The Little Engine That Couldn’t

The new Eclipse 500 lightjet will no doubt make a lot of customers happy

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Cessna’s T-37 was dubbed “Tweety Bird” for its shrill Teledyne CAE J-69s. (USAF)

IT’S AUGUST 26, 2002, A CLEAR, HOT MORNING at Albuquerque International Sunport. Poised for takeoff on Runway 17 is a small orange and white twin-engine jet carrying a heavy load of hype and hope. A press release from its manufacturer says the first flight of this prototype will do nothing less than “forever change the landscape of transportation.” The Eclipse 500’s promised $837,500 price tag—an astonishingly low figure, barely a quarter that of the next cheapest jet—and 56-cents-a-mile direct operating cost have brought in deposits for more than 2,000 airplanes, potentially making it the best-selling private jet in history even before it flies.

Two engine nacelles, stovepipe-skinny and barely four feet long, sprout from the rear fuselage. They hold the key to the Eclipse’s remarkable price and performance claims: a pair of Williams International EJ22 fanjets, breakthrough powerplants developed by Sam Williams, the renowned guru of small jet engines. Using what Eclipse calls “disruptive” technology, the EJ22 has churned out 770 pounds of thrust in ground tests, yet, at 85 pounds, you could pick it up.

This 9:1 thrust-to-weight ratio is unprecedented, almost double that of any commercial jet engine. It's the breakthrough that can make the Eclipse 500 a landscape changer.

Albuquerque Tower clears N500EA for takeoff, and test pilot Bill Bubb releases the brakes and shoves the twin thrust levers forward. The EJ22s spool up into a soft whoosh and the airplane begins to accelerate down the runway.

But something's wrong. The acceleration is lethargic, especially for an airplane loaded so lightly. In the hot, thin, mile-high air, the EJ22s can generate barely half their rated thrust. After a leisurely takeoff roll of more than 3,000 feet, the airplane lifts off and begins a gentle climb, paralleling the Sangre de Cristo mountains off its left wing. For about an hour, Bubb flies the planned test routine, checking out general handling qualities and systems operation. Overall, the flight is free of major glitches.

And yet, as the little jet taxies back toward the cheering employees at the Eclipse hangar, it's already clear that the new EJ22 engines aren't going to hack it.

The Eclipse 500 never again flew with EJ22s. Three months later, Eclipse Aviation announced: "The EJ22 is not a viable solution for the Eclipse 500 aircraft, and Williams International has not met its contractual obligations." Williams conceded that it had run into "a number of challenges" with the EJ22 but insisted it had satisfied the contract, implying that the airplane had simply grown too heavy.

Eclipse hurriedly signed a deal with Pratt & Whitney to develop a smaller version of a more conventional engine. The PW610F would develop 900 pounds of thrust, but it would weigh 260 pounds—triple the weight of the EJ22. The extra power would give the Eclipse 500 a bit better speed and climb, but there was a big downside: an empty-weight gain of 700 pounds and a 20 percent increase in fuel consumption. The remarkable price and cost projections eventually ballooned to $1.3 million and 89 cents a mile. Three years later, flight tests of the P&W-powered Eclipse 500 are proceeding smoothly, but it's still not clear whether it will change the landscape of transportation.

The failure of the Williams EJ22 to achieve Federal Aviation Administration certification in the Eclipse and the engine's disappearance from public view were bitter disappointments to those who for decades have yearned for a certified engine that could lead to a new generation of small, affordable jets. The failure was also a blow to the reputation of its creator, Sam Williams, now 84, who essentially invented the small turbofan engine in the 1960s and remained its unchallenged mastermind for more than three decades.

Williams wasn't the first to build a tiny jet engine. Back in the early 1950s, the French-built Turboméca Palas, with 330 pounds of thrust, inspired the creation of half a dozen oddball experimental Euro mini-jets. The Palas grew into the Marboré series (660 to 1,058 pounds of thrust), which powered a number of small military jets, such as the Morane-Saulnier 760 Paris four-seater and Cessna T-37 trainer. (The latter used the J-69, a version of the Marboré made by the U.S. company Teledyne CAE.) In the 1970s, the French firm Microturbo lowered the bar with the 220-pound-thrust TRS 18, which flew in the Italian Caproni A21J sailplane and in U.S.

designer Jim Bede's BD-5J airshow jet. Only 24 inches long, the TRS 18 is still the smallest jet engine ever to power a manned aircraft.

Those early mini-engines had a problem, though. Like all turbojets, they sucked up prodigious amounts of fuel. Worse, small aircraft are penalized by the pitiless exponential mathematics of scaling down: Reduce an airplane's length by half, and internal volume for fuel shrinks eightfold. The BD-5J had an endurance of about an hour or so and a range of around 300 miles.

To be commercially viable, a small jet engine had to be fuel-efficient. That meant it had to be a turbofan. While Pratt & Whitney and Rolls-Royce began pushing ahead with turbofan technology in large engines in the 1960s, it was left to a young Purdue graduate and former Chrysler engineer named Sam Williams to create a small, fuel-efficient turbofan.

Williams left Chrysler in 1954 to start his own company. His first jet engine, prosaically named Jet No. 1, made its first run in 1957 at a meager 60 pounds of thrust. It weighed just 23 pounds; an old Williams publicity photo showed a smiling June Cleaver lookalike holding it in one hand. An improved version, the WR2, ran in 1962. Hewing closely to Frank Whittle's 1930 turbojet configuration, the WR2 had a single-stage centrifugal compressor and a single-stage turbine. The reference book Jane's All the World's Aircraft described the engine as "simple in design, almost to the point of appearing crude." In 1964, a more powerful version of the WR2 became the first Williams jet to fly, powering the Canadair CL-89 reconnaisance drone. The follow-on WR24 series, despite horrendous fuel consumption, was Williams' first big commercial success, eventually powering more than 6,000 short-range Northrop target drones.

In 1967, Williams completed its breakthrough engine. The WR19, a turbofan based on the WR2 core, produced 430 pounds of thrust, weighed only 67 pounds, and was nearly twice as fuel-efficient as the WR2. It powered two short-lived 1970s contraptions: the Bell Jet Flying Belt, a Buzz Lightyear-style jet backpack; and the WASP II flying platform, a sort of aerial Segway Human Transporter.

The WR19 also caught the eye of military planners studying the concept of a long-range cruise missile. Williams' timing was perfect; the WR19 was the only small engine with the fuel efficiency the cruise missile mission demanded. An up-rated version of the WR19, the 600-pound-thrust F107, eventually became the prime mover for the Navy Tomahawk and Air Force Air-Launched Cruise Missile, with production of more than 6,500 engines over 30 years. For creating the F107, Williams was awarded aviation's highest honor, the Collier Trophy, in 1979.

Williams had begun tinkering with a small civilian turbofan based on his cruise missile technology as far back as 1971. But it would be a huge step to take a specialized Tomahawk powerplant, which only had to start once and run for three or four hours, and adapt the technology to produce a commercially viable engine.

Small size itself creates many design problems. Turbine blades can be made smaller, but air molecules can't; as a result, skin friction and boundary layer effects are proportionally greater. (In engineering argot, a small engine is inherently less efficient because it operates at a low Reynolds number, an aerodynamic coefficient that relates component size to the air's inertial and viscosity effects.) Compressor and turbine blade tip clearances are proportionally greater, resulting in greater tip losses. To maintain the most efficient turbine and compressor blade tip speeds, small engines must spin faster. Small turbine blades are also harder to cool. Oil passages become narrower, making lubrication tricky. Manufacturing tolerances shrink to watchmaker scale.

In 1978 Williams signed a deal to develop the WR44, an engine with 850 pounds of thrust for the five-passenger Foxjet 600, an aircraft eerily similar to the Eclipse but doomed to mockup status. A subsequent flirtation with the ill-fated American Jet Industries Hustler likewise went nowhere, and it wasn't until 1988 that a Williams engine finally took wing with a human aboard. A pair of 1,800-pound-thrust FJ44s powered Burt Rutan's Triumph, a proof-of-concept prototype for a Beech light business jet.

It was Cessna that jumped on the light-jet concept, however, and in 1992 the Cessna CitationJet, with a pair of FAA-certified FJ-44-1As, rated at 1,900 pounds of thrust and weighing 450 pounds, became the first production aircraft with Williams engines. At a bargain $3.2 million, it quickly became the best selling bizjet in history. Once again, Williams had jump-started a whole new class of aircraft, and once again he had the niche to himself.

But the elusive Foxjet category still beckoned. In the early 1990s, Williams began developing a fanjet in the 700-pound-thrust class. The new engine would be a clean break from the philosophy of gradual evolution and refinement that had guided the 35-year progression from Jet No. 1 to the FJ44. Developing this new technology would be expensive, but again Williams' timing was impeccable. The General Aviation Propulsion (GAP) initiative, a pet program of NASA Administrator Dan Goldin, promised to revitalize the moribund lightplane industry with innovative engine technology. In 1996 Williams teamed up with NASA for a four-year, $100 million effort to "reduce the cost of small turbine engines by a factor of ten and revolutionize the concept of personal air transportation," as a NASA press release put it.

When NASA engineers first saw Williams' radical new GAP design, the FJX-2, they were skeptical. "We weren't sure if they could really do this," recalls Leo Burkardt, the GAP program manager. "Their projected performance, weight, and cost were so much better than the other proposals that even if they only got halfway there, it would still be better than anybody else."

John Adamczyk, the NASA senior technologist on the project, still remembers his shock upon first seeing the FJX-2's parts laid out. "I just shook my head in amazement at how small it all was. It looked like someone was assembling a Swiss watch." A five-stage compressor from the FJX-2 that Williams showed off at the 1997 Oshkosh, Wisconsin airshow looked more like the business end of a Cuisinart than the seeds of an aeronautical revolution. With each stage intricately carved from a single piece of titanium, it weighed one pound, three ounces. “You could hold it in the palm of your hand,” recalls Adamczyk, still awestruck.

But the doubts vanished a year or so into the program, after the first test of the main compressor. “All the numbers matched our analysis,” remembers Adamczyk. “It really gelled at that point.” The complete engine first ran in August 1999 and was soon hitting its predicted thrust numbers. Four engines eventually accumulated a total of almost 900 starts and more than 500 hours of running time in the test cell. Testifying before Congress in 2000, Sam Williams declared the FJX-2 a “major success.” Adamczyk, a 30-year veteran who has worked on numerous jet engine projects, calls the FJX-2 “one of the high points of my career.”

All the while, Williams had been promoting the concept of a very light jet (VLJ) that could eventually use his new engine. In 1996, he’d hired Burt Rutan to build a demonstrator aircraft, the four-seat V-Jet II. Williams’ contract with NASA called for the V-Jet II to fly with a pair of FJX-2s as the capstone to the GAP project. But it initially flew with FJX-1s, man-rated versions of the F107 cruise missile engine rated at 550 pounds of thrust. With Goldin in attendance, the V-Jet II created a sensation at Oshkosh in 1997 with the noisy, underpowered FJX-1s. Among the thousands of salivating airplane buffs in the audience was a wealthy pilot and businessman named Vern Raburn.

An early Microsoft executive and stockholder, Raburn had just left a job overseeing the technology investments of billionaire Microsoft co-founder Paul Allen, for whom he jetted around the country at the controls of a Williams-powered CitationJet. Raburn had the restless soul of an entrepreneur, and he had long nurtured the same vision as Williams: a small, inexpensive jet airplane. Galvanized by the V-Jet II and reports of the extraordinary little FJX-2, Raburn signed a deal with Williams in May 1998 to jointly develop a five- or six-seat VLJ. It would be powered by an FAA-certified version of the FJX-2, to be called the EJ22. Together, Sam Williams and Vern Raburn were going to revolutionize aviation.

With $60 million in investors’ money, a board of directors studded with high-tech corporate heavyweights, and an exclusive deal with Williams for the EJ22, Raburn launched Eclipse Aviation in March 2000. Williams, citing the Eclipse deal, persuaded NASA to skip the FJX-2 flights in the V-Jet II. This enabled Williams to get its final GAP payment sooner and turn immediately to the task of transforming its test-cell tour de force into a viable FAA-certified engine.

Exactly how did such a little engine achieve such extraordinary performance? Officially, nobody’s saying. The Williams company, privately held and with a long history of military projects, is secretive about technical details. NASA and Eclipse people who worked on the project, bound by confidentiality agreements imposed by Williams, are likewise mum.

“I think I can tell you that the main reason for the engine’s light weight is the architecture,” says NASA’s general aviation champion, Bruce Holmes, referring to the configuration of a jet engine’s fan, compressors, combustor, and turbines. “But I’d go to jail if I told you what that architecture was.”

Holmes can rest easy. I managed to ferret out the FJX-2's architectural secret anyway: Instead of the usual two compressors, it had three, each spinning independently at its optimum rotation speed on one of three concentric shafts and driven by its own turbine. Designers call this unusual configuration a three-shaft, or three-spool, engine (see "Spools," above).

The giveaway is on the instrument panel of the original Eclipse 500. Most jets have two readouts: N1 for the low-pressure (LP) compressor/fan, and N2 for the downstream high-pressure (HP) compressor. The Eclipse had an N3 gauge, which points to the presence of a third, intermediate-pressure (IP) compressor. Ed Lays, a retired Williams engineer not bound by any secrecy agreements, confirms that the FJX-2 was a three-shaft design.

A three-spool engine can be very efficient. "It gives you a lot of flexibility in matching compressors and turbines," says Burkardt ("Not that I'm saying the FXJ-2 was or was not a three-spooler," he adds dutifully). However, a three-shaft engine is mechanically complex, with "bearings and seals out the ying-yang," in the words of Teledyne CAE veteran designer Gerry Merrill. Only two three-spool engines have ever been certified for commercial use: the Rolls-Royce RB.211 family of airliner engines first certified in the '70s, and the Garrett ATF3, a fearsomely complex and troublesome bizjet engine that flopped in the marketplace 10 years later.

The decision to abandon the simple, well-proven two-shaft configuration of all previous Williams fanjets set off controversy within the company. "Some of the guys who'd worked on the FJ44 didn't have much confidence in the EJ22," says Lays, who explains that one impetus for the three-shaft design came from Sam Williams' son Gregg, then a Williams VP and now company president, who'd spent two years working with Rolls-Royce on the RB.211. "Gregg was hooked on three-spool engines back then," Lays recalls.

The axial high-pressure compressor showcased at Oshkosh was also a departure for Williams, which had used centrifugal compressors in all its previous engines (see "Compressors," p. 23). Other rumored design features-—compact in-line combustors, tiny integral accessories mounted directly on the main shaft—will not be revealed until next year, when a five-year NASA embargo on the release of FJX-2 technical publications expires.

The key to the FJX-2's extraordinarily light weight was its manufacturing technology. Williams, with decades of experience building jewel-like cruise missile engines, is unrivalled in its ability to craft tiny, durable jet engine parts with great precision. Burkardt quotes one of the losing bidders for the GAP program at the Oshkosh show where Williams exhibited its tiny compressor. "The guy told me, 'Now I know why you chose them instead of us,' " Burkardt recalls. "No other company could build this engine."

But could Williams get it certified? While the FJX-2 merely had to produce thrust in a test cell, the EJ22 would have to pass a battery of FAA tests to prove that it could start reliably, run without a hiccup for thousands of hours, supply bleed air for pressurization and de-icing, run a generator, be easy to service and repair, and survive the real-world ingestion of gravel, ice, and birds. (Birds do not scale down either; an EJ22 swallowing an FAA-mandated four-pound bird is the equivalent of a Boeing 777 engine ingesting a small cow.)

While Williams wrestled with these challenges, Eclipse began building the first test airframes. By the summer of 2002, the airframe of N500EA was ready to go. Williams, although behind schedule, was reporting good progress with the engine development. So it was with keen anticipation that some 50 Eclipse employees gathered in the 2 a.m. darkness to welcome a Falcon jet freighter as it pulled up to the Eclipse hangar. The first EJ22 was off-loaded, uncrated, and gently set down on the hangar floor. "It was pretty and new and shiny, and everybody just sat there stroking it," recalls Raburn. "It was fantastic."

The euphoria died, however, when the engine refused to start. It took an impromptu mixture adjustment, over the objections of Williams engineers, to get it going. And that was just the beginning. The starters overheated and failed. Seals leaked. Shrouds cracked. Fan blades broke. The fuel controller had problems. Serious snags bedeviled the integration of the engines to the airframe. "Within a few days we realized that the engine was massively immature," recalls Raburn.

To make matters even worse, the EJ22 had not been designed to be repairable or serviceable in the field. "We had to ship engines back to Williams 15 or 20 times in the first 90 days," says Raburn. "The air freight company ended up just basing their plane here. The pilots told us, 'We're not flying back home, because we know you're going to need us again in a few days.' "

After about six weeks, Eclipse managed to get two engines running at the same time. (Still, one wouldn't start for the official rollout ceremony, so the airplane had to be towed out of its hangar to meet the aviation press.) Eclipse discovered that at high power settings, the EJ22s ran hot and could not achieve their expected thrust without exceeding inter-stage turbine temperature limits. On that anemic first takeoff, it was the combination of those temperature limits and density altitude that reduced the engine thrust to barely half the nominal 770 pounds.

Disillusioned with Williams, Eclipse brought in an outside consultant, who concluded that the engine was, at best, still two or three years away from certification. Eclipse had neither the time nor the money for such an extended effort. "The core problem was that the EJ22 was radically more complex than anything Williams had ever done before," says Raburn. "It was so tiny and so complex that we came to believe it could never be robust enough to operate the way our customers were going to operate it. It's got to be a bulletproof engine that just runs and runs and runs. The EJ22 was never going to do that. It was like a Ferrari V-12 in a New York City bus."

After being dropped by Eclipse, the EJ22 quickly disappeared from public view. Williams removed all mention of it from the company Web site, and halted efforts to have it certified. "There's no airplane out there for it," explains Sam Williams in an odd reversal of the bold "If you build it they will come" philosophy that drove the company to dominate the cruise missile and light business jet marketplace.

Still, the company continues to work on the EJ22's technology. "We've had that configuration up to 1,000 pounds thrust," says Williams, presumably referring to a somewhat similar engine the company is pursuing for the Department of Defense's VAATE (Versatile Affordable Advanced Turbine Engine), sort of a military version of the GAP program. With DOD money, efforts to certify the EJ22 could still be revived if the right airplane came along.

Why did the EJ22 fail? Perhaps Williams overreached by abandoning the core design philosophies of simplicity and incremental change that had served the company so well over the years. Tellingly, Williams returned to those core values last year with its smallest FAA-certified engine in company history: the FJ33. It's nothing fancy, just a simple, robust two-shaft engine of 1,000 to 1,500 pounds of thrust that is essentially a scaled-down version of the FJ44. Already, half a dozen new VLJs are being designed around it.

Despite its ultimate failure as a commercial engine, the EJ22 was a conceptual breakthrough. It inspired the VLJ category, which NASA predicts will grow to a fleet of 13,500 by 2025, in the same way that earlier Williams engines inspired the cruise missile and light bizjet categories. Without the EJ22, there would be no Eclipse 500, no realistic hope of jet travel within reach of thousands of new customers. Even Raburn, despite the enormous angst the EJ22 caused him, concedes, "It was certainly a noble experiment."