G. Keith Richey: The Cold War Aerospace Technology History Project (Interview 2)

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Dr. G. Keith Richey: We’re here in the Cold War Gallery, of the National Museum of the United States Air Force, a wonderful collection that covers airplanes from about 1945 up to the end of the Cold War. I wasn’t involved with all the aircraft in this collection, but I’ll highlight some of the aircraft that I was involved with in my career at Wright-Patterson, from 1961 to about 1997.

00:00:31 F-15: I’d like to talk a little bit about the F-15. The F-15 is an air-superiority fighter designed for hard maneuvering and generated in the 1970s, where the emphasis was on both close-in combat and long-range combat, air-to-air, with missiles. I was involved with the airframe propulsion integration, which has to do with the inlet airframe integration; also the exhaust nozzle airframe integration in the back. This inlet is called a two dimensional variable ramp inlet, and it’s designed to capture clean flow coming off the fuselage and entering the air intake so that the flow distortion to the twin engines—the two F-100 Pratt and Whitney engines—are delivered with clean flow so they can operate at extreme maneuvers. This airplane can pull very high G’s and extreme angles of attack and fly from subsonic up to about Mach 2.5.

The idea then, was to have a two-dimensional inlet. This is based to some extent on the North American RA-5J Vigilante reconnaissance airplane, a successful propulsion integration, an arrangement where there was little problems between the inlet and the airframe. When we come out of the late ’60s with some of the problems in the F-111 that I’ll describe later, McDonnell-Douglas wanted to make sure that they had a good system which will allow clean airflow to the engine. And it was quite successful.

In order to match the airflow between various mach numbers, this initial ramp actually rotates down. It’s a unique design. There’s been
nothing before it or after it the same way, where this whole section here
rotated down and there was a break right about there, and the whole inlet
the airflow between the inlet and the engine.

00:02:39 F-16: This is the F-16 Falcon, the ultimate hot-rod. It was designed in
the early 1970s by General Dynamics, Ft. Worth, Texas. In the late ‘60s
and early ‘70s, the Flight Dynamics Laboratory where I worked had a
series of research programs called Tailor-Mate. The object of Tailor-Mate
was to develop options for airframe propulsion integration for future
fighter highly maneuverable aircraft, aircraft which would fly a Mach
number range from subsonic to low supersonic, up to about Mach 2. The
emphasis was on close-in combat, not so much emphasis on interception
and high-speed aircraft such as the F-15 or what was in development also
at the time, the SR-71.

The Tailor-Mate program developed a series of inlet-airframe
combinations, one of which was what we called the single-inlet shielded
configuration. We used the flow from the fore-body of the airplane, the F-
16, to straighten out the flow before it came into the air intake. The air
intake was designed to deliver clean air flow to the engine, in this case an
F-100 Pratt and Whitney 25,000 pound afterburning turbofan engine. This
airplane has a thrust-to-weight ratio of well over one. It can reach very
high speed going straight up, and it’s used even today by the Air Force
Thunderbird acrobatic team. It is a single seat airplane with a lot of
maneuverability in all directions so that the inlet-airframe combination
had to be able to deliver clean air flow over a wide maneuvering range of
angle of attack, sideslip and Mach number. The maximum Mach number
is roughly 1.6 to 1.8 with this airplane. That’s the reason it’s called a
fixed capture external compression inlet, and it doesn’t have the ramp
structure that the F-15 inlet has.

This inlet was designed by the engineers in Project Tailor-Mate,
and it was adapted to the F-16 by an engineer at General Dynamics named
Harry Hillaker. In his references, Mr. Hillaker refers to the Flight
Dynamics Laboratory as the origin of this combination of airframe
propulsion. It’s been one of the most successful marriages we’ve ever seen
between an airplane and an inlet, because it works flawlessly. There’s
been virtually no compressor stall problems with the F-16 in its
development. It’s been a very reliable system.

The only thing they’ve had to worry about was the fact that this
inlet is fairly close to the ground so that it might suck up debris from the
runway as you’re taking off at high power settings. But the Air Force is
very good about keeping its runways clean, and there’s been very little
evidence of foreign object damage with this inlet. The other thing it does
is that the boundary layer that comes off the fuselage is diverted. This is
called a plow, a boundary layer plow, and it diverts a little bit of the
boundary layer off of the fuselage, around and off to the side. This is a
kind of a scoop here for some cooling, but it’s a very clean installation, so that it really operates quite well over a complete range of Mach number.

The back end of the F-16 is also very clean. The F-15 had some problems with dual-jet interaction; this being a single jet aircraft, it didn’t have those kind of problems, so that the back end of the F-16 is also very clean. Again as we’ll talk a little bit later, the F-111 was kind of the genesis of a lot of the late ’60s, early ’70s issues with airframe propulsion integration. And then the laboratory picked up on that, and it ran several very successful programs, one having to do with inlet airframe integration, the other had to do with exhaust nozzle airframe integration. The group that I ran in the Flight Dynamics lab at that time directed those programs. The inlet program was with General Dynamics. The nozzle airframe integration program was with Lockheed. Both those companies then were able to transfer the information over to the next generation of aircraft. In the case of General Dynamics, we saw it coming in with the F-16. In the case of Lockheed, we eventually saw some of our work being translated into the F-22 Raptor aircraft, a very advanced design with respect to nozzle and inlet airframe integration.

00:07:25

F-111: One of the products of the Cold War driven by the Soviet threat was the development of the F-111 fighter bomber. The F-111, as you can see here, is a fairly large aircraft designed to fly long distances at high altitude, then drop down on the deck, a few feet above sea level, following the terrain in order to avoid threat radars. This was before the days of stealth, so the aircraft had to fly below the radar in order to penetrate enemy defenses, and that was the reason for the development of the F-111.

The F-111 originally was to be a dual service aircraft, joint between the Air Force and the Navy. It was designed to accommodate both a fighter-bomber for the Air Force and a long-range interceptor for the Navy. This was in the days of Secretary Robert McNamara who believed that commonality of design and airframe could save money, a noble idea but one which didn’t work out very well in the case of the F-111. It was kind of the ultimate compromise and particularly in regards to the Navy mission was deficient, and later on the Navy would drop the airplane, but the Air Force would continue development of the F-111 into what turned out to be a rather capable fighter-bomber.

But it had its problems in development. The first flight of the F-111 was in 1964 after contract award had been made in 1962 to General Dynamics, a rather controversial award because of the competition between General Dynamics Ft. Worth and the Boeing Company of Seattle. The Air Force evaluation board actually preferred the Boeing design, but Mr. McNamara believed there was more commonality in the design proposed by General Dynamics, so Mr. McNamara, then Secretary of Defense, overrode the recommendation of the service selection board and chose the General Dynamics F-111.
Given that, let’s talk a little bit about the airplane itself. It is a large airplane, weighs over 100,000 pounds, designed to fly both subsonic, including Mach 1.2 on the deck; that was their original design, supersonic at sea level, a very difficult problem, all the way up to Mach 2.5 at altitude for use as an interceptor. It was not designed to be a particularly maneuverable aircraft; it was designed to launch missiles out of its weapons bays down here below. It was all internal carriage of the missiles and armament, even though some of the airplanes were designed for external carriage of weapons as they were developed later on.

About 1965 and 1966, as the airplane got into development flight testing, a problem occurred between the inlet and the engine. Basically the engine would stop running at critical flight conditions of maneuvering, what we called compressor stalls, since the flow back to the Pratt and Whitney TF-30 afterburning turbofan engines was highly distorted from the arrangement of the inlet and airframe as I’ll discuss in a few minutes.

This was the first integration (in the early ‘60s) between an airplane and an afterburning turbofan. Engines up to that time had all been straight turbojets. It turned out there were some interesting interactions between an afterburning turbofan, where some of the airflow goes around the engine and some goes through the engine, because it allows a communication of what goes on in the back of the engine with what happens in the front of the engine. So for example when you light off the afterburner of a turbofan engine, you actually can sense those pressure pulses coming forward and being picked up at the compressor face. A conventional turbojet couldn’t do this because it’s a single flow path.

There was a phenomenon here called compressor stall of an afterburning turbofan engine which had not been previously identified. It turned out that the problem with the inlet airflow combination of the F-111 was what we called dynamic distortion, or time-dependent distortion. Before that, engineers had always looked at the steady state flow as delivered at the compressor face of an engine with a series of screens and probes, and they were able to then tailor an engine so that it would be able to take that flow pattern delivered by whatever inlet was on the airplane. In the case of the F-111, the flow was very unsteady—I’ll discuss that in a couple of minutes—the flow was very unsteady so that the flow at the compressor face of the engine was jumping around and had different flow patterns as a function of time. And so that eventually we had to look at the characteristics of the engine against a snapshot in time, just a few milliseconds, basically the time for a compressor blade makes one full revolution. If a compressor blade made one full revolution when the flow was distorted, the engine will react to that flow as if it was steady state and, in fact, stall. So the problem with the F-111 as it began to get into flight test was that these engines were stalling, quitting, even at take-off when the pilot would light the afterburner, start down the runway, the engine would quit—not a good thing. It would stall when the airplane did...
mild or moderate maneuvering. The engines would stall when the airplane tried to go supersonic, particularly as it approached about Mach 2.2 and up to 2.5, the engine would just be very unreliable and would stall.

As you might expect, this got the attention of Mr. McNamara very quickly because this was kind of his baby, and of course the press was very interested in the progress of the F-111. There were Congressional review committees, such as one called the Senator Stephens Committee. Senator Stephens was looking at the whole issue of the development of the F-111 and particularly the award of the F-111 to General Dynamics. So there was a lot of scrutiny about the F-111 as it was developed. The reason I’m telling this story is that this became the genesis of work in the Flight Dynamics Laboratory following the late ‘60s and early ‘70s, as I mentioned before, to develop options for future aircraft which did not have compressor stall problems, particularly with attention to the dynamic distortion problems that the F-111 had. So we learned a tremendous amount from the F-111.

The involvement of the laboratory to solve the F-111 stall problem was a joint effort between the laboratory engineers and engineers in the F-111 System Program Office, specifically Mr. Fred Rall, a brilliant engineer, himself also a propulsion integration specialist. Mr. Rall knew about the issues before the airplane was ever designed and he expressed his concern in the source selection board. It turned out that those concerns were overridden as we said before by the powers that be. But Mr. Rall had worked for several years with General Dynamics to make the design as good as they could.

The problem with the F-111 is the flow coming off of the wing up here and the fuselage has to be kind of squeezed together as it comes into the air intake. This is what’s called a plow, a splitter plate, where you’re trying to scrape off some of the boundary layer coming down this rather long fuselage to keep it from spilling into the inlet, because the boundary layer is always unsteady and it’s always distorted and by the time it goes in and gets mixed around a little bit and gets to the compressor face, it delivers unfavorable air to the engine face. So the idea was to remove some of the boundary layer coming off the fuselage by this splitter plate.

Well, it turned out that boundary layer was a little bit thicker on the fuselage than was anticipated, because it’s not an exact science (this is before the days of computational fluid dynamics). The boundary layer was spilling over the splitter plate and coming into the inlet. That’s the reason that in this particular design they actually bulged out this splitter plate a little bit to try to capture more of the boundary layer, but you’re limited in how much you can actually bulge it out, because you then interfere with the flow to the inlet. So it’s what they call a bulge splitter plate; the original F-111 design had a straight splitter plate just like that so there’s three or four inches of boundary layer that was spilling into the inlet.
Also, the boundary layer coming off the wing up here was to be captured by a series of capture inlets here. In the original design, those were like little doors that captured the boundary layer, the secondary boundary layer coming off the wing, another one behind, and the designers tried to route that to the back of the airplane, again to reduce drag, because of the need to have low drag in this airplane. That didn’t work either because the flow just didn’t go back, and it backed up and then spilled back into the inlet. So the original design had boundary layer spilling from here, had boundary air spilling from there. There’s some flow separation down on the bottom of the inlet because it was sharper at that time, and so the flow was really kind of a mess coming back into the inlet.

Well, Pratt and Whitney knew about all that, and based on steady-state wind tunnel tests, they knew what they had to deal with. So Pratt and Whitney did their best to design an engine which would accommodate the steady state characteristics of that rather distorted flow. There were some compromises in performance, but overall the inlet was expected to be all right, based on steady state measurements. However, as we got into flight, it turned out that the flow was not steady whatsoever, as I said earlier. Well, this was a mystery to engineers at General Dynamics and the F-111 System Program Office, and the laboratory since no one had any experience at that time with what was called dynamic distortion.

As we got into it, we started to look at what is the flow really doing. We put a couple of noise probes actually in the inlet, and we started looked at reducing data from those noise probes. This was a very laborious process back in those days—this is the ’66, ’67 timeframe—to reduce the data on those unsteady probes, and we found out that the flow in there was extremely noisy. So we said if it’s noisy at one or two points at the compressor face, maybe it’s noisy over the whole flow, and so then we began to look at instrumentation on an aircraft which would look at the entire flow face in a dynamic way.

When we did that, we were able then to compute what was called the dynamic distortion and when we were able to do that, we’d get a match between the actual flow of the inlet and the place at where the compressor stall should occur, so there wouldn’t be any surprise stalls. The stalls would occur where they were supposed to.

That didn’t solve the problem, though. The fact was that the airplane was still undergoing compressor stall problems which basically eliminated its ability to perform its mission, so a lot of pressure in the late ’60s was on fixing that issue. Through a series of wind tunnel tests and flight tests, engineers at General Dynamics and the Air Force came up with a series of modifications to the basic F-111A inlet and variations for the later versions of the F-111. The first variation was to move the splitter plate out here, make it wider so to capture more boundary layer. The second variation was to not capture the boundary layer up here beneath the wing but just to divert the flow in a plow here at the top. Another variation
was to thicken up the inlet lip so as to reduce the flow distortion and the flow separation off the inlet here. All of those fixes together opened up the envelope of the F-111A, opened it up to about twenty-five degrees of maneuvering at subsonic speeds, opened up the stall-free envelope to about Mach 2.2, and the airplane could go straight and level at 2.5 but you couldn’t maneuver very well. That became the basis of the inlet for the F-111A.

By that time, the F-111A was in series production because it was a system the Air Force Tactical Air Command desired very much to have in its inventory, driven by the threat of the Cold War, the ability of the airplane to fly at low level to avoid radar, the ability of the airplane to fly at high speeds, intercept Soviet aircraft, so it was a keystone system in the development against the Soviet threat in the late ‘60s. There was a pressure for the airplane to be put into inventory and so by the time the inlet changes had been made, General Dynamics had produced well over a hundred of the F-111s, and you just couldn’t go back and make radical changes because airplanes were in production, and they were going into service with this modified inlet. This modified F-111A inlet, then, was able to give the Air Force an operational capability that was better than the original design but still had some deficiencies.

Later on, Mr. Rall came up with a more radical change in the design which essentially moved the entire inlet out about five or six inches further off the fuselage and in the F-111D models and later models of the F-111, you see no splitter plate here at all, and you see a very much wider dispersion between the side of the airplane and the air intake. This was to get it out of the distorted flow off the fuselage and off the wing, so that in fact the inlet had clean flow. It was a very successful design also, and that design was eventually put into all later models of the F-111.

About 140 aircraft were put into service with the United States Air Force with this inlet here, which is called Triple-Plow I, triple-plow because there are three plows around the inlet to divert the flow. Triple-Plow Two, originated by Mr. Rall, moved the entire inlet out, and those inlets were put into production versions of the F-111 from about 140 on to about number 690 or so; roughly 700 F-111s were produced by General Dynamics, and it was retired from service in 1996. So over that time frame, it was developed through a lot of problems, not only with the air intake, but with the structures on the variable sweep wing. It eventually became a very capable airplane. And of course the F-111 was replaced as time went on with other aircraft such as the B-1 and eventually modern aircraft such as the F-22 for the fighter-bomber role and the B-2 in the bomber role.

But it was this kind of an airplane arrangement that generated the research that the laboratory had. So the laboratory in this case is responding to a need which has been shown up by an operational system, and responding to the Air Force’s desire to have a good family of fighter aircraft in the future, a future beyond 1970, such as the F-16 and the F-15,
and later on, the F-22, which would be free from compressor stall problems. So it was a very good arrangement between the laboratory and the systems engineers at the system program offices at Wright-Patterson to develop a technology and then use it in later systems.

F-22: This is the F-22 Raptor. It’s the newest operational airplane in the United States Air Force. It’s appropriate that it’s in the museum at the entrance to the Cold War Gallery because it kind of came out of the Cold War and was a bridge system between the Cold War and the situation we have today with uncertain threats, the Global War on Terrorism, and the idea that a future threat could come up somewhat like the Soviet Union was in the Cold War.

What’s different about this airplane are three things. First of all, it’s the first supersonic fighter-bomber designed for stealth. The shape of the airplane, the shape of the inlet, the shape of the wings, and particularly the exhaust nozzle in the back were designed for a reduced radar cross-section, or stealth. Also the airplane was designed to be able to fly supersonic at 1.6 Mach number without afterburner, in what we call supercruise mode, the first airplane that could do that. Also then it was designed to be a multi-role aircraft—air superiority, fighter-bomber, even for attack. So stealth, supercruise, and multi-role were the hallmarks of the F-22 development.

The inlet and the nozzle came out of a series of programs that was generated by the Flight Dynamics Laboratory in the late ‘70s and early ‘80s. The design of the F-22 was put into place in the ‘80s. The inlet was designed based on a series of research programs which followed Tailor Mate in the ‘60s, by the Flight Dynamics Laboratory, and this is called a Caret inlet where the shape of the airplane and the shape of the inlet are designed as a unit, so that it really becomes one flow field rather than two separate flow fields, as was the case of airplanes up to that time. Computational fluid dynamics was used extensively to design the inlet and airframe combination by Lockheed and by the laboratory engineers.

In the back, the engine exhaust nozzle is called a two-dimensional nozzle. This is very unique in that the F-22 was the first airplane to be developed with a two-dimensional nozzle. As you can see inside, the engines are of course circular and so that normally the exhaust nozzle maintains a circular shape to expel the flow from the engine through the exhaust nozzle. In the 1980s, the lab, the Flight Dynamics Lab, worked closely with NASA-Langley, a fellow named Bill Henderson, to develop a series of two-dimensional nozzles. The idea originally was to have reduced drag for a twin-engine fighter aircraft that didn’t have the drag problems that we’d seen on the F-111 and the F-15, where the flow in the back of the airplane is producing extra drag on the airplane. A two-dimensional nozzle was designed to fit better into the boxy back end of a fighter airplane, and so the lab and NASA-Langley worked together to develop a series of two-dimensional nozzles.
The lab also then emphasized the ability of a two-dimensional nozzle to also incorporate thrust vectoring. It’s actually easier to vector thrust up and down in order to provide pitch augmentation for a maneuverable airplane using a two-dimensional nozzle than it is by using a symmetrical nozzle. Later on, designs were put together for a multi-access thrust vectoring nozzle which would be able to pitch vector at both the vertical and horizontal planes, giving even more flexibility. Some of the modern Soviet aircraft now are picking up on the multi-access thrust vectoring. The lab worked on the thrust vectoring, also on thrust reversing, of a two-dimensional nozzle, and ran a flight test program using an F-15 airplane to demonstrate the flight worthiness of a two-dimensional thrust vectoring/thrust reversing nozzle.

Lockheed picked up on the lab program and used a two-dimensional nozzle design in the F-22 for two reasons. One, of course, it had less radar return from the back so it fit in with the stealth characteristics of the F-22. The other reason was that using thrust vectoring allowed more stability of the airplane at high angles of attack, and so that you had the ability to control the airplane at extremely high angles of attack, because the F-22 is both a close-in maneuvering airplane and a long-range stand off missile airplane to provide a response to a wide variety of threats. The F-22 is what we call a fifth-generation fighter aircraft, beginning back with the early days of fighter aircraft after World War II, and the joint-strike fighter is also a fifth-generation aircraft.

Sixth generation? Hard to tell what it will be. Some people think it might be unmanned. Some people don’t think so. But certainly it will have a lot of the legacy from the laboratory programs, and the legacy from the F-22, because we’re going to have stealth in the future as a requirement, and we’re going to have supersonic operation in the future for a wide variety of threats that we might face. So that whatever the future holds in the area of fighter aircraft, it will be based strongly on the legacy of the laboratory programs in the ‘60s and ‘70s, the development of the F-22 in the ‘80s and ‘90s.

During the decade of the 1990s, the laboratory at Wright-Patterson Air Force Base put over one billion dollars of research and development into various aspects of the F-22, everything from engine research to composites, to aerodynamics, to propulsion integration, avionics. Laboratory programs at that time were all focused towards the development of technologies which allowed this airplane to come to pass. Those were all put together into this F-22 system, which is now becoming operational with the Air Force. It’s a system that will probably last the Air Force for at least thirty or forty years. The F-22 is a very capable system, and certainly capable of going against any threat that we can foresee in the future.