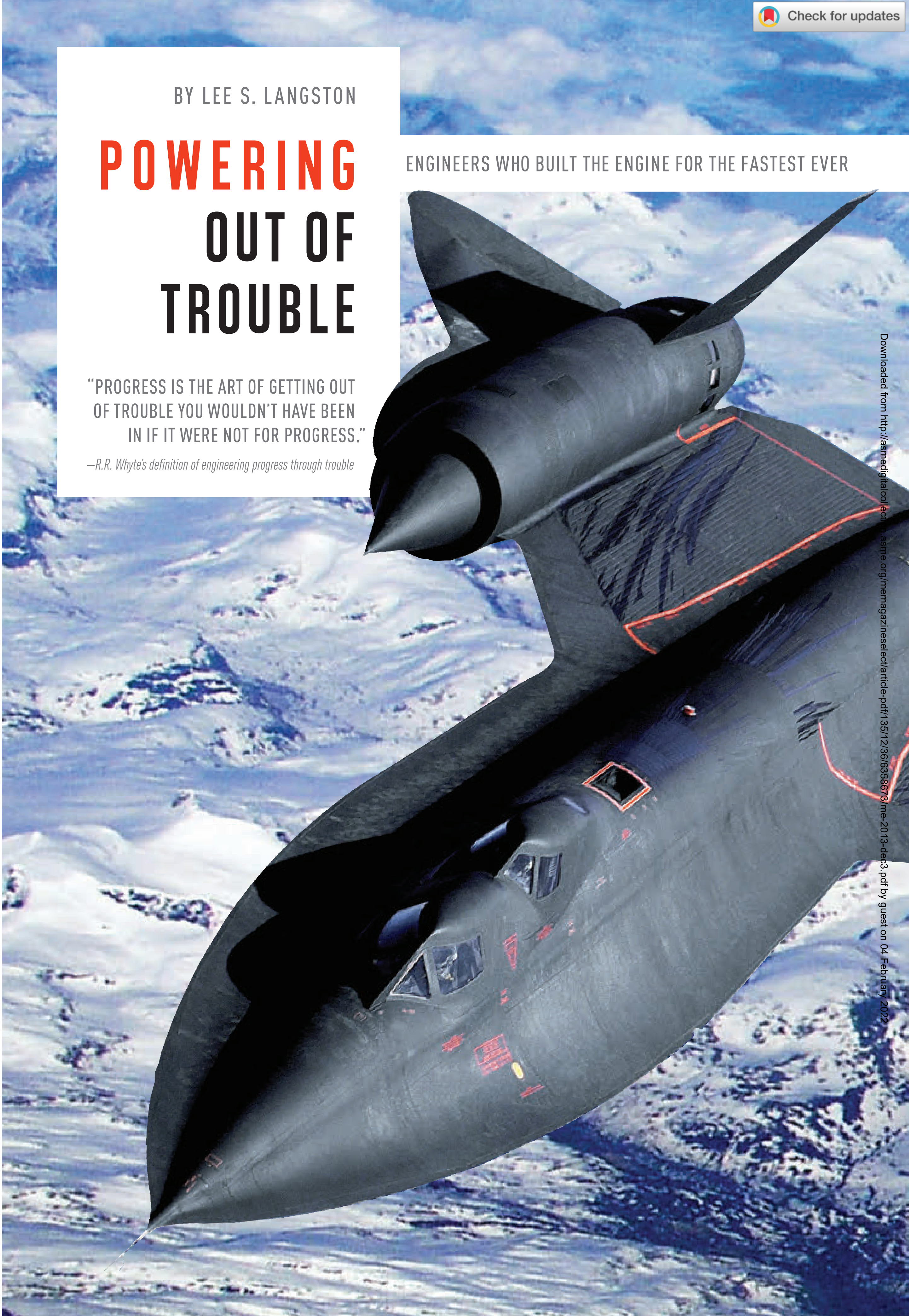
BY LEE S. LANGSTON

POWERING OUT OF TROUBLE

ENGINEERS WHO BUILT THE ENGINE FOR THE FASTEST EVER

"PROGRESS IS THE ART OF GETTING OUT OF TROUBLE YOU WOULDN'T HAVE BEEN IN IF IT WERE NOT FOR PROGRESS."

—R.R. Whyte's definition of engineering progress through trouble



AIRCRAFT HAD TO SOLVE TWO KINDS OF PROBLEMS: ➤THOSE INHERENT TO THE CONCEPT. ➤THOSE RESULTING FROM THE FIRST SET OF SOLUTIONS.

The F35 Joint Strike Fighter is a military aircraft that has no shortage of detractors. Some say it's too expensive, or that designing one plane capable of conventional take-off and landing, short take-off and vertical landing, and carrier-based operations has led to a craft too compromised to do anything well. There are even some who question whether manned fighter aircraft make sense in an age of drone warfare.

I'm not in a position to weigh in credibly on military procurement. What I can say is that to meet the punishing demands of the F35's mission profile, the engineers at Pratt & Whitney who have been developing the F135 turbojet engine have drawn on decades of progress to produce one of the most advanced gas turbines ever built. Using more than 30 years of film cooling research, for instance, the engineers have found a way to operate the single-crystal superalloy airfoils within the F135 at 3,600°F, well past the melting point for the material.

And yet, the F135 is not the most advanced, most extreme, most superlative-laden military aircraft engine ever built. That title is held by Pratt & Whitney's J58, which powered the SR-71 Blackbird supersonic reconnaissance aircraft. This afterburning, single rotor turbojet had a nine-stage 8:1 pressure ratio compressor and a two stage turbine, yielding 32,500 pounds thrust. The CIA flew an A-12, the single-seat version of the aircraft, powered by two J58s in early 1963, less than four years after Pratt started work on the project. The double-seat Air Force SR-71 first flew under J58 power on December 22, 1964.

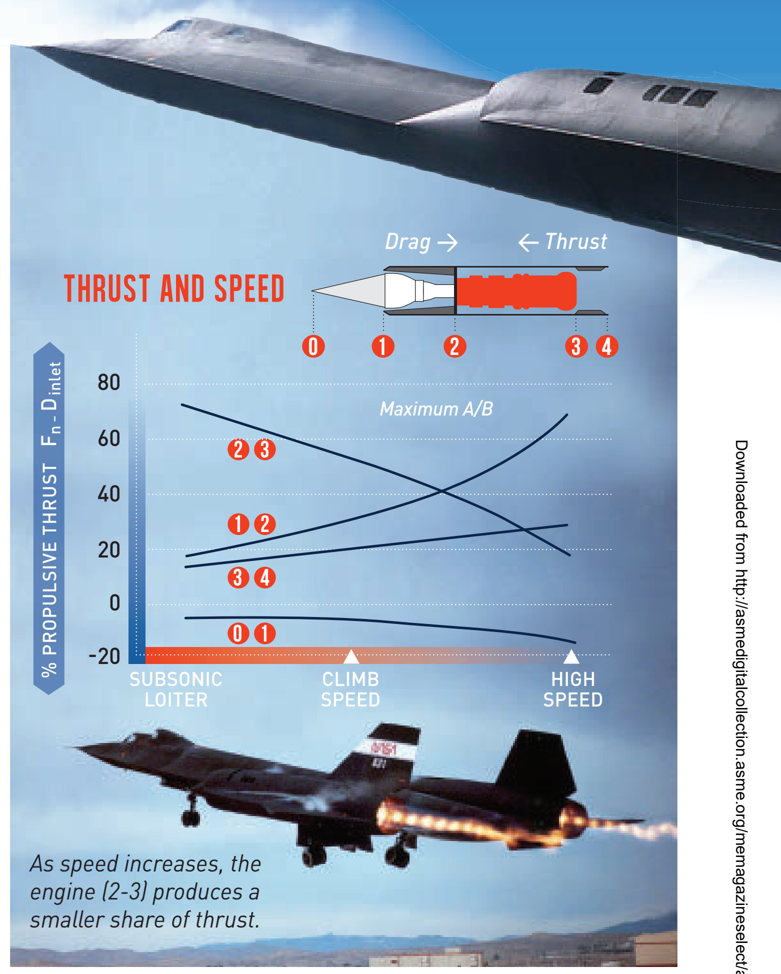
In March 1990, a Blackbird set a Los Angeles-to-Washington speed record, flying to its final resting place—a hangar owned by the Smithsonian Institution. It made the trip in just 64 minutes, 20 seconds.

Clarence L. "Kelly" Johnson, the leader of the acclaimed Lockheed Skunk Works, where the SR-71 was developed, wrote in his autobiography, "The power plant for the Blackbirds is a marvelous development on the part of Pratt & Whitney. It is the only engine of its kind in the world."

It should be noted that the work on the J58 was done only with the aid of slide rules.

I have had the good fortune to have been associated with Pratt J58 engineers, and have been privy to some of the stories they tell of the development of this remarkable engine. A pair of recent books—one by Richard Graham, a retired Air Force SR-71 pilot and officer, the other by John Whittenbury, who was a Lockheed Skunk Works design engineer in the 1990s—describe how that group of engineers found ways to overcome the nearly impossible demands of the design specifications to produce one of the most underappreciated engineering triumphs of all time.

We may never see the likes of it or them again.



As speed increases, the engine (2-3) produces a smaller share of thrust.

RECORDS SHOW THAT 32 SR-71S WERE BUILT,

as well as 18 planes of earlier models with such designations as A-12, YF-12, and M-21. (The “SR” stands for “strategic reconnaissance.”) The planes were designed for sustained flight at speeds in excess of Mach 3 at 85,000 feet or higher, and they were flown by the CIA, the Air Force and NASA, starting in 1963 and ending operations in 2001.

The engine to power that aircraft was first developed for another plane. In the mid-1950s, Pratt & Whitney Aircraft in East Hartford, Conn., had been working on a 30,000 pound thrust afterburning turbojet for a Navy attack fighter that would dash to Mach 3. After that program was scrapped, P&WA was ordered to proceed with the development of engines for five covert reconnaissance aircraft for the CIA. The company gave the new engine the model designation JT11D-20, but the resulting engine is still referred to in the Blackbird community as the J58.

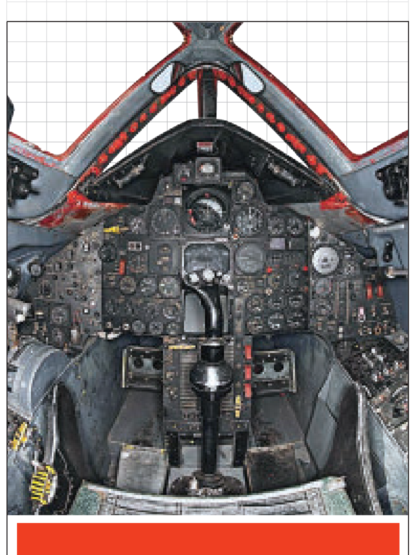
The company transferred the J58 project to its new 7,000-acre Florida Research and Development Center for a complete redesign to fulfill the reconnaissance mission requirements of the new aircraft. The isolated swamp land of FRDC was an ideal site for the early development and testing of the highly classified and noisy engines. Located inland, west of West Palm Beach, it had no neighbors in sight.

The noise and vibration levels of a J58 afterburning engine under test were enormous. On a few occasions, as a young East Hartford P&WA engineer, I had meetings at FRDC. Anytime I was near an operating J58 test stand, I needed to wear ear protection; even so, I could still feel the engine noise as a strong vibration in my chest.

Norm Cotter, who retired in 1981 from FRDC as senior vice president, remembers taking visiting government officials out to a J58 test stand in a company car. After a demonstration engine run, they left the safety of the test stand to find the car's side-view mirror lying on the parking lot pavement—a victim of the J58's vibration and noise.

The isolation of FRDC also aided the tight security imposed on the Blackbird project. Cotter said that for the most part, engineering staff working for four years on the J58 were unaware of the existence of the Blackbird, until President Lyndon Johnson disclosed the program in a 1964 speech. (Among some J58 old-timers, there is an apocryphal story that the very first J58s, for security reasons and time constraints, were shipped cross country to Lockheed in California in a bread delivery trailer truck.)

TIGHT QUARTERS A Blackbird pilot might have to remain in this cockpit for as long as 11 ½ hours. The cockpit and the rest of the aircraft was cooled by the JP-7 fuel.



The FRDC swampland may have provided more than security. The area was home to bobcats, poisonous snakes, and panthers. The late Wallace “Wally” Bowley, was a young FRDC engineer on the J58 program, performing heat transfer tests on J58 equipment. One winter morning he was running tests, in which heated cooling water was being returned to a pool surrounding the test stand. Alligators from the encircling swamp found they liked the warm water. As he looked out, Bowley could see a ring of floating alligators, staring at him, with their snouts tracing out a rough isotherm, seeking water not too hot and not too cold.

The design specification for the J58 called for continuous operation at Mach 3.2 up to 100,000 feet. Cycle studies showed that such performance would require continuous engine afterburner operation rather than conventional intermittency. This steady, pedal-to-the-metal operation was a first, for either a military or commercial jet engine.

According to Norm Cotter, full-scale testing of the original J58 compressor revealed the lack of sufficient stall margin at the higher Mach numbers. Stall occurs when the flow of air separates from the airfoil surfaces of the compressor, and creates a sudden blockage—or even reversal—of the engine flow.

Cotter said that the P&WA engineers considered using variable vanes or stators within the nine stage compresor, but decided to go with

bleeding off some of the airflow.

The J58 already had airflow bleed provisions intended to release some of the compressor air flow during engine starting to prevent choking of downstream compressor stages, which would result in stall of upstream stages. For conventional modes of operation, bleeding and venting compressor air results in a net loss of performance, so bleed valves are shut once the engine reaches full flow conditions. However, performance studies done by FRDC engineer Bob Abernethy showed that for a J58 application requiring continuous high Mach number afterburner operation, ducting compressor bleed air directly into the afterburner not only eliminated the stall margin limits, but it also provided better engine performance.

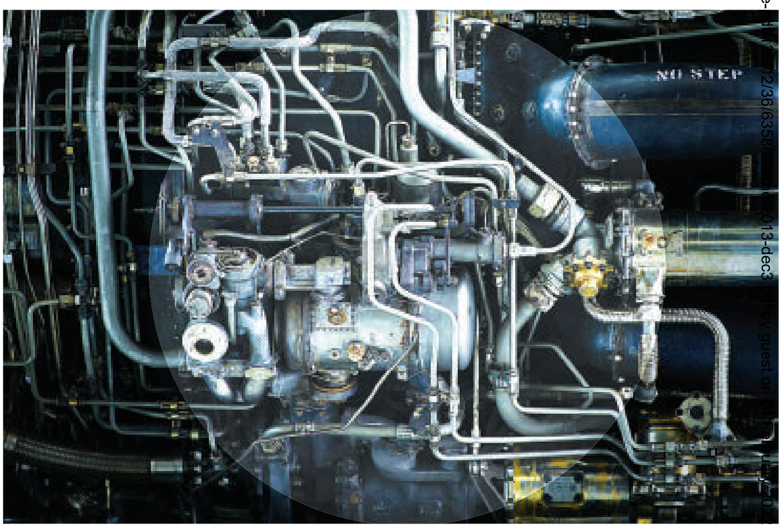
According to Bill Webb, an FRDC retired vice president, the resulting installation of six large bleed ducts running from just aft of the fourth stage of the nine-stage compressor to the afterburner resulted in a 22 percent increase in airflow, a 19 percent increase in net thrust, and a 20 percent advantage in fuel consumption at cruise supersonic flight conditions. Afterburner ducting continuously exposed to 3,200 °F exhaust gases was benevolently cooled by the compressor bleed air.

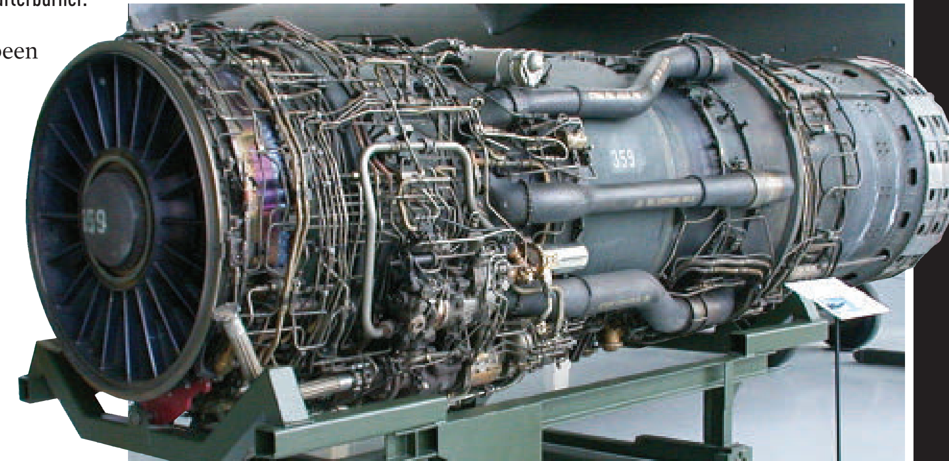
The J58 Blackbird engine is a variable cycle engine, a turbojet/ramjet combined-cycle engine. It is a conventional afterburning turbojet for takeoff and transonic flight, and it approximates a ramjet during high-speed supersonic cruise.

The compressor bleed/afterburner solution and resulting improvement in performance conforms to R.R. Whyte's definition of engineering progress through trouble: "Progress is the art of getting out of trouble you wouldn't have been in if it were not for progress."

Both of the Blackbird's twin nacelles contain an engine supersonic inlet, the J58 engine with its afterburner, and an exhaust ejector nozzle. All three components contribute to the Blackbird's propulsive thrust in varying proportions, depending on flight speed.

Within their internal gas paths, jet engines operate in subsonic flow regimes. Thus the Blackbird's supersonic inlet must provide subsonic flow to

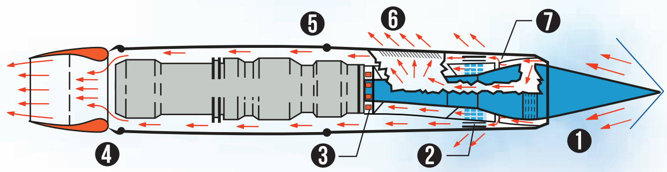




J58 UP CLOSE
Now a museum display (top), the J58 engines featured an air-driven afterburner turbo fuel pump (center) and six bleed ducts (bottom) running to the afterburner.

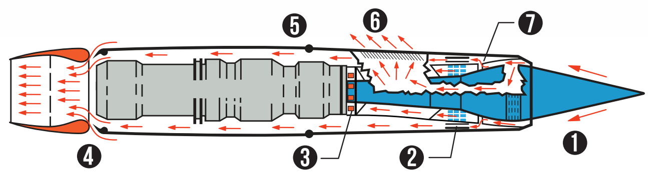
FROM TAKEOFF TO MACH 3.2

The SR-71 Blackbird operated under conditions as mundane as a runway and as extreme as supersonic flight. This was accomplished by changing the flow of air through the inlet, J58 engine, and exhaust ejector nozzle.



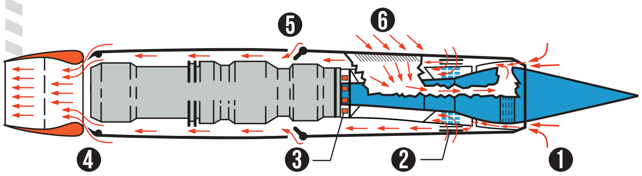
0.0 0.5 **1.5** 2.5 3.2

1 Spike forward. **2** Forward bypass, doors open, as required to position inlet shock. **3** Aft bypass, doors closed. **4** Tertiary doors closed, ejector flaps opening. **5** Suck-in doors closed. **6** Centerbody bleed overboard. **7** Shock trap bleed supplies engine cooling air.



0.0 **0.5** 1.5 2.5 3.2

1 Spike forward. **2** Forward bypass, doors closed. **3** Aft bypass, doors closed. **4** Tertiary doors open, ejector flaps closed. **5** Suck-in doors closed. **6** Centerbody bleed overboard. **7** Shock trap bleed supplies engine with cooling air.



0.0 0.5 1.5 2.5 3.2

1 Spike forward. **2** Forward bypass, doors open. **3** Aft bypass, doors closed. **4** Tertiary doors open, ejector flaps closed. **5** Suck-in doors open. **6** Centerbody bleed

TEST FIRING The noise and vibration from a J58 test was so great that it could rattle the side-view mirror off nearby cars. The engine was developed at an isolated research center in Florida.

the J58 compressor inlet, over the full range of flight speeds. It does this with a movable centerbody, a right circular cone with a half angle of 13 degrees. In a fully forward axial position, it provides subsonic flow to the engine, up to Mach 1.6.

Beyond Mach 1.6, the cone centerbody retracts axially to "start" the supersonic shock system. In a 26-inch fully retracted aft position, at the design cruise Mach number of 3.2, an oblique shock system exists with the lead shock stretched between the cone's apex and the nacelle lip, to yield a maximum total pressure recovery of 40:1.

This efficient conversion of inlet air flight speed kinetic energy provides a net axial pressure force on the inlet's internal surfaces to add forward thrust. (The sudden loss of this efficient oblique shock system is called an "unstart" and instantly yaws the aircraft, necessitating swift and nimble action by the pilot and engine control system to restore it.)

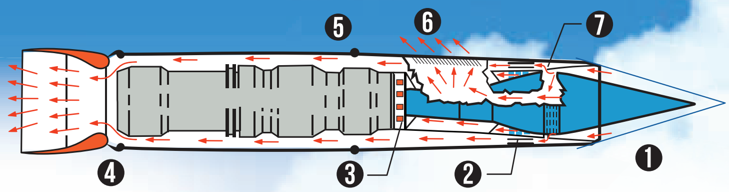
At a given operation condition, the engine will accept a specific amount of air flow depending on its power (throttle) setting. The inlet recovery system, consisting of the movable cone and sets of nacelle bypass doors, then adjusts to provide the needed flow. The exhaust ejector nozzle, downstream of the J58 afterburner exit, has sets of free-floating blow-in doors and trailing-edge flaps, all adjusted during flight by internal and external pressure forces, to maximize thrust.

At take-off and low-speed flight the J58 engine/afterburner provides most of the thrust. At the Mach 3.2 design cruise speed, the inlet provides 54 percent of the total thrust with 28.4 percent by the ejector nozzle and only 17.6 percent coming from the engine. If one didn't know better, one might advocate for no engine, in light of these supersonic thrust figures.

THE FUEL SYSTEM ON BLACKBIRDS WAS multipurpose and truly unique. Because of the extreme range of pressure and temperature encountered with speed and altitude, a very low vapor pressure, high flashpoint fuel was used. This fuel, JP-7, could not be spark ignited. It required the use of liquid pyrophoric fluid triethylborane—TEB, which explodes with an apple-green flame on contact with air—for both ground and air starting of the engine and afterburner. This Pyrophoric Ignition System was later rechristened the Chemical Ignition System after someone noticed the indecorous acronym.

The six Blackbird JP-7 fuel tanks had a total capacity of 11,000 to 12,000 gallons, giving Blackbirds a range of roughly 2,000 to 3,000 miles, depending on altitude and speed. For longer missions aerial refueling by KC-135Q model tankers was needed for every two hours or so of flight and always after the Blackbird's initial takeoff. According to Bill Webb, the longest Blackbird flight was an 11 ½-hour circuit from Griffith Air Force Base in New York to Israel, Egypt, and Syria during the 1973 Yom Kippur War, and required five in-flight refuelings.

As the topped-off tanks were depleted, the



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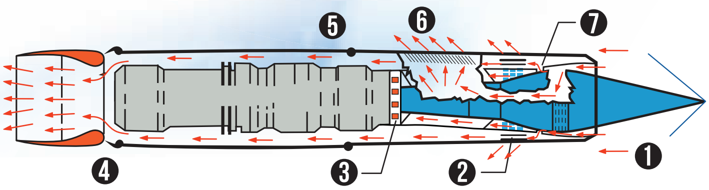
1 Spike retracted. **2** Forward bypass, doors closed; will open as required to position inlet shock. **3** Tertiary doors closed, ejector flaps open. **4** Suck-in doors closed. **5** Centerbody bleed overboard. **6** Shock trap bleed supplies engine cooling air.



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1 Spike retracting. **2** Forward bypass, doors open, as required to position inlet shock. **3** Aft bypass, doors scheduled open. **4** Tertiary doors closed, ejector flaps opening. **5** Suck-in doors closed. **6** Centerbody bleed overboard. **7** Shock trap bleed supplies engine cooling air.

resulting ullage was inerted with gaseous nitrogen, evaporated from two onboard liquid nitrogen filled dewars. This was important: Because the tanks were comprised of the Blackbird's titanium skin, at Mach 3, the external boundary layer temperatures could be 700 °F or higher, causing the skin temperature to reach as much as 600 °F in some spots. This would heat the JP-7 to 300°F or higher, and in the absence of the inert nitrogen, the fumes of the fuel at that temperature would explode.

The heat of Mach 3 flight caused other problems. The J58 could have compressor air inlet temperatures as high as 800 °F at supersonic speeds. The engineers were faced with the quandary, where do you "dump" heat to cool things? The answer was the JP-7 fuel, which was used to cool the cockpit, equipment bay air, engine oil, TEB tank, and engine accessory equipment. Valving in the fuel heat sink system sent hot fuel to the engine and afterburner if below 295 °F, or back to the fuel tanks for reuse.

As related to me by Bill Webb, a 1,900-psi hydraulic system, powered by an engine-driven variable displacement pump, was used to activate the engine exhaust nozzle, the bleed system, and other engine systems. Since conventional hydraulic fluids were not suitable at the high nacelle temperatures, it was again decided to use the JP-7 fuel itself. The fuel had no lubricity, so a small amount of fluorocarbon was added to allow pumps and servos to work. Getting the hydraulic system to operate without seizure or leaking in an engine nacelle environment of 1,200 °F, with combustible fuel at 1,900 psi, required thousands of hours of slide-rule powered design, redesign, and testing.

In 1959, all P&WA jet engine turbine airfoils were uncooled, with a maximum allowable gas temperature entering turbines of 1,650 °F—just below the softening point of the superalloys used for the airfoils. The J58 supersonic cruise conditions pushed the turbine inlet gas temperature to 2,000 °F, necessitating air cooled airfoils in the J58 turbine's first stage. This was a first for the company, setting the design stage for turbine cooling in future military and commercial jet engines.

INFLIGHT SERVICE Although the SR-71 had six fuel tanks, the plane had to be refueled every 2,000 to 3,000 miles, and always after take-off.

Unbeknownst to many Blackbird historians, the first real engine test of single-crystal turbine blades, a P&WA invention now used on most high-performance gas turbines, was carried out on the J58 in the 1960s. The single-crystal technology wasn't yet ready, but later models of the J58 made use of directionally solidified turbine airfoils, a first in production engines.

There are many more stories that could be told about the J58. But the people who worked on the project are consistent on one point. John Dalton, a Boeing technical fellow who earlier served as an Air Force officer managing 500 personnel maintaining SR-71s, told me anyone he knew associated with the Blackbird and its engine considered it to be a high point in their life. Norm Cotter, Pratt's retired senior vice president, avers that any J58 program participant will tell you it was the best engine program, in all respects, on which they ever worked.

Kelly Johnson was right: The J58 was truly a marvelous development and, to this day, the only engine of its kind in the world. We may never see the likes of it again. **ME**

FOR FURTHER READING

Graham, Richard H., SR-71: *The Complete Illustrated History of the Blackbird, the World's Highest, Fastest Plane*, Zenith Press, 2013.

Whittenbury, John R.,"Lockheed Blackbirds (A-12, YF-12, M-21, and SR-71)," *Fundamentals of Aircraft and Airship Design*, vol. 2, pp. 432–512, Carichner, Grant E. and Nicolai, Leland M., American Institute of Aeronautics and Astronautics, 2013.

Connors, Jack, *The Engines of Pratt & Whitney: A Technical History, American Institute of Aeronautics and Astronautics*, pp. 321–337, 2010.

Taylor, Edward S.,"Evolution of the Jet Engine," *Astronautics & Aeronautics*, vol. 8, pp. 64–72.

Abernethy, Robert B.,"Recover Bleed Air Turbojet," U.S. Patent Office, No. 3, 344,606, 1967.

Whyte, R.R., ed.,"Engineering Progress Through Trouble," The Institution of Mechanical Engineers.

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