

*Recollections from the "Skunk Works"*

## DEVELOPMENT OF THE LOCKHEED SR-71 BLACKBIRD

Clarence L. Johnson

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 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 reducing 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 communications 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. 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 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, 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 one-seventh of an acre!



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 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 sophisticated 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 platform 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.

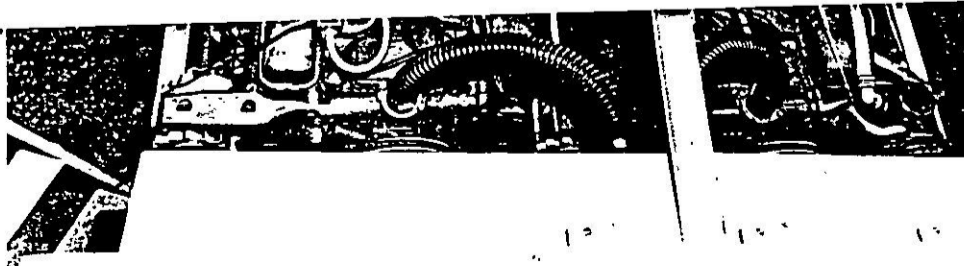
By far the most tunnel time was spent optimizing the nacelle inlets, bleed designs, and the ejector. A quarter-scale model was built on which over 250,000 pressure readings were taken. We knew nacelle air leakage would cause high drag so an actual full-size nacelle was fitted with end plugs and air leakage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

With the engines located half way out on the wing span, we were very concerned with the very high yawing movement 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 following this article.

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, until more sophisticated air starting systems were developed and installed in the hangars.



*SR-71 Blackbird***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, 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 worked fine.

The second test unit was the forward fuselage and cockpit, which had over 6,000 parts in it of high curvature, thin gauges, 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 TMC had at its 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.

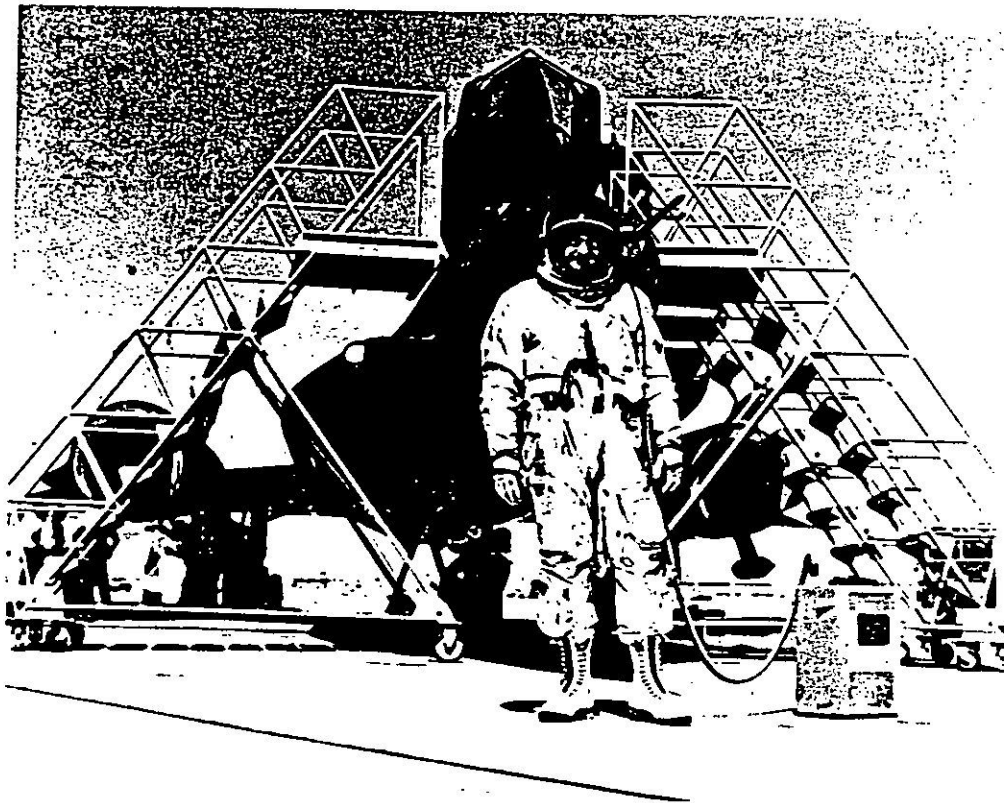
Drilling and machining high strength titanium alloys, such as B-120, required a complete research program to determine best tool cutter designs, cutting fluids, and speeds and feeds for best metal removal rates. We had particular trouble with wing extrusions which were used by the thousands of feet. 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 on a 50,000-ton press. 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 undergauge while in the acid bath, we set up a new series of metal gauges two thousandths of an inch thicker than the standard 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. To use titanium efficiently required an on-going training program for thousands of people—both ours in manufacturing and in the Air Force in service.

## SR-71 Blackbird



YF-12A test pilot in full pressure suit with walk-around oxygen kit.

Throughout this and other programs, it has been crystal clear to me that our country needs a 250,000-ton metal forging 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 it has more and larger forging presses than we do.

#### Fluid Systems

Very difficult problems were encountered with the use of fuel tank sealants 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 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 not removed from the nacelles during construction could be sucked into the engines on starting with devastating results. Damage to the first-stage compressor blades from an inspector's flashlight used to search for such foreign objects amounted to \$250,000! Besides objects of the above type, the engine would suck in rocks, asphalt pieces, etc., from the taxi-ways and runways. 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 elements 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!

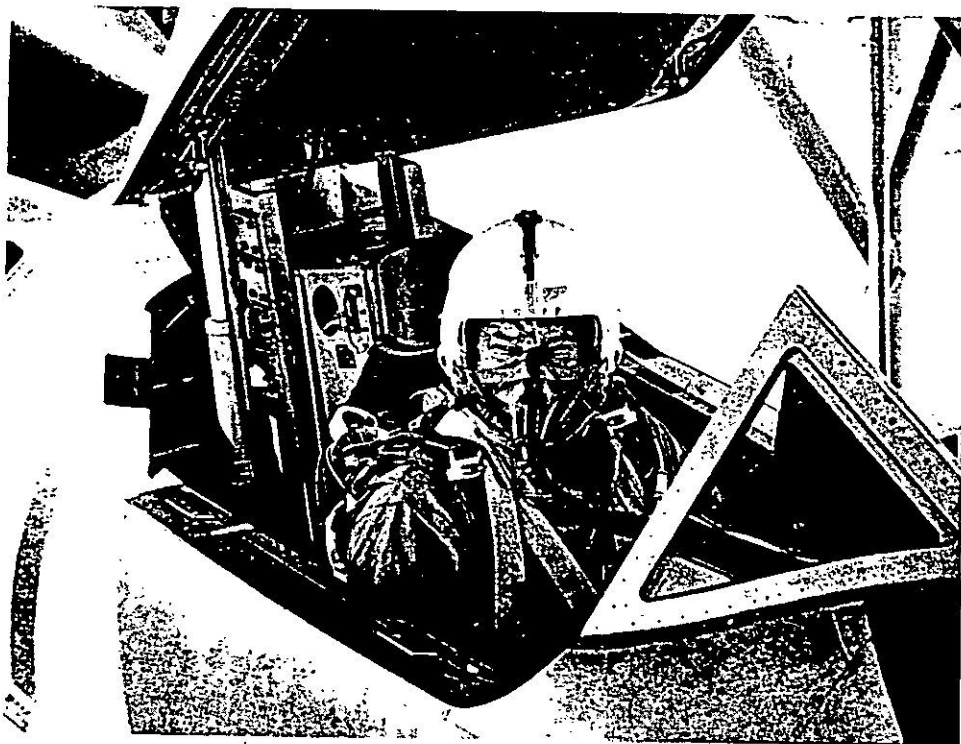
Flight planning had to be done very carefully because of sonic boom problems. We received complaints from many sources. One such stated that his mules on a pack-train wanted to jump off the cliff trail when they were "boomed." Another complained that fishing stopped in lakes in Yellowstone Park if a 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.

*SR-71 Blackbird***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 18,000 such refuelings have been made to date by all versions of the Blackbirds. 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.



The author about to fly in an early A-12 flight test.

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*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. He 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.