8-94-2

Adventure into the technical unknown

J58/SR-71 PROPULSION INTEGRATION

William H. Brown

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 aerodynamic 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.

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 Aicraft, 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 complete 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.

COMPARISON OF J58 DEVELOPMENT OBJECTIVES WITH THEN-CURRENT PRODUCTION ENGINES

	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
Afterburner Operation	Intermittent	Continuous

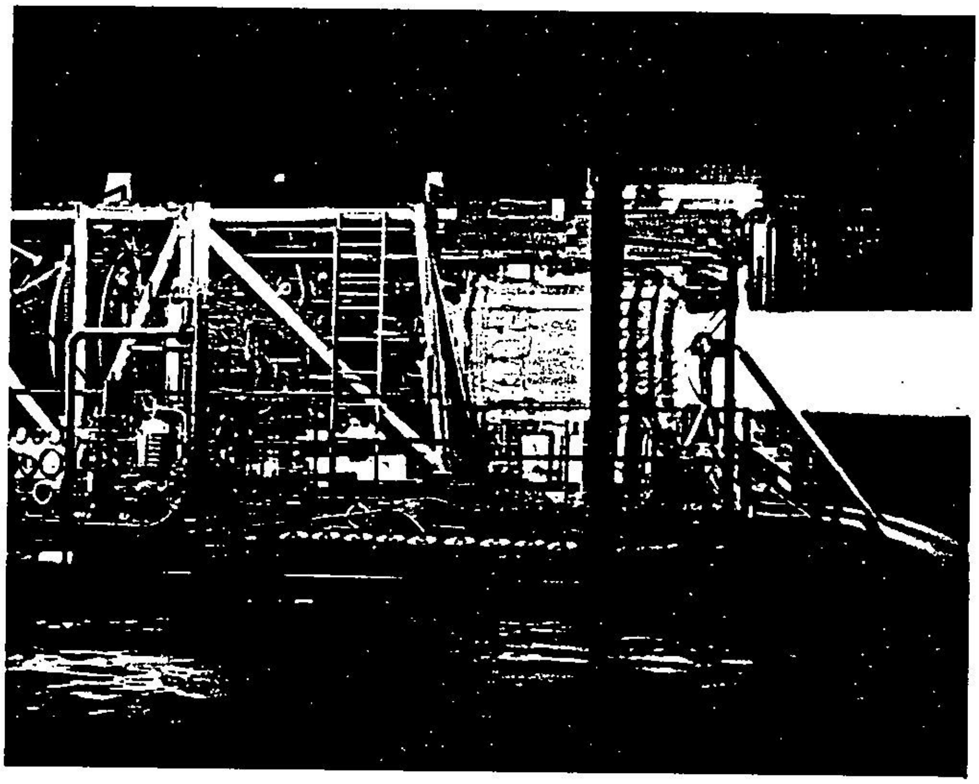
Increased Requirements

The table shows 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 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 requirement. 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.



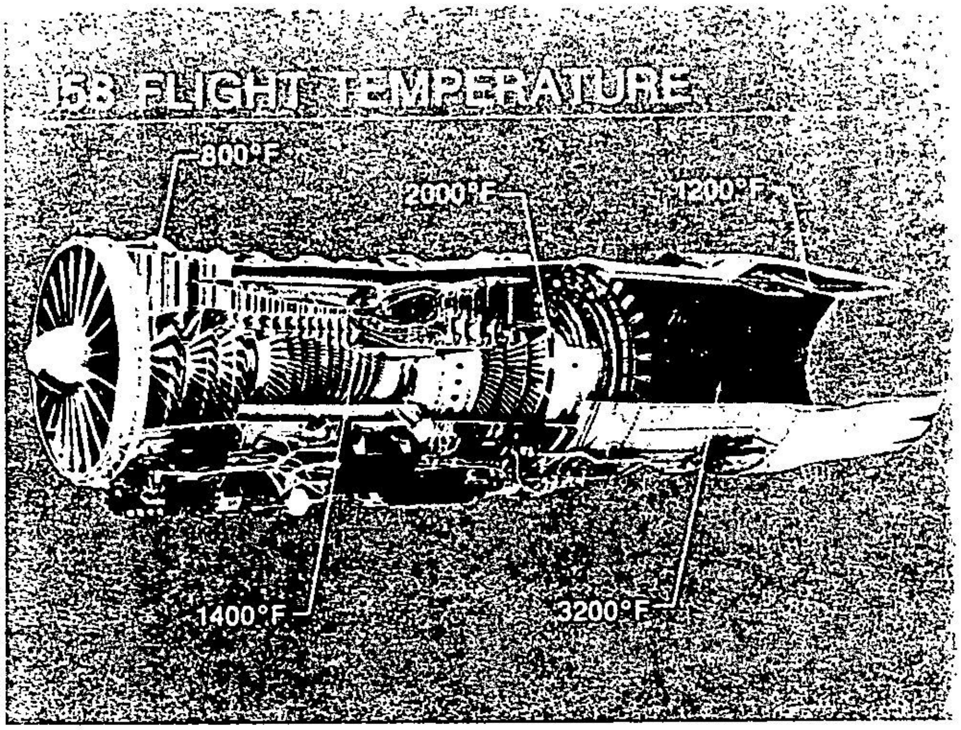
J58 Engine under test.

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 fluoro-carbon 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.

Instrumentation for Testing

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. On a test stand built as a partial solution, 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 system 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 filght 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.

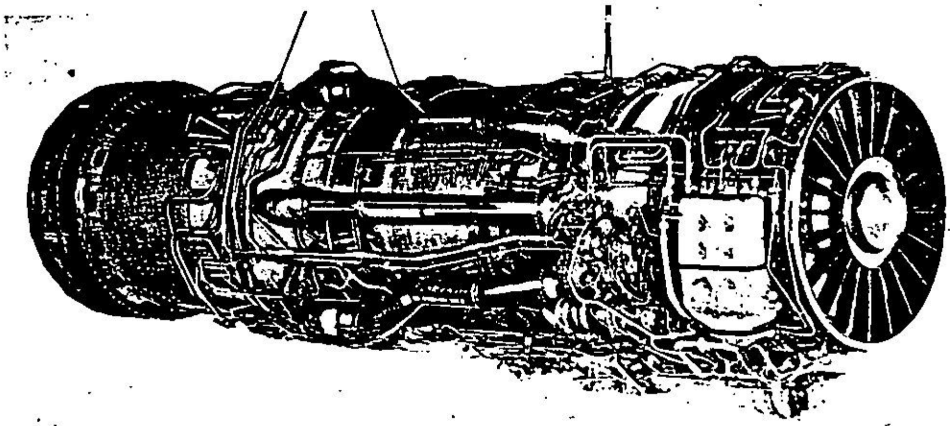
The first problem happened very early—the engine wouldn't start! The small inlet wind tunnel model did not show the inlet being so depressed at the starting J58 airflows. In fact, instead of air flowing out of the compressor fourth stage through the bleed ducts into the afterburner, it flowed the other way! As a temporary fix, Lockheed removed an inlet access panel for ground starts. They later added two suck-in doors 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.

A Shifting Gearbox

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



Pratt & Whitney J58 (JT11D-20) engine.

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 pressure spikes at the engine fuel inlet were going off scale. This overpressuring 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. 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 gauge 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. This modification has worked well ever since.

Trouble on the Wrong Side

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. 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.
3. Derichment valve with unstart signal installed on engine to protect turbine.

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.

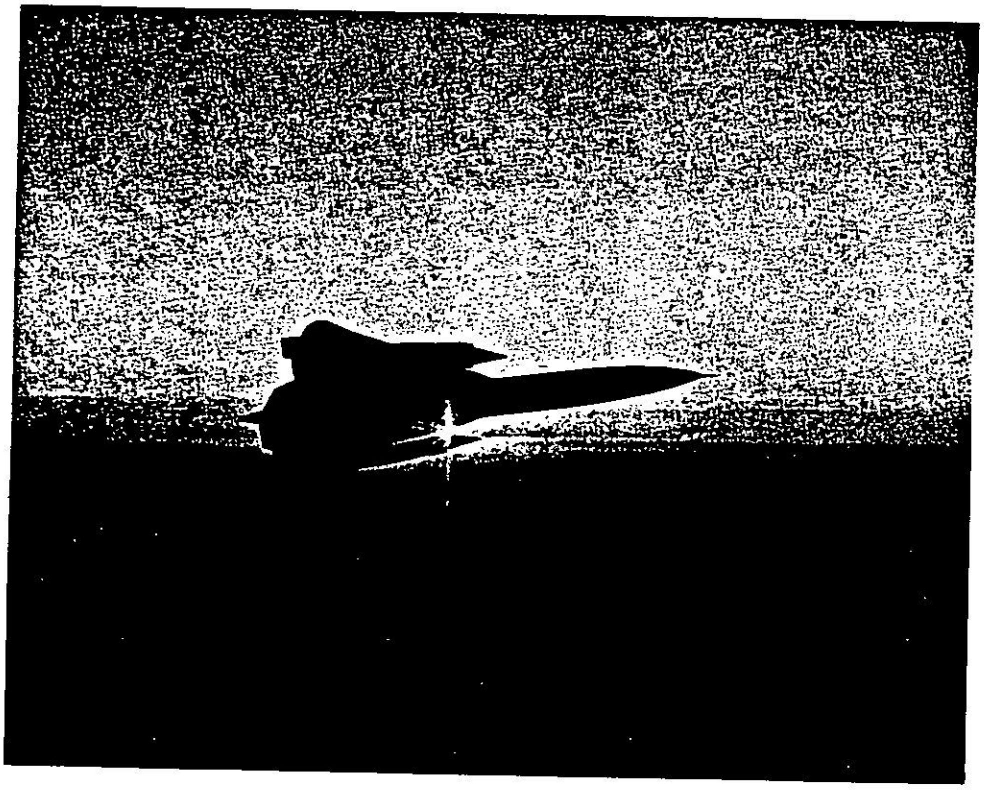
As you have probably noticed, I have had difficulty in differentiating between "we" Pratt & Whitney Aircraft and "we" Lockheed. But that is the kind of program it was.

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

Management Philosophy

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



Lockheed SR-71 in flight.

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 was 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.