraulic system. This phenomenon did not show up either during Lockheed's or Pratt & Whitney Aircraft's rig testing nor during the engine ground testing because of the large fluid volumes involved. To solve the problem Lockheed invented a "high-temperature sponge" (promptly named "the football") which they installed in an accumulator ahead of the engine. This reduced the pressure spikes to a tolerable level.

A mounting-related problem occurred under certain conditions of down load on the wing. At these conditions, the outer half of the nacelle would rotate into the engine and crush the engine plumbing and anything else in the way. Originally, the engine was mounted on a stiff rail structure at the top of the nacelle with a stabilizing link from the top of the engine rear mount ring to the aircraft structure as shown in Figure G. To solve the crushing problem Pratt & Whitney Aircraft redesigned the rear mount ring so that a tangential link could be installed between the engine

and the outboard side of the nacelle. This maintained a finite distance between the nacelle and engine under all conditions.

As mentioned previously, there was a minimum of electronics in the engine control system because electronics would not survive the environment and the fuel was already too hot to provide cooling. Consequently, control adjustments normally made automatically had to be made manually. For example, the pilot operated a vernier trimmer to make fine adjustments in the EGT (Exhaust Gas Temperature) as conditions varied from standard (one such device was used successfully in the U-2). The pilot was provided with a curve of EGT versus engine inlet temperature to make the required manual adjustments. However, unexpectedly sharp atmospheric changes were encountered. These, in combination with the speed of the aircraft, resulted in changes too fast for the pilot to handle. By the time he read the engine inlet temperature and adjusted the EGT, the inlet temperature had changed. This caused some inlet unstarts (highly reduced inlet airflow) and other undesirable results. To correct this unacceptable state of affairs, Pratt & Whitney Aircraft proposed to revise the aircraft EGT gage by feeding in an engine inlet temperature signal and adding some additional gadgetry to trim automatically. The digital EGT readout was retained as was an override manual trim in case of failure. See Figure H. This modification has worked well ever since.

The most sensational and most confusing problem at the high Mach number condition was inlet unstarts. These occurred without warning and were seemingly inconsistent. To add to the confusion, the pilots consistently reported the unstart occurring on the wrong side of the airplane. This anomaly was solved rather quickly when Lockheed found that the Stability Augmentation System (SAS) slightly overcompensated for the sudden one sided drag. This led the pilot to believe that the wrong side had unstarted, and consequently, his corrective action usually resulted in worsening the problem.

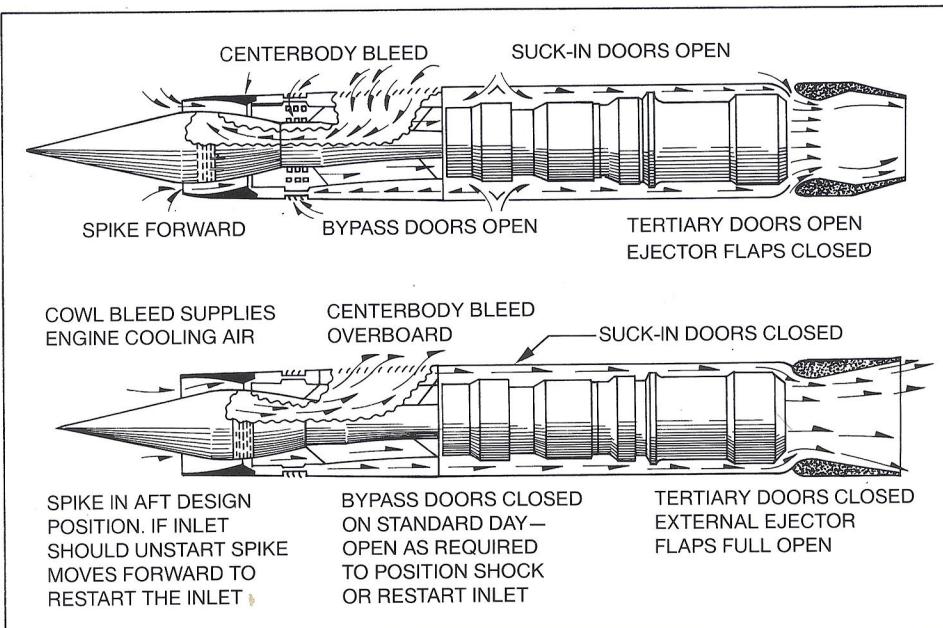


FIGURE F Air Flow Patterns—Static Aircraft, at top; Air Flow Patterns—High Speed, at bottom.

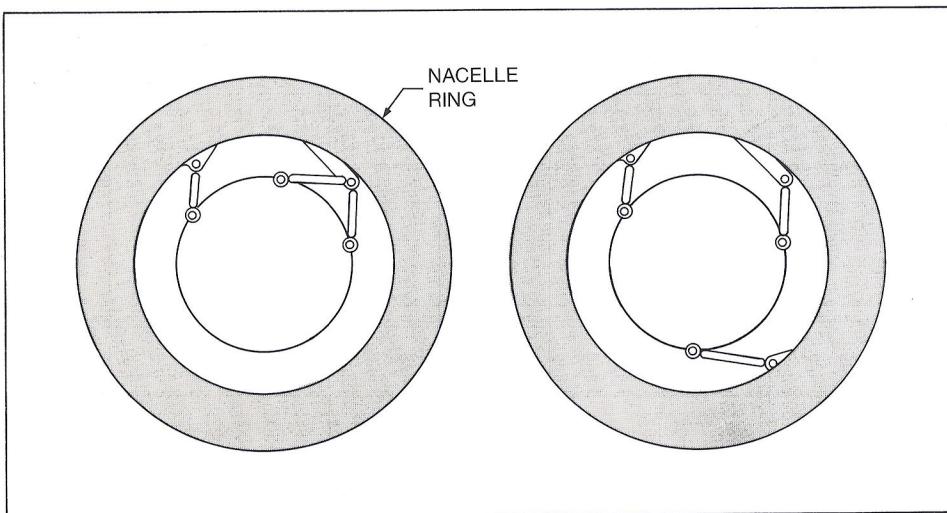


FIGURE G Original Engine Mount at left; Modified Engine Mount at right

Oddly enough, the engine did not blowout. It just sat there and overheated because the inlet airflow was so reduced that the engine minimum fuel flow was approximately twice that required. Worst of all, the inlet would not restart until the pilot came down to a much lower altitude and Mach number. A great many tests and investigations were conducted including the possibility of engine surge being the initiator. This was not the case. Three major causes were finally isolated:

1. Manual trimming of engine.

2. High, inconsistent nacelle leakage at the approximately 40:1 pressure ratio.
3. Alpha signal (angle of attack from noseboom) to inlet control subject to G-loading.

The following improvements were incorporated by Lockheed and Pratt & Whitney Aircraft essentially as a package:

1. Improved sealing of the inlet and bypass doors.
2. Auto-trimmer of engine installed (Ref. Figure H).
3. Derichment valve with unstart sig-

nal installed on engine to protect turbine (Ref. Figure H).

4. Increased area inlet bypass doors and addition of an aft inlet bypass door which bypassed inlet air direct to ejector.
5. Added a "G" bias on inlet control.
6. Automated inlet restart procedure on both inlets regardless of which unstarted.

The foregoing six items essentially eliminated inlet unstart as a problem. An additional benefit was also realized by the ability to use the aft inlet bypass door in normal flight instead of dumping all inlet bypass air overboard. As this air became heated as it passed over the engine to the ejector instead of going overboard, drag was substantially reduced. Also better sealing of the nacelle reduced drag further.

As you have probably noticed, I have had difficulty in differentiating between "we" Pratt & Whitney Aircraft and "we" Lockheed. But that is the kind of program it was.

In any complicated program of this magnitude we all do something dumb and we both did our share. Here is one from each of us: "We," (Pratt & Whitney), became so obsessed with the problems of hot fuel and hot environment that we neglected the fact that sometimes the fuel was cold when the environment was hot and vice versa. When this occurred, the engine fuel control did not track well. To correct this, we had to insulate the main engine control body from the environment and make all the servos, etc., respond only to fuel temperature. Eventually, we had to make a major redesign of the control.

Lockheed and Pratt & Whitney Aircraft spent many hours coordinating the inlet and engine arrangement so that doors, bleeds, air conditioner drive turbine discharge, etc., would not affect any of the engine control sensors in the engine inlet. In fact, the air conditioner turbine discharge was located 45 degrees on one side of the vertical centerline and the engine temperature bulb was located 45 degrees on the opposite side. To save design time, Lockheed built one inlet as a mirror image of the other. It is now easy to conclude where the 1200°F air conditioner turbine dis-

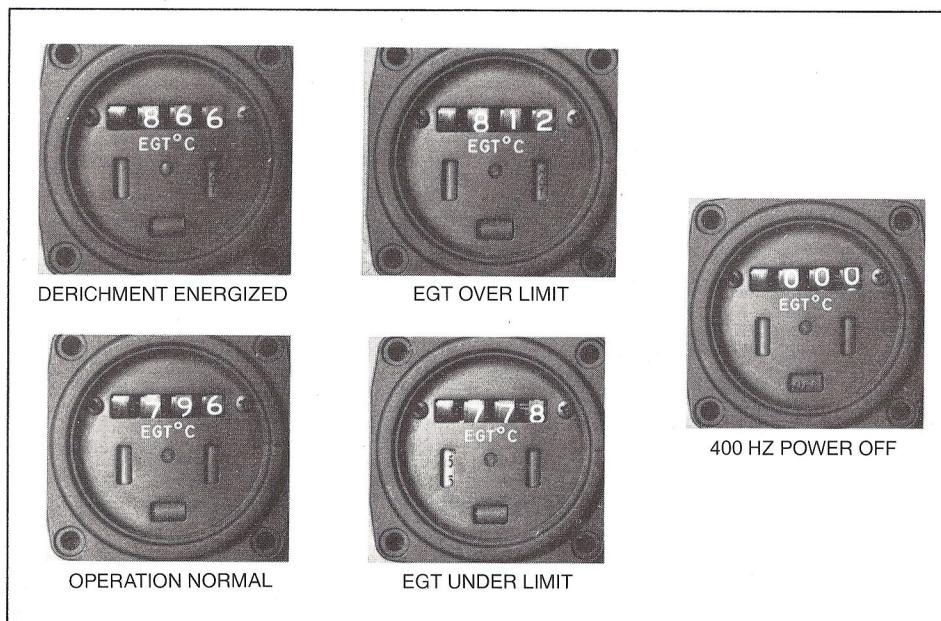


FIGURE H Exhaust Gas Temperature Vernier Control System—EGT Error Gage Operating Modes



J58 Engine Under Test

charge turned out to be!! For a while the fact that one engine always ran faster than the other was a big mystery!

That this complex, difficult program was successful is attributable, in large part, to the management philosophy adopted by the Government people in charge. Their approach was that both the engine and airframe contractors must be free to take the actions which in their judgment were required to solve the problems. The Government management of the program was handled by no more than a dozen highly qualified and capable individuals who were oriented toward understanding the problems and approaches to solutions, rather than toward substituting their judgment for that of the contractors. Requirements for Government approval as a prerequisite to action were minimal and were limited to those changes

involving significant cost or operational impact. As a result, reactions to problems were exceptionally quick. In this manner, the time from formal release of engineering paperwork to the conversion to hardware was drastically shortened. This not only accelerated the progress of the program but saved many dollars by incorporating the changes while the number of units were still relatively small.

On this program, the Government fully recognized that many of the problems involving either the engine or airframe manufacturer, or both, could be solved most effectively by a joint engineering effort and the contracts were written to allow this activity without penalties. As a result, an extremely close working relationship between the engineering groups was developed and flourished until the

SR-71 became fully operational. This method of operation led to prompt solutions of many problems which, under a more cumbersome management system, could have severely impeded the program by introducing very costly delays or forcing inappropriate compromises because of contractual interpretations.

In summary, the method of managing this program by the Government resulted in shorter development time, faster reaction to field problems, reduced retrofit costs, and earlier availability of production systems incorporating corrections for problems uncovered by operations in the field. The result was an operating system incorporating a magnum step in the state-of-the-art at an earlier time and at less cost to the Government than would otherwise have been possible.

I have little to add to Mr. Brown's fine paper except to record an interesting approach to the problem of ground starting the J-58. We learned that it often required over 600 horsepower to get the engine up to starting RPM. To obtain this power, we took two Buick racing car engines and developed a gear box to connect them both to the J-58 starter drive. We operated for several years with this setup, Figure 5, until more sophisticated air starting systems were

developed and installed in the hangars, Figure 6.

STRUCTURAL PROBLEMS

The decision to use various alloys of titanium for the basic structure of the Blackbirds was based on the following considerations:

1. Only titanium and steel had the ability to withstand the operating temperatures encountered.
2. Aged B-120 titanium weighs one half

as much as stainless steel per cubic inch but its ultimate strength is almost up to stainless.

3. Conventional construction could be used with fewer parts involved than with steel.
4. High strength composites were not available in the early 1960s. We did develop a good plastic which has been remarkably serviceable but it was not used for primary structure.

Having made the basic material choice,

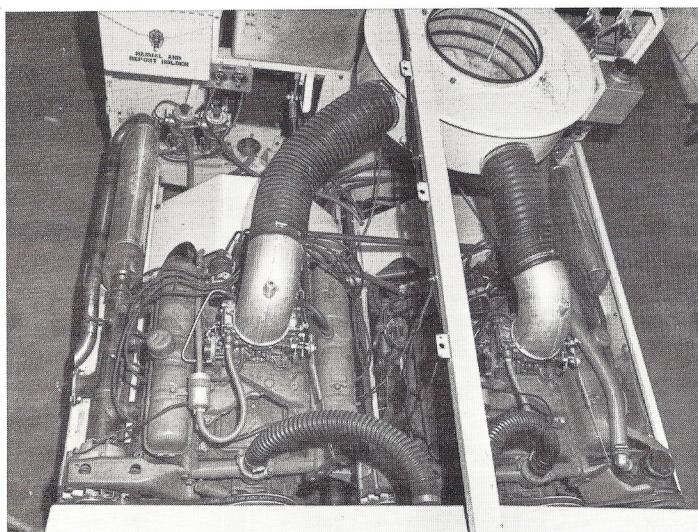


FIGURE 5 Provisional Engine Starter Cart Which Used Two Buick Racing Car Engines Geared to a Common Shaft Drive to Rotate the J58 Engine. This Rig Produced Over 600 Horsepower for Starting.

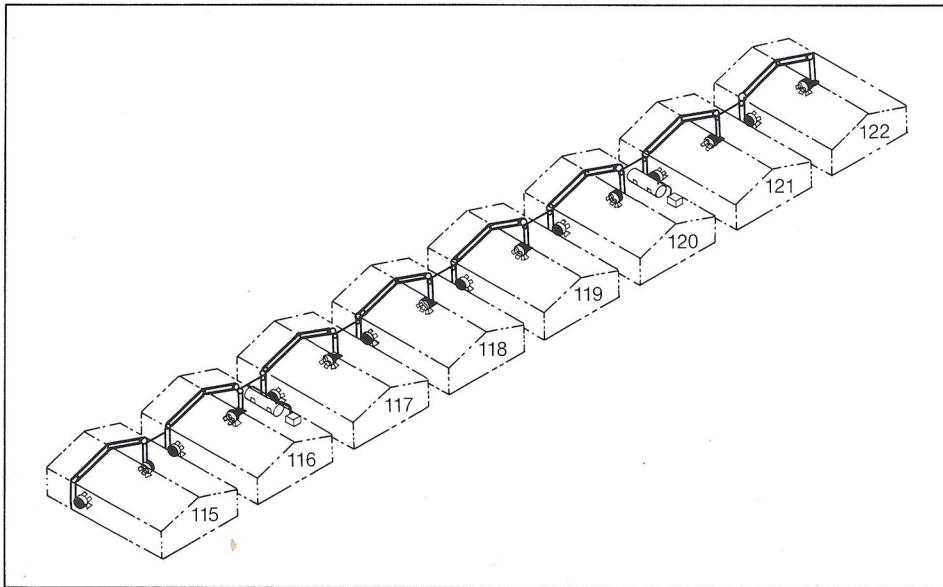


FIGURE 6 Final Air Starting System Built into Operational Hangars

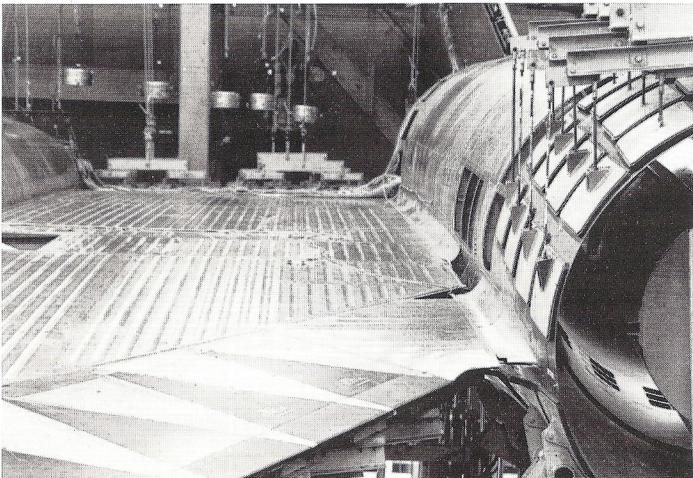


FIGURE 7 Upper Wing Surface Showing Wing Chordwise Corrugations. Taken During Static Tests at Design Limit Load.

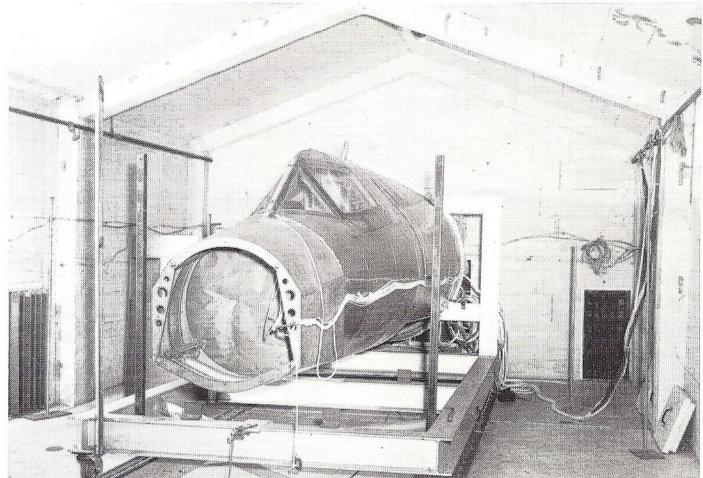


FIGURE 8 Fuselage Cockpit Section in Oven for Testing Effects of High Temperatures on Structure and Systems

we decided to build two test units to see if we could reduce our research to practice. The first unit was to study thermal effects on our large titanium wing panels. We heated up this element with the computed heat flux that we would encounter in flight. The sample warped into a totally unacceptable shape. To solve this problem we put chordwise corrugations in the outer skins and reran the tests very satisfactorily. At the design heating rate, the corrugations merely deepened by a few thousandths of an inch and on cooling returned to the basic shape. I was accused of trying to make a 1932 Ford Trimotor go Mach 3 but the concept, shown in Figure 7, worked fine.

The second test unit, Figure 8, was

the forward fuselage and cockpit; which had over 6,000 parts in it of high curvature, thin gages, and the canopy with its complexity. This element was tested in an oven where we could determine thermal effects and develop cockpit cooling systems.

We encountered major problems in manufacturing this test unit because the first batch of heat-treated titanium parts was extremely brittle. In fact, you could push a piece of structure off your desk and it would shatter on the floor. It was thought that we were encountering hydrogen embrittlement in our heat-treat processes. Working with our supplier, Titanium Metals Corporation, we could not prove that the problem was in fact hydrogen. It was finally resolved by throwing out our whole acid pickling setup and replacing it with an identical reproduction of what TMCA had at their mills.

We developed a complex quality control program. For every batch of ten parts or more we processed three test coupons which were subjected to the identical heat treatment of the parts in the batch. One coupon was tensile tested to failure to derive the stress-strain data. A quarter-of-an-inch cut was made in the edge of the second coupon by a sharp scissor-like cutter and it was then bent around a mandrel at the cut. If the coupon could not be bent 180° at a radius of X times the sheet thickness without breaking, it was

considered to be too brittle. (The value of X is a function of the alloy used and the stress/strain value of the piece.) The third coupon was held in reserve if any reprocessing was required.

For an outfit that hates paperwork, we really deluged ourselves with it. Having made over 13 million titanium parts to date we can trace the history of all but the first few parts back to the mill pour and for about the last 10 million of them even the direction of the grain in the sheet from which the part was cut has been recorded. On large forgings, such as landing gears, we trepanned out 12 sample coupons for test before machining each part. We found out the hard way that most commercial cutting fluids accelerated stress corrosion on hot titanium so we developed our own.

Titanium is totally incompatible with chlorine, fluorine, cadmium, and similar elements. For instance, we were baffled when we found out that wing

panels which we spot welded in the summer, failed early in life, but those made in the winter lasted indefinitely. We finally traced this problem to the Burbank water system which had heavily chlorinated water in the summer to prevent algae growth but not in the winter. Changing to distilled water to wash the parts solved this problem.

Our experience with cadmium came about by mechanics using cadmium-plated wrenches working on the engine installation primarily. Enough cadmium was left in contact with bolt heads which had been tightened so that when the bolts became hot (over 600°F) the bolt heads just dropped off! We had to clean out hundreds of tool boxes to remove cadmium-plated tools.

Drilling and machining high strength titanium alloys, such as B-120, required a complete research program to determine best tool cutter designs, cutting fluids, and speeds and feeds for best metal removal rates. We had particular

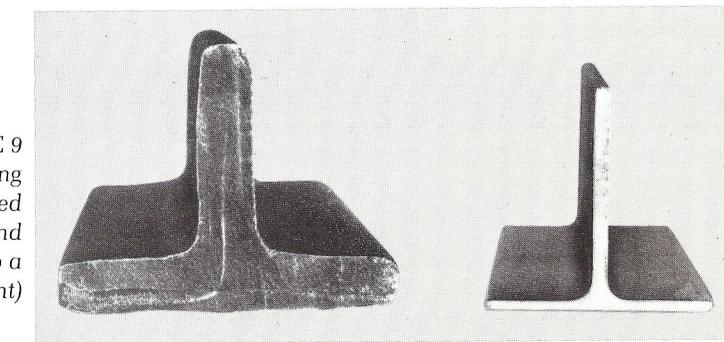


FIGURE 9
Titanium Wing
Extrusion as Received
from the Mill (left) and
After Machining to a
Finished Part (right)

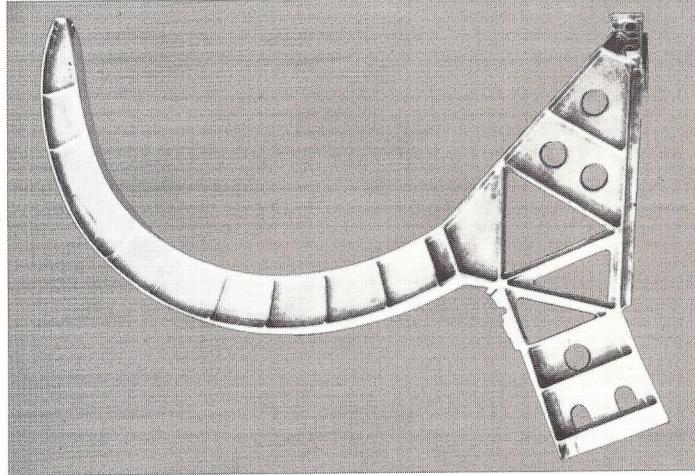
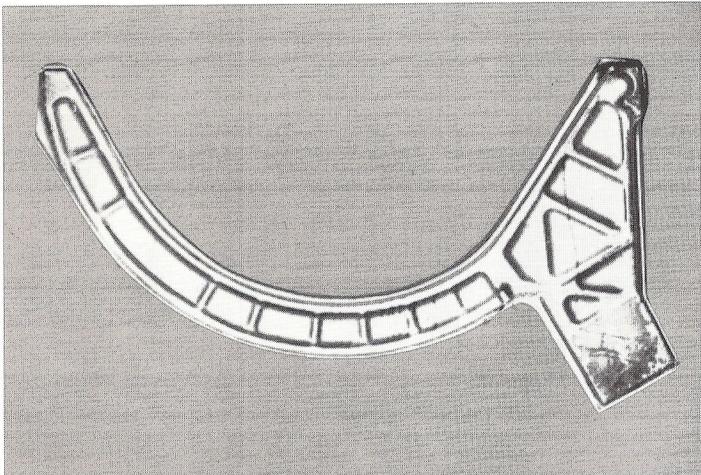


FIGURE 10 This Nacelle Ring was Originally Made from 30 parts. These Parts were Machined on Old, Outdated Profiling Machines and then Assembled into the Final Ring Segment in 487 Hours. Today, the Ring Segment is Made from a Single Forging (left) Weighing 325 pounds and is then Machined on Profilers of Advanced Design to Produce the Finished Part (right) in 150 hours.



FIGURE 11 Machine Shop with Numerical Controlled Milling Machines



FIGURE 12 Wing Fuel Tank Showing Structure and Sealant After 100 Hours Flying at Mach Numbers Over 2.6

trouble with wing extrusions, Figure 9, which were used by the thousands of feet. Initially, the cost of machining a foot out of the rolled mill part was \$19.00 which was reduced to \$11.00 after much research. At one time we were approaching the ability at our vendor's plants to roll parts to net dimensions, but the final achievement of this required a \$30,000,000 new facility which was not built.

Wyman Gordon was given \$1,000,000

for a research program to learn how to forge the main nacelle rings, Figure 10, on a 50,000-ton press which was successful. Combining their advances with our research on numerical controls of machining and special tools and fluids, we were able to save \$19,000,000 on the production program.

To prevent parts from going undergage while in the acid bath, we set up a new series of metal gages two thousandths of an inch thicker than the



FIGURE 13 Engine Name Plate Sucked into an Engine on Ground Run Up!

standard gages and solved this problem. When we built the first Blackbird, a high-speed drill could drill 17 holes before it was ruined. By the end of the program we had developed drills that could drill 100 holes and then be resharpened successfully.

Our overall research on titanium usage was summarized in reports which we furnished not only to the Air Force but also to our vendors who machined over half of our machined parts for the program; Lockheed's machine shop for this program is shown in Figure 11. To use titanium efficiently required an ongoing training program for thousands of people—both ours in manufacturing and in the Air Force in service.

Throughout this and other programs, it has been crystal clear to me that our country needs a 250,000-ton

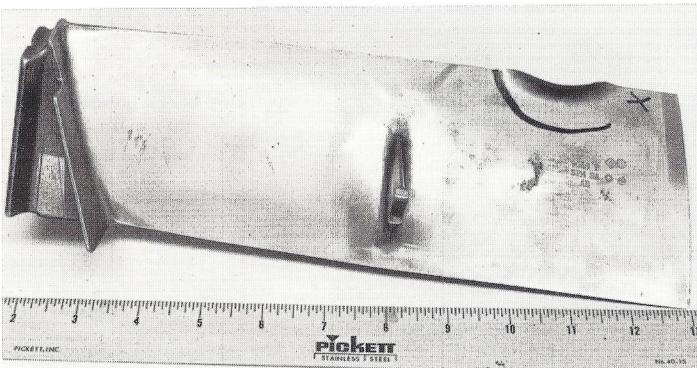


FIGURE 14 First-Stage Compressor Blade After Hitting Inspector's Flashlight—Total Engine Damage \$250,000

metal forming press—five times as large as our biggest one available today. When we have to machine away 90 percent of our rough forgings today both in titanium (SR-71 nacelle rings and landing gears) and aluminum (C-5 fuselage side rings) it seems that we are nationally very stupid! My best and continuing efforts to solve this problem have been defeated for many years. Incidentally, the USSR has been much smarter in this field in that they have more and larger forging presses than we do.

FLUID SYSTEMS

Very difficult problems were encountered with the use of fuel tank sealants, Figure 12, and hydraulic oil. We worked for years developing both of these, drawing as much on other industrial and chemical companies as they were willing to devote to a very limited market. We were finally able to produce a sealant which does a reasonable job over a temperature range of minus 90°F to over 600°F. Our experience with hydraulic oil started out on a comical situation. I saw ads in technical journals for a "material to be used to operate up to 900°F in service." I contacted the producer who agreed to send me some for testing. Imagine my surprise when the material arrived in a large canvas bag. It was a white powder at room temperature that you certainly wouldn't put in a hydraulic system. If you did, one would have to thaw out all the lines and other elements with a blow torch! We did finally get a petroleum-based oil developed at Penn State University to which we had to add

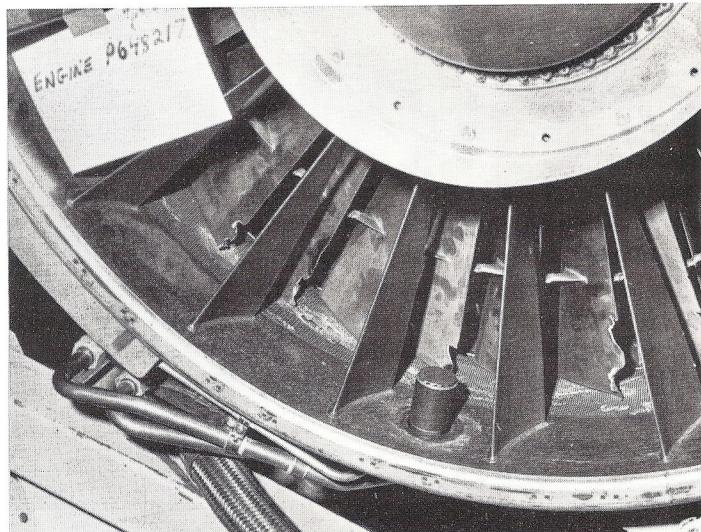
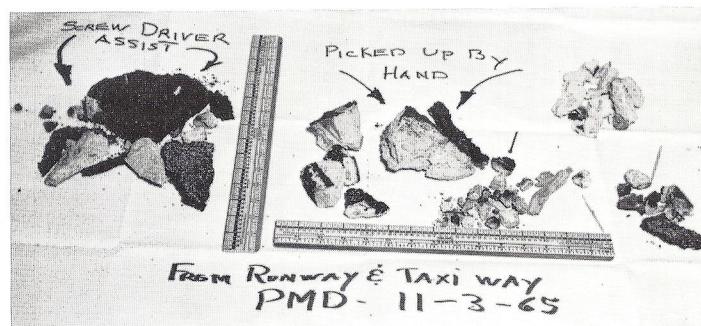


FIGURE 15
Taxiway/Runway Debris Which Could
be Sucked into
Engines on Take-off



several other chemicals to maintain its lubricity at high temperatures. It originally cost \$130 per gallon so absolutely no leaks could be tolerated.

Rubber O-rings could not be used at high temperatures so a complete line of steel rings was provided which have worked very well. Titanium pistons working in titanium cylinders tended to gall and seize until chemical coatings were invented which solved the problem.

THE FLIGHT TEST PHASE

The first flight of the A-12 took place 26 April 1962 or thirty months after we were given a limited go-ahead on 1 September 1959. We had to fly with Pratt & Whitney J75 engines until the J58 engine became available in January 1963. Then our problems really began!

The first one was concerned with foreign object damage (FOD) to the engines—a particular problem with the powerful J58 and the tortuous flow path through the complicated nacelle structure. Small nuts, bolts, and metal scraps,

Figure 13, not removed from the nacelles during construction could be sucked into the engines on starting with devastating results. Figure 14 shows damage to the first-stage compressor blades from an inspector's flashlight used to search for such foreign objects. Engine damage—\$250,000! Besides objects of the above type, the engine would suck in rocks, asphalt pieces, etc. from the taxi-ways and runways, Figure 15. An intensive campaign to control FOD at all stages of construction and operation—involving a shake test of the forward nacelle at the factory, the use of screens, and runway sweeping with double inspections prior to any engine running—brought FOD under reasonable control.

The hardest problem encountered in flight was the development of the nacelle air inlet control. It was necessary to throw out the initial pneumatic design after millions of dollars had been spent on it and go to a design using electronic controls instead. This was very hard to do because several ele-

ments of the system were exposed to ram-air temperatures over 800°F and terrific vibration during an inlet duct stall. This problem and one dealing with aircraft acceleration between Mach numbers of 0.95 to 2.0 are too complex to deal with in this paper.

Initially, air temperature variations along a given true altitude would cause the Blackbird to wander up and down over several thousand feet in its flight path. Improved autopilots and engine controls have eliminated this problem.

There are no other airplanes flying at our cruising altitude except an occasional U-2 but we were very scared by encountering weather balloons sent up by the FAA. If we were to hit the instrumentation package while cruising at over 3,000 feet per second, the impact could be deadly!

Flight planning had to be done very carefully because of sonic boom problems. We received complaints from many sources. One such stated that his mules on a pack-train wanted to jump off the cliff trail when they were "boomed." Another complained that fishing stopped in lakes in Yellowstone Park if a boom occurred because the fish went down to the bottom for hours. I had my own complaint when one of my military friends boomed my ranch and broke a \$450 plate glass window. I got no sympathy on this, however.

OPERATIONAL COMMENTS

The SR-71 first flew 23 December 1964. It was in service with the Strategic Air Command a year later.

In-flight refueling from KC-135s turned out to be very routine. Over eighteen thousand such refuelings have been made to date by all versions of the Blackbirds and they have exceeded Mach 3 over 11,000 times.

The SR-71 has flown from New York to London in 1 hour 55 minutes then returned nonstop to Beale Air Force Base, including a London/Los Angeles time of 3 hours 48 minutes.

It has also flown over 15,000 miles with refueling to demonstrate its truly global range. It is by far the world's fastest, highest flying airplane in service. I expect it to be so for a long time to come.



CLARENCE L. (KELLY) JOHNSON is serving as senior advisor to corporate management and the firm's advanced development projects (Skunk Works). He retired from his post as senior vice president of the corporation in January 1975 and from the board of directors in May 1980.

Johnson joined Lockheed in 1933 as a tool designer. After assignments as flight test engineer, stress analyst, aerodynamicist, weight engineer, and wind tunnel engineer, he became chief research engineer in 1938. In 1952, Johnson was named chief engineer at Lockheed's Burbank, California plant, now the Lockheed-California Company. When the office of corporate vice president—research and development was established in 1956, he was chosen for the post. He became vice president—advanced development projects in 1958, a member of the board of directors in 1964 and a senior vice president of the corporation in 1969.

Johnson has played a leading role in the design of 40 world renowned aircraft—among them the F-80, America's

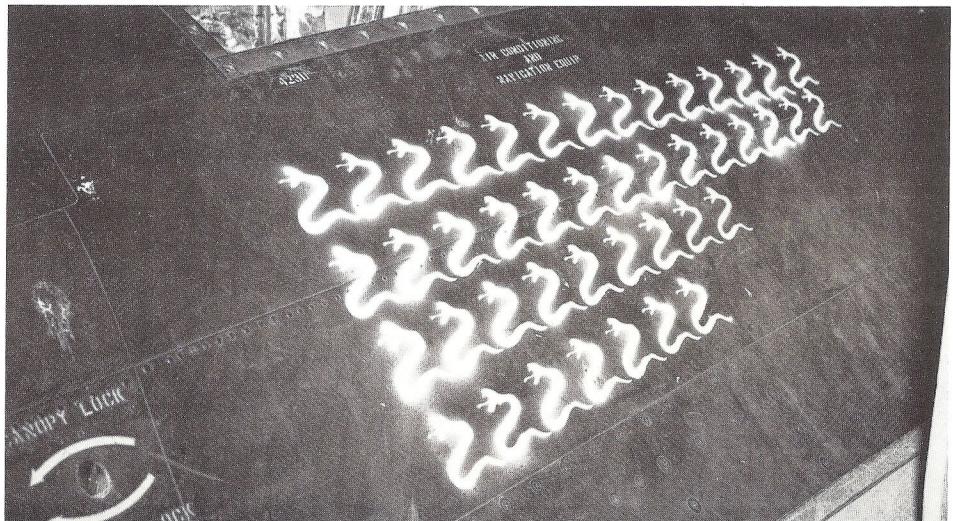
first production jet; the high altitude U-2; the double-sonic F-104 Starfighter; and the spectacular 2000-m.p.h. YF-12A and SR-71.

A native of Michigan, Johnson was born in Ishpeming on February 27, 1910. He later moved to Flint, was graduated from Flint Junior College, and completed his education at the University of Michigan, where he received his bachelor of science degree in 1932 and his master of science degree in aeronautical engineering in 1933.

Many honors have come to him for his unique contributions to aerospace development through the years, and to the defense of the United States and the Free World. Among these, Mr. Johnson has won the Collier Trophy twice and has also received two Theodore von Karman and two Sylvanus Albert Reed Awards. In 1964, President Lyndon B. Johnson presented to him the Medal of Freedom, the highest civil honor the President can bestow. He was elected to the Aviation Hall of Fame in 1974 and is the 1981 recipient of the Daniel Guggenheim Award.

Johnson is an honorary fellow of the American Institute of Aeronautics and Astronautics, a fellow of the Royal Aeronautical Society, and a member of the Society of Automotive Engineers and Tau Beta Pi and Sigma Xi engineering fraternities.

Mr. Johnson is married to the former Nancy Powers and they reside in Encino, California.



Southeast Asia Combat Missions for One SR-71—June 1971