BOEING 787
DREAMLINER

GUY NORRIS AND MARK WAGNER

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PROLOGUE

OCTOBER 26, 2002, WAS A COLD, UNSETTLING DAY FOR MANY SEATTLE CITIZENS. The news that Saturday morning was full of stories about the bloody end to a Chechen hostage crisis in Moscow, as well as growing signs of imminent U.S. military intervention in Iraq. Just over a year had passed since the horrifying 9/11 attacks on America, and the world remained an uncertain place.

Few of those scurrying along Seattle’s busy waterfront on Alaskan Way could therefore have guessed that a meeting was taking place that morning at Pier 66 that would bring some much-needed good news and at the same time fundamentally alter the destiny of the world’s air transport industry. There, beneath steely gray skies and cold rain showers, delegates from a dozen airlines were quietly meeting with Boeing officials at the Bell Harbor Conference Center.

While decidedly low-key, the meeting was also pivotal. Boeing hoped, once and for all, that the gathering would help it figure out what the airlines wanted most in the next-generation airliner: speed or efficiency. No one knew for sure at the time, but it would decide not only Boeing’s design priorities for the twenty-first century, but also begin a chain reaction that would impact the aerospace industry for years to come.

Anchoring the meeting was Walt Gillette, a soft-spoken Texan with a reputation for solid engineering over a long career at Boeing stretching back to 1966. Gillette, who in media interviews referred to himself as “older than dirt,” had been involved in almost every Boeing jetliner since the 707. Now he was tasked with steering the company’s aircraft development in a bold new direction and away from the lower-risk, lower-cost derivative approach of the past decade.

Boeing heritage infused Gillette’s blood. He had been brought up on flying tales of World War II from his uncle, a B-17 veteran, and Gillette’s many achievements included a breakthrough installation design that enabled the low-slung 737 wing to be fitted with the high-bypass CFM56 engine. The move transformed the fortunes of the 737, effectively launching it into the history books as the best-selling airliner of all time. Now he was pursuing answers that would help plot Boeing’s commercial jetliner development course for the next fifty years or more.

Since early 2001, Boeing had been courting airlines with an intriguing high-speed design called the Sonic Cruiser. But all the time, Boeing had a “reference model” in its back pocket, a theoretical concept that shifted all the new technology in the Sonic Cruiser from speed to efficiency. The model, dubbed Project Yellowstone, was only meant to be a gauge against which the true advantages of the technology could be judged, but to Boeing’s surprise it started to attract just as much interest as, if not more than, the Sonic Cruiser.

But was this interest real? Were the airlines really more interested in efficiency than the holy grail of higher speed? Of course, times were tough for some carriers after 9/11, but how many wanted efficiency and how many still demanded speed? Boeing had to know, and the huddle on that cold, overcast day on Seattle’s Pier 66 was the best way to find out.

“We’d had a series of meetings with these airlines, and after about three of these gatherings we finally had to know what they thought,” recalled Gillette. In front of the top strategic planners for the top airlines, he drew a graph on a whiteboard. Along the bottom of the graph was range, while the vertical axis was payload. “Some were clearly intrigued by the reference model, and some clearly wanted more speed. There were dots all over the graph,” he recollected.

“We told them this was not a decision meeting, but that Boeing had to decide what to offer,” recalled Gillette, who later viewed the meeting as one of the most productive he ever had. The results were gold dust. After all the airline representatives left, Boeing gathered up the charts and reviewed the results. The airlines were virtually unanimous, and none gave a high rating to Sonic Cruiser’s Mach 0.98 cruise capability, while all gave maximum points to Yellowstone, which had a 20 percent cut in fuel burn relative to a 767. The bottom line was that speed was out and efficiency was in. From now on, the course was set, and the journey toward the Dreamliner had begun.
INTRODUCTION

The story of the 787 defies the imagination. Not since the 1960s and the heady days of Apollo, Concorde, and the Boeing 747 has an aerospace story captivated such global attention or prompted as much intrigue. News of the project leaked out at the fledgling Sonic Cruiser stage, far earlier than Boeing wanted. But the reaction sparked an unprecedented level of interest that refused to dissipate when the project morphed into the 7E7 and later evolved into the 787 Dreamliner. In a new media world of instant web access, blogging, and twittering, the exposure was almost too much. “It was like working in a gold fish bowl,” former project leader Mike Bair once remarked.

At first the spotlight was kind, and the project’s high-profile technology and innovations basked in the glow of success as record orders poured in. But problems derailed the project, and Boeing’s challenges turned the Dreamliner into an industrial nightmare. The public glare became the frightening spotlight of the inquisitor. Yet this intense scrutiny also revealed the true extent of the huge mountain Boeing had set out to climb with the 787, and which it still is on course to conquer as it brings the Dreamliner to market. To fundamentally change either design practice, or a production system, or structural design philosophy or systems architecture, is challenging enough—with the 787 Boeing undertook to change all of these at one time. This is why, in short, the 787 is the most delayed project in the company’s storied history.

Yet, in the long run, these are also the same reasons why the 787 is set to emerge as a revolutionary change for the commercial aerospace industry, and as a flagship for Boeing’s ambitions in the second decade of the twenty-first century. Speaking to Aviation Week & Space Technology on the eve of its planned—but eventually postponed—first flight in June 2009, Boeing chairman, president, and CEO James McNerney succinctly summarized the 787 experience: “You saw ambition outrun ability to execute. We’ve had to learn from that. But you’ve got to remember that we’re going to build an airplane that will be analogous to the 707 in terms of its game-changing impact. My prediction is airplanes will be built like this for the next seventy-five to eighty-five years.”

This book traces the almost decade-long story of the 787 from its earliest roots to the start of flight-testing and illustrates how this process reshaped Boeing and much of the industry along the way. It is also a tale of human endeavor and innovation on a gigantic scale and is a testament to a project team determined to overcome seemingly insurmountable obstacles blocking the long runway to the sky.
Chapter 1
BRINGING BACK THE MAGIC

Like a great tree, the true roots of Boeing’s 787 Dreamliner go deep, back to the early 1990s, when the company’s secretive product development group was focused on very different kinds of aircraft: behemoths capable of carrying six hundred to eight hundred passengers. The work was sparked by Asia’s burgeoning “Tiger” economies in the late 1980s, and the need to service the trunk routes to main Asian cities from North America and Europe with bigger aircraft.

In 1991 United Airlines Chairman Stephen Wolf challenged Boeing to come up with a transpacific aircraft with about six hundred to seven hundred seats. Dubbed the N650, it sparked efforts by both Airbus and Boeing that more than a decade later would lead to the A380 and stretched 747-8. Boeing called its super jumbo studies the NLA, short for new, large airplane. Duane Jackson—a Boeing veteran who, like Walt Gillette, had worked on virtually every commercial product since the 707—was appointed chief engineer of design for new airplane product development.

The genesis of the 787 can be traced back to 1991, more than a decade before Boeing Commercial Airplanes President Alan Mulally’s December 2002 announcement of plans to focus on a new, super-efficient twinjet. Pictured at its rollout in July 2007, the 787’s smooth skin and flowing lines belie the complex genealogy encompassing everything from 747 replacement studies and supersonic airliner research to multirole fighter projects. Mark Wagner

“At the time [Boeing Chairman] Phil Condit decided we needed to do something more serious. We formed a large team in Factoria, near Bellevue, and began studying double-deckers and single-deckers,” Jackson recalled. Some “big guns” oversaw the NLA. John Hayhurst, a former marketing vice president, was brought in as vice president, large airplane development, and the 777 chief engineer, John Roundhill, became chief project engineer. More than a hundred alternative configurations were evaluated, ranging from 747 stretch designs to outlandish giant flying wings. Aircraft lengths ran all the way up to 280 feet and wingspans to 290 feet, while takeoff weights peaked at a staggering 1.7 million pounds. The biggest designs could seat up to 750 passengers in a three-class arrangement, and even more in dual or single classes.

But the clearest message from the NLA studies was that it would cost a staggering amount to develop, and by the end of 1992, this prompted Boeing to take the almost unthinkable step of courting the European partner companies of Airbus into joint studies. The exercise became known as the very large commercial transport (VLCT) and toward the final phase of its bizarre existence even included Airbus itself. The unholy alliance ended in disarray in July 1995, with the two groups failing to find sufficient common ground to go forward. Boeing re-focused on two 747 derivative studies, called the 747-500X/600X, and Airbus returned with its partners to pursue the A3XX—later to become the A380.

Over the following year and a half, Boeing’s new, large aircraft morphed progressively from baseline 747 derivatives into 747 look-alikes with 777 technology. This suited most of the prospective customers who had baulked at the prospect of sticking with 747-400 technology for the sake of commonality, but they had to pay a price. The adoption of new 777-style features forced Boeing to revise estimated development costs up, to about $7 billion. The price of the 600X rose to a hefty $230 million in projected 2001 dollars, and by this time, with more
than a thousand design and systems engineers, the project was reputedly costing the company a staggering $3 million a day.

Aside from suffering “sticker shock,” the carriers potentially most interested in a new super jumbo were distracted by Airbus’s concurrent decision to accelerate development of its A3XX. But there was something else going on. Boeing was seeing first signs of market fragmentation on routes across the Pacific, and with it a weakening of the jumbo trunk-route market. This same phenomenon would come to have a direct bearing on the midsize market and the development of the 787.

Boeing’s December 1996 launch target came and went, and at a board meeting on January 19, 1997, Boeing officially decided to pull the plug on the 747-500X/600X project. The designs had achieved a 10 percent reduction in direct operating costs relative to the 747-400, but “we just couldn’t make a business case for it. The small size of the market meant the money we’d have spent on it, with or without the effect of fragmentation, just did not make sense,” said Boeing’s product strategy and marketing vice president at the time, Mike Bair.

But what did all this have to do with the 787? The answer lay with using advanced materials to fight costs. “During the NLA period, we investigated a lot of advanced technology, including looking at what the impact would be of a large composite wing,” said Jackson. The key to using composites, as the study indicated, was that it allowed the aircraft to be “cycled down” in size. As composites weighed less, lower-power engines were required, and fuel consumption was therefore lower because the overall weight was reduced. This meant that less fuel was required for the same mission, further reducing the overall size of the aircraft and its landing gear, and further reducing weight.

The demise of the 747-500X/600X had two more significant contributions to the destiny of the 787 in coming years. Alarmed at the way the costs of the 747 derivative study had spiraled, Boeing decided to completely rewrite the book on how to develop new products. The “book” was called the Airplane Creation Process Strategy (ACPS) and focused on cost control through the use of new and novel processes. The strategy was directed by Walt Gillette, fresh from his stint as chief project engineer on the 747-500X/600X, and both the lessons learned from ACPS and its leader would come to have a direct bearing on the 787.

Gillette “was focused on the engineering resource and was trying to get our design house back in order after all the issues we’d had,” recalled Roundhill. The driving notion behind ACPS was the “one in ten” vision in which a completely new aircraft could be developed to initial concept level in less than one year, and with an overall projected program cost of less than $10 billion. Development time for new models traditionally ranged from five to seven years, but the ACPS dream of driving this down hinged on the use of a formalized creation process that, once set up, would continuously spin like a wheel.

Another much less well-known influence on the 787 springing from the axing of the 747 derivatives was the 1997 launch of a very small-scale study into a future large aircraft. “I was left to start up another small effort called the LAPD [large aircraft product development], covering the 450- to 550-seat range,” said Jackson. Compared to the starlike status formerly enjoyed by the recently abandoned 747 study, however, the LAPD was treated like a poor orphan and given virtually no funding.

Twins are in the 787 DNA. Product development strategy in the 1990s was strongly influenced by the growing popularity of twin-engined designs on long-range, direct flights and “market fragmentation.” Boeing 767 and Airbus A300 twins blazed new trails that larger-capacity A330s and 777s later developed. Here 777s, dominating this aerial view of London Heathrow’s Terminal 3, replaced older-generation trijets and 747s. Although the average number of seats per aircraft grew by 7 percent between 1980 and 1990, it grew by only 2 percent over the next decade. Mark Wagner

The LAPD also faced funding competition from a new product lineup dominated by a flurry of derivatives. Development was simultaneously under way on the stretched 757-300, 767-400ER, and 777-300, as well as the
newly renamed 717-200, the former Douglas MD-95. In the midst of all this, Boeing was completing certification of the next-generation 737 family as well as ramping up production rates from seven 737s a month in 1996 to a planned twenty-four a month by October 1998.

Faced with all these pressures, something had to give, and sure enough, this happened in a big way later in 1997. Certification of the 737-700 and 737-800 was delayed by development issues, and just when nobody thought it could get worse, a parts shortage developed on the 747-400 line. In October, faced with a production crisis, Condit had no choice but to reveal all. Wall Street was stunned by the manufacturing meltdown, which would force the company to write off $2.6 billion, easily the biggest charge in Boeing’s history to that point. In the blink of an eye, shares fell 8 percent, wiping out a staggering $4.3 billion in value, while further losses followed.

The problems required painful surgery to correct, including the laying off of up to twelve thousand employees by the end of 1998. “We all knew if we didn’t fix it, we wouldn’t be around to fix it because we would not survive another business cycle with the system we had,” recalled Boeing Commercial President Ron Woodard, who would lose his own job over the crisis. The “get well” focus drove the urgency of initiatives such as “lean manufacturing” deep into the psyche of Boeing and helped lay some of the bedrock on which the foundations of the 787 would later be built.

Projected development costs of $7 billion and indifferent airline interest doomed the 747-500X/600X launch attempt in 1996. The rewinged 747-500X would have carried 460 passengers more than 8,700 nautical miles. The 747-600X, which stretched almost fifty feet longer than the 747-400, would have carried an additional load of 55 passengers on ranges up to 7,700 nautical miles.

**NOVEL APPROACHES**

However, despite the company’s greater financial woes, product development was the future, and studies had to continue. “But the dilemma we had was we didn’t have much priority. How could we achieve our needs without funding?” recollected Jackson. The answer came in part from Stuart Buchan, a systems guru who had risen through the ranks at Boeing Commercial since arriving from the company’s Vertol site in Philadelphia. Buchan, who originally came to Boeing as a “brain drain” engineer from the economically depressed United Kingdom in the 1960s, suggested a novel solution that gave systems suppliers an unprecedented development role.

“Stu understood the overall systems industry, and as it became clear we weren’t going to get much internal systems support, he took it upon himself to go outside Boeing and get systems suppliers to come in on their own budget. From this a multi-disciplinary, multicompany team system concept developed, and it was an outstanding success,” said Jackson. “We got the best talent from these companies, which got involved because they got a chance to be in on something that might go somewhere.”

Under the new scheme, partially inspired by greater systems supplier involvement in projects led by Bombardier, Embraer, and Honeywell, the visiting engineers occupied cubicles in Boeing office space alongside the depleted ranks of the LAPD project team. “Boeing folks would participate just enough to ‘buy in’ at a systems level—it was a very novel approach,” Jackson added.

Other changes would impact the destiny of the 787. To help cope with a shortage of structures staff to support product development studies, Boeing agreed to a deal with Japanese aerospace companies to provide twelve engineers, led by a structural manager from Mitsubishi. The agreement continued a long-standing relationship with Japan, which was now a key partner on all the company’s major products, particularly the 767 and the 777.

Changes also came on the heels of joint new, small airplane (NSA) studies with the project development group in Renton. Early involvement in LAPD would smooth the way for massive Japanese input to the 787. The NSA work
in Renton paralleled the LAPD project in Everett and, under John Yeeles, also explored cost-cutting development strategies based on lessons learned with the MD-95, recently acquired through the 1997 merger with McDonnell Douglas.

Three years earlier, when the beleaguered Douglas Aircraft sought to launch the MD-95, a re-engined one-hundred-seat successor to the DC-9, it ran into problems. Notoriously under-resourced and starved of investment, Douglas only succeeded by coming up with a radical scheme. Instead of trying to do everything itself, it opened its doors to share the development costs, as well as the risks and revenues, with international partners. While the business case remained doubtful for the MD-95 itself, the financial wisdom of the outsourcing model appealed to Boeing. At the time, projected development costs for the little twinjet were about $500 million, of which only $200 million was reportedly out of Douglas’s pocket.

To help spearhead Boeing’s recovery, meanwhile, Alan Mulally was recalled from Boeing’s defense business to become president of Commercial Airplanes in September 1998. Mulally, who would later also become chief executive in March 2001, had built a reputation for leadership during the development of the 777, and many hoped his appointment would spur a renaissance.

“At that time, when Alan Mulally came back, we clearly had to demonstrate we could produce aircraft at a profit,” recalled Roundhill, who at the time was vice president of product strategy and business development. Gillette “was focused on the engineering resource and was trying to get our design house back in order after all the issues we’d had,” he added.

By the end of 1999, the LAPD study was wound up and, as it has involved outsiders, it also gave Boeing product development a chance to look itself in the mirror. The systems suppliers involved in LAPD debriefed Boeing and spoke openly about what was right—but mostly about what was wrong. The process was a valuable education for Boeing on how to work with outsiders in the future—but vitally these applied primarily to systems, rather than structural suppliers.

But as Boeing rolled into the new millennium, it was having problems with its own workforce. In February 2000, negotiations with the Society of Professional Engineering Employees in Aerospace (SPEEA) broke down, and the company was hit by a strike. The impact was immediate on product development, which, to save money, was consolidated across the company. The remnants of the LAPD team were ordered down from Everett to Renton, where they were merged with the ACPS and NSA efforts in building 10-85, a relatively anonymous blue-and-white building that was to become the focus for Boeing’s PD think tank.
Production nightmares overtook Boeing in 1997 when the Next Generation 737 ran into “a perfect storm” created by late changes to the horizontal stabilizer, certification issues with the overwing escape exits, and a simultaneous production ramp-up. Boeing soon ran out of room to perform the rework, as this image of Renton’s crowded ramp can attest. Mark Wagner

While Boeing was on strike, Airbus was nearing launch of its A3XX super jumbo, and appeared to be well in the ascendancy with a clear family plan based on just three main products, including the A320 and A330/340 versions. The PD group was given a new priority—find out how to simplify Boeing’s future product strategy along similar lines.

The answer, it seemed, involved the concept of “platforms.” Instead of a plan to succeed its broad range of 717, 737, 747, 757, 767, and 777 products on a one-for-one basis, Boeing began to envisage a simpler “platform” approach, covering the one-hundred- to six-hundred-passenger range. At first the plan included four main platforms, or P-1 through -4, all of which would share as much common hardware and systems as possible to fit the ACPS processes, cost, and schedule goals. To show how the plan would work, platform planners used the analogy of Black & Decker hardware to illustrate its concept, citing the use of the same common core components in everything from drills to saws.

The base technology components for the platforms were 777 structures, systems, avionics, and propulsion. The P-1 study was focused on the lower-capacity end of the market, at about 100 to 200 seats, covering the capacity range catered to by the 717, 737, and 757. P-2 was focused on the middle of the market, in the 180- to 300-seat size, and encompassed ranges from one thousand to six thousand nautical miles. The P-3 study was primarily in the 300- to 400-seat and above range, covering the 777 and lower 747 capacity sizes. P-4 was the top end of the 747 market and above. The platform idea also suited Boeing’s all-embracing Project 20XX, which aimed to project a clearer view of the company’s future product development strategy for the twenty-first century.

“The task changed from LAPD to working on platforms,” recalled Jackson. But the platform idea had its drawbacks. “One of the dilemmas of this approach was it assumed we weren’t going to develop much new technology,” he said. “We were looking at configurations that looked like 777s, except some were smaller and some were larger. But the problem was marketing wanted more and more features—LD3 capability, wider seats, greater comfort, and particularly range.” It was worse in the midmarket, where Boeing’s 767 was losing ground to the increasingly popular A330-200. “With 777 technology there was no chance you’d ever get an aircraft better in cash operating costs than the 767 you’re trying to replace. There was no hope for something like that,” he said.

Something needed a shake-up, and Jackson, a quietly spoken engineer, felt the need for more urgency. “I felt it was time to get a little more bold in my nice-guy attitude. I got John Roundhill’s blessing to get more aggressive because I wanted to get something for people to get excited about.” Roundhill recalled that “Duane Jackson, the chief engineer of new airplanes, said it was time we took a hard look at an aircraft that would be capable of making a big leap in operating economics and fuel burn. He was talking about 10 percent better operating economics and 20 percent lower fuel burn.”

The spark for Jackson’s enthusiasm came in spring 2000, when he gave a presentation to the structural
organization on the theoretical benefits of composite wings. In the meeting was Jim Renton, the structures representative for the Phantom Works, Boeing’s advanced development group that had been absorbed with the 1996 McDonnell Douglas merger. Later Renton showed up in Jackson’s office and said, “I saw your story and we’d like to help. What can we do for you?” recalled Jackson.

At the time, Jackson was running two studies involving composites. One was a 737-size aircraft with a composite wing, which he hoped might even be built as a full-size demonstrator. The other was a composite fuselage, though with the structure comprising barrels made from composite panels rather than one-piece sections. Renton arranged for Jackson’s team to get full access to Phantom Works’ advanced composite specialists, “and by mid-2000 it started to look encouraging,” Jackson said.

The problem was how to get all this taken seriously in the upper echelons. This was 2000, and the large-scale use of composites for primary structure in the fuselage and wing was only recently emerging in combat aircraft and was unheard of in commercial airliners. Jackson needed to work the company system as much as the technology, and that could be just as risky, but the goals were worth it.

Jackson realized he needed the support of Phantom Works President David Swain. Working to his advantage was Swain’s directive to “sell” the Phantom Works and its advanced technology throughout the Boeing enterprise. Jackson needed Swain and vice versa. David Anderson, director of commercial airplane product development, and Peter Rumsey, director of new airplane product development, “tolerated my being more aggressive by going along with it,” recalled Jackson.

Renton worked with Jerry Ennis, Phantom Works’ vice president of advanced manufacturing, prototyping, and produce processes, to help Jackson’s cause. Ennis, who had come to the fore during the development of Boeing’s X-32 Joint Strike Fighter concept demonstrator, “came over from St. Louis and got me in front of Dave Swain, who was very encouraging,” said Jackson. “So we worked together and we came up with a proposal to show John Roundhill.”

Behind the scenes Swain, a veteran whose career spanned from the Gemini rocket to the C-17 airlifter, also worked the process at the very top of the company. He discussed the merits of composites with Boeing Chairman and President Phil Condit, who in turn passed along his recommendations to Alan Mulally. Condit and Mulally were both top engineers in their own right, and their endorsement of the radical composites plan was passed along the line to Roundhill.

**NINETY-DAY STUDY**

The scene was set, therefore, for a crucial evaluation of all the key technologies that would be brought to play in the next-generation airliner. “Staying close to Gillette, I went to see Roundhill and we put together plans for a multidisciplinary team that over three months would look at aerodynamics, structures, systems, and operations,” Jackson said. The so-called ninety-day study crucially included a Phantom Works contingent as well as Boeing’s commercial product development team.

The ninety-day study “had real high people” involved, said Jackson, and the authority to poach top people from various departments. “We spent about six weeks before that getting ready for the study. The preparation included going to each functional leader to get the best, most experienced person from that discipline to be dedicated full-time to the study. That way, the study results would be credible.”

The involvement of Phantom Works, a shadowy organization set up in the best traditions of Lockheed Martin’s supersecretive Skunk Works, also brought a new edge of subterfuge. “We put everyone in a dedicated, secret place. Phantom Works insisted on it, and we even had a vice president of security. They even put cables and chains in the ceiling to make sure you couldn’t get through the roof,” he recalled. The team set up at the Renton complex in a site across the parking lot from building 10-85 in the more imposing 10-20, colloquially known as the “black building.” Systems teams from external companies were gathered on the sixth floor, while the secret heart of the project pumped quietly into life behind locked doors on the fifth floor.
Boeing looked seriously at high-wing designs as part of its NLA study, and closely evaluated the An-124, BAe 146, and the C-17, pictured here. No high-wing super jumbo ever emerged, but the shoestring budget of the exercise sparked a systems supplier revolution that would profoundly impact the 787. One study, named the Model 763-241, was configured with a 69-foot-tall T-tail, a 262-foot span and a length of more than 250 feet. Mark Wagner

The joint Boeing-Japanese JADC new small airplane (NSA) study included a long, hard look at the novel partnership behind the launch of the MD-95, newly acquired in the merger with McDonnell Douglas. Renamed the 717 in 2000, an Air Tran–operated example is seen in company with an Alaska Airways 737 at Everett on the eve of the 787 rollout. Mark Wagner

The obvious focus for the study was the P-2 767 replacement, and the pace was intense. “We had people trapped in that room for eight hours a day or more for the whole of the last part of 2000. I’d never seen anything like it before,” Jackson remembered.

The ninety-day study focused on three main projects, which were code-named after U.S. national parks at the suggestion of Brian Nield, manager of new airplane product development. A conventional, Mach 0.85 cruise speed project took precedence and was called Yellowstone, while another was a high-speed design code-named Glacier. The third was a blended-wing-body (BWB) design inherited with the McDonnell Douglas merger and code-named Project Redwood. “We needed to make sure we weren’t overlooking something,” said Roundhill.

Of the three, Redwood was the most outlandish, essentially a flying wing without a conventional fuselage. “There
were questions about potential passenger reaction to not having windows, as well as emergency evacuation,” said Roundhill. Although Phantom Works studies showed the potential for up to a 20 percent improvement in direct operating costs versus late 1990s aircraft, it was simply too far ahead of its time to have meaningful relevance.

Glacier and Yellowstone were different stories, and while Yellowstone became the focus for the Phase 1, which the ninety-day study represented, smaller-scale studies were conducted in parallel on Glacier. The leading role of Yellowstone quickly transformed the ninety-day study into the “Y study.” As this was aimed at the P-2 market, the new product development strategy morphed this into Y-2 to take into account the use of new technologies. In due course the Y term completely replaced the older P nomenclature and extended into other areas yet to be tackled. The 737 replacement thus became Y-1, and the longer-term 777 successor was now called Y-3. There was no Y-4 to replace P-4, as this requirement was considered redundant.

As the festive season approached and the study wrapped up, results from Yellowstone were “terrific,” said Jackson. “We had a lightweight, really good cash-operating cost aircraft, and it was outstandingly financially successful compared to anything we’d looked at over the past umpteen years.” The team laid out a provisional schedule for Yellowstone in the final days before the holiday break, as well as parallel plans for a further exploratory study of Glacier.

The extraordinary Glacier, details of which were to explode unexpectedly into the news in early 2001, was a sleek, futuristic design. It was the brainchild of a small group of designers at Renton who had worked high-speed aerodynamic studies for the recently abandoned high-speed civil transport (HSCT) project. The NASA-led effort sought to develop technology for a Mach 1.5 airliner with up to three hundred seats, or about three times larger than the Anglo-French Concorde, but had run out of money by 1999.

Boeing’s X-32 demonstrator did not win the Joint Strike Fighter competition, but it broke valuable new ground on advanced digital design and manufacturing techniques, including simulation of assembly processes, that would prove invaluable on the 787. The X-32’s one-piece wing was an equally vital bellwether for the goals set for the Dreamliner. Thanks to the lean assembly tools, the ungainly fighter was assembled in half the expected time, and for almost 40 percent less than projected.

The ex-HSCT group had proposed a basic Y-2 design that would cruise right on the edge of the sound barrier in the transonic zone, where drag rise was usually notoriously high. “They were pretty positive about this concept and had advanced CFD visualization of why it would work at Mach 0.98,” Jackson recalled. “So it was a very exploratory effort, but it had to be, and it was led from more of an aerodynamic perspective than from a traditional configuration sort of approach.”

Jackson also briefed Mike Bair, the newly appointed vice president of business strategy and marketing, to “acquaint him with what we were doing.” Boeing’s continuing efforts to develop and launch a stretched 747, dubbed the 747X, based on the back of a freighter version, were meanwhile foundering, and the results of the ninety-day study made extra-fascinating reading to both Bair and Condit, with whom he shared the details.

For all this period, despite the growing focus on the midmarket, “the story of a bigger 747 kept coming up,” recalled Gillette. “By 2000 we were looking at a 17 percent increase in payload capacity with the 747X.” In June 2000 Boeing had even brought in all its key 747 customers for a detailed presentation on three proposed variants: a 747-400X, 747X, and 747X Stretch. Assuming orders were taken for ten to thirty aircraft, the new program was expected to be launched in the first quarter of 2001.

Although externally similar to the current 747, the advanced derivative plan included a host of new 777-style features, including flight deck, avionics, and cabin, as well as lighter-weight materials to help increase range and payload. The $4 billion plan included the design and construction of a larger wing with 17 percent more area and an
8 percent bigger span.

But airlines were simply not interested in the 747X project, or even, it seemed, the large-capacity market. “Instead we started getting some extremely explicit input from the customers for Boeing to start looking at something in the middle of the market—and something with more range. It kind of fitted in well with where we were going with Glacier,” recalled Roundhill.

As 2001 began and with the clock ticking toward the cutoff point at the middle of the year when the 747X needed to be launched to still make the 2005 service entry target, the market appeared to make up Boeing’s mind for it. FedEx, which Boeing really hoped would save the day by ordering the 747X, ordered the A3XX—by now launched as the A380.
One of the ninety-day-study candidates was Project Redwood, a blended-wing-body concept derived from initial work conducted by McDonnell Douglas before the 1997 merger. Although too ambitious for the time, the long-term potential efficiency of the BWB continued to be explored, and in 2007–2009 the X-48B subscale test vehicle was tested at Edwards AFB, California, in a joint NASA–Boeing project. The configuration offers fuel savings of up to 30 percent compared to current tube-and-wing designs.

As most of the aerospace world watched the battle of the titans play out between the A380 and the 747X, an international patent application was quietly filed on January 19, 2001, by two of the Boeing engineers behind project Glacier. Filed by Chester Nelson and Gerhard Seidel, it was couched in the cold, formal language of the patent office as “an integrated and/or modular high-speed aircraft and method of design.” However, the small sketch accompanying the filing told a far more exciting story—a dramatic, curvaceous aircraft configured with canards and a delta wing and capable of a “supersonic or near-sonic cruise Mach number.”

It would soon become known to the world as the Sonic Cruiser—a design that would catch everyone’s attention and imagination. The stunning looks of the Glacier, and the fact that analysis indicated that 15 to 20 percent greater speeds could be obtained at costs equal to the present 767, were compelling enough for studies to be taken further.

To some it had the feel of a potential game changer. “When I first saw it I was immediately enamored. I thought ‘wow, that really looks cool’, and we just felt it was worth a look,” said Roundhill. “So we started down the path of the Sonic Cruiser—though we didn’t call it that at the time. Meanwhile, we continued in parallel with a second phase of Yellowstone, and we had all the enthusiasm from Phantom Works to participate,” added Jackson.

It didn’t take long for news of it to leak out, and two days after the patent filing, an article in the Wall Street Journal gave the first to hint that Boeing’s plans included a two-hundred-to-three-hundred-seat aircraft capable of transonic speeds, cruising at Mach 0.95. As these plans were supposedly guarded within the innermost sanctums of Boeing’s product development group, it was with some shock and dismay that the company began seeing details leaked to the press before it could even start to brief all its customers.

Condit decided it was time to formally reveal the existence of “Project 20XX” and the associated middle market studies without giving anything away on Glacier. During a press conference to announce the financial results for 2000, Condit hinted that “a new middle market aircraft” was going to be the new focus for product development and that the company was “going to look at where the market is.”

From now on developments moved at sonic speed. With Condit’s encouragement, Mulally, Roundhill, and Bair spent a good chunk of March touring airlines in one of the Boeing corporate Challenger jets, showing astonished executives a small concept model of Glacier. “We also looked at how a fast aircraft would fit in with their fleets, and we hired fleet planners from the airlines. That wasn’t difficult: there were a lot of them available in those days,” Roundhill remembered.

The news, or lack of it, fueled the belief in some quarters that the Sonic Cruiser was some kind of publicity stunt—a deliberate response to Airbus and its massive A380 public-relations campaign throughout 2000 and early 2001. Nothing could have been farther from the truth, as Bair later recalled. “If we had been given a choice, we would not have said anything about the Sonic Cruiser until we were ready. It was still a product-development study, but enough information came out about it that it was impossible to keep it quiet.”

**NEW DIRECTIONS**

Finally, at a press conference on March 29, 2001, Boeing announced it was shelving plans to develop the 747X and was instead turning its attention to the far more exotic-sounding Sonic Cruiser. The initial studies of the novel-looking aircraft were aimed at a twin-aisle variant seating 225, sized around the 767-300 for gate suitability and
Mulally said, “This is the airplane our customers have asked us to concentrate on. They share our view that this new airplane could change the way the world flies as dramatically as did the introduction of the jet age.” Airline talks, he said, showed that “they would strongly value an airplane that can fly faster, higher, and more quietly over very long ranges.

“We have an airplane that will open a new chapter in commercial aviation, and we are changing our new product development efforts to focus more strongly on this airplane that has caused such excitement among our customers. It will be an ideal complement to our current family.” Walt Gillette, the 747X program manager, was appointed to lead Sonic Cruiser development.

To the rest of the world, the first real view of the Sonic Cruiser was nothing less than astonishing in its audacity and innovation. Designed with a double-delta or “cranked arrow” planform, it combined a high-speed inboard section with a higher aspect-ratio outboard section. Twin tails, slightly canted inboard, were mounted on the inboard sides of the engine nacelles, which were semirecessed into the wing. Inlets with S-shaped ducts were tucked away beneath the leading edge of the wing, invisible on all the first artist impressions.

At about 200 feet in length and with a maximum takeoff weight of about 450,000 pounds, the twin-engine aircraft was designed around 777 powerplants to shorten the design cycle. The configuration was designed for cruise speeds between Mach 0.95 and 0.98, and altitudes between 40,000 and 50,000 feet. This was aimed at cruising high above the rest of the world’s lumbering subsonic jet fleet, and slashing flight times by more than one hour for every 3,100 miles flown. The speed would shave about two hours from transatlantic trips and more than three hours across the Pacific.

Both Gillette and John Roundhill, who was named marketing vice president, knew that the key to success was breakthrough technology, making it more dependent on technical achievement than any Boeing commercial program since the 707.

The number one challenge was proving the viability of the unusual cranked delta configuration, which was key to the entire transonic concept. “It’s all a question of how we arrange the pieces to allow area rule,” said Gillette. “The final shape is more drawn by evolving up from a subsonic aircraft with a constant cross section, than coming down from a supersonic design.”

Officially the Sonic Cruiser was designated a “near-sonic transport” and used a classic Sears-Haack cross-sectional area distribution. This was named for William Sears, a leading American aerodynamicist who was responsible for the flying wing designs of Jack Northrop; and German mechanical engineer Wolfgang Haack, whose mathematical analysis was used to design low-drag sniper bullets in World War II.

Sonic Virgin? Sir Richard Branson’s Virgin Atlantic Airways was one of the first carriers to put its name publicly behind the high-speed Sonic Cruiser concept. Gareth Burgess
Although never built, nothing quite captivated the minds and imagination of the aerospace world like the Sonic Cruiser. Couched in dry language, the patent application was titled simply “Integrated and/or modular high-speed aircraft,” but arguably did more than any commercial project since the Concorde to excite widespread public interest.

Designers were forced to use increasingly novel aerodynamic solutions to meet the seemingly insatiable appetite for high-speed travel in the late 1950s. Convair pushed toward the high-drag transonic area by mounting antishock bodies on the trailing edge of the CV990’s thin, thirty-nine-degree-swept wing. The bulbous pods, resembling inverted canoes, delayed the formation of the drag-inducing supersonic shock wave, taking advantage of the recent discovery of “area ruling” by legendary aerodynamicist Richard Whitcomb. The pods, also called “Küchemann Carrots,” after their inventor, are seen to good effect.
In aeronautical engineering, a Sears-Haack body—which traditionally is cigar-shaped—is the best shape for reducing wave drag. This forms when air passing over the aircraft accelerates to supersonic speeds, even if the aircraft itself is going subsonically. The supersonic flow creates shock waves, which produce wave drag. To minimize this drag, Sonic Cruiser designers tailored the cross-sectional area distribution of the airliner to closely resemble the Sears-Haack shape.

Although high-speed aerodynamics had played a pivotal role in helping Boeing achieve high subsonic cruise speeds with the 707 and the 747 in particular, the most obvious deliberate shaping in U.S. airliner design for higher speeds had been the trailing-edge shock bodies on the Convair CV-990. The aircraft’s Mach 0.91 cruise speed, which at the time made it the world’s fastest airliner, was largely due to large, canoe-like fairings on the upper trailing edges of the wings. The devices cut wave drag and were nicknamed “Küchemann Carrots” after their designer, Dr. Dietrich Küchemann.

Boeing’s design breakthrough on the Sonic Cruiser was to shape the aft fuselage, delta wing, and semirecessed engine nacelles so it achieved the much-vaunted Sears-Haack area distribution.

The eye-catching shape genuinely looked like it wanted to go faster, and indeed Boeing aerodynamicists believed the Sonic Cruiser was easily capable of low supersonic speed. The difference with the Sonic Cruiser approach was that it was more economically feasible to produce a high-speed airliner from a transonic design than to work the drag reduction problems of speeding up a conventional subsonic design. Mike Bair said, “Instead of making a slow aircraft go faster, we have a design for a fast aircraft that goes a bit slower.”

All the talk of “sonic” performance inevitably raised questions about Boeing’s longer-term ambitions. Was this a stealthy gambit to gain the once “holy grail” of air transport ambitions: a supersonic airliner? “No,” was Gillette’s short answer. Although the aircraft would need to be tested at speeds slightly in excess of Mach 1 as part of certification requirements for its intended cruise speed of Mach 0.98, Gillette insisted the Sonic Cruiser was not a would-be Concorde in disguise. “We are looking at Mach 1 and not any faster, but we think in ten to twelve years the time will come when we believe the technology will be there for a variable supersonic transport [SST]. Frankly, the maturity of the technology is not yet there for a modern Mach 1.4 to Mach 2 SST,” he said.

Project Glacier pinpointed Mach 0.98 and Mach 1.02 as the apparent “sweet spots” for a transonic design. “The baseline focus is near the speed of sound, and that was selected based on environmental requirements, particularly sonic boom and other criteria. We did look at faster aircraft, and the data indicates so far that a Mach 1.2 or 1.6 aircraft would have a much higher fuel burn. With a twin-engined aircraft you just can’t get the nonstop design range we’re looking for on this project,” added Roundhill.

Besides, Boeing said going just a little bit faster did not make that much difference from the travel time perspective. The Mach 1.02 option “doesn’t make a big difference in terms of time. The aircraft is clearly stable at that higher speed, but it would require a bigger engine because the increase in drag is dramatic,” he said.

Tests at the University of Washington’s low-speed tunnel and Boeing’s transonic tunnel confirmed good stability and performance characteristics to Mach 1.08. “It turns out to be longitudinally statically stable. The canard-configured aircraft showed no indication of ‘Mach tuck,’ and pitch characteristics were ‘steady and level.’ The strain gauges on the wing showed no buffet onset,” said Gillette. As a result of the tests, the canard was moved aft slightly in later configurations, and the vertical tails moved outboard and forward. “We looked at the control needs and the interference effect of the canard wake,” said Roundhill.

As Boeing continued to drive toward finalizing the shape through early 2001, it became increasingly obvious that simple derivatives of 777 engines would not work. “This aircraft has a different relationship of climb thrust to takeoff thrust, and we found the optimal core size was smaller than the 777,” said Roundhill. The findings “argue for a major change, if not a brand-new engine.”

Core size is traditionally set by top-of-climb thrust requirements, while noise limits generally govern fan pressure ratio (PR) and bypass ratio, hence the configuration of the low-pressure spool. Under the standard relationship between these factors, the Sonic Cruiser engine would have had a sea-level thrust of more than one hundred thousand pounds. However, the integrated engine configuration of the Sonic Cruiser, added to a 9.2-foot-diameter size restriction of the “semi S-duct” inlet and Boeing’s exhaust velocity requirements, meant the takeoff thrust target was closer to ninety thousand pounds. As a result, all three engine makers began studying powerplants using core technology derived from their respective 777 engine families (see chapter 6)—a move that would prove vital to the eventual birth of the 787.
The British Aircraft Corporation/Sud-Aviation–designed Concorde relied on a high finesse ratio, slim fuselage, and a shapely ogee-delta wing platform to smoothly transition the transonic region on its way to Mach 2.2. Boeing’s high-speed concepts, including all the Sonic Cruiser variants, required additional area ruling because they were all wider-fuselage designs. Some area ruling was, however, needed to deal with shock effects on Concorde’s curvaceous belly fairing between the engine nacelles, as can be seen in this view of a British Airways aircraft departing on a spring evening in April 1997. Mark Wagner

Debate meanwhile raged over how big the baseline aircraft should be. Initially sizes ranged from a single-aisle 100-seater to a twin-aisle 300-seater, with cruise speeds between Mach 0.95 and 0.98, and ranges from 6,000 to 9,000 nautical miles. Although the airlines strongly pushed Boeing toward a larger 300-seat family, Boeing was eager to develop the longer-range, point-to-point capability of smaller, midcapacity Sonic Cruisers. The main configuration was a 767-size 250-seater with a 9,000 nautical miles range, giving it the “legs” to fly Singapore to Los Angeles and save three hours over the 747. Increasing range to 10,000 nautical miles would give it capability for London to Sydney nonstop, saving up to five hours—but the extra-range variant would be limited in size to 225 seats.

An innovative design feature of the Sonic Cruiser was its low-drag inlets beneath the wings. Similar in cross section to the ovoid F-16 inlet but skewed outward, they stood proud from the airframe and clear of the boundary layer, ensuring a flow of “clean,” undisturbed air into the shallow S-ducts feeding the buried engines. The configuration, revealed in some detail for the first time at the 2001 Paris Air Show, also posed some challenges, particularly with foreign-object ingestion. Mark Wagner
Early Sonic Cruiser configuration studies included optional aft body configurations with vertical stabilizers canted both inward and outward. They also looked at empennage designs with split elevons and others with a single, wide “beaver tail.” This offered the advantage of increasing the overall length of the inboard wing, thereby reducing the thickness-to-chord ratio (the chord being the distance between the leading and the trailing edges of the wing). This reduced drag and distributed lift over the aft body, thereby reducing loads on the wingbox. A drawback of the beaver tail was reduced cabin length, which made it less suitable to a Y-2 market, but better for a supersonic one-hundred-seater or business-jet design. Further work on this was pursued as the Model 765-071, under NASA’s Fundamental Aeronautics Program.

As the Sonic Cruiser concept evolved, the engine moved aft into the nacelle for improved access, engineering, and certification concerns, while the tips of the triple-delta wings became raked. Other aspects of the baseline design remained otherwise unchanged, with a low aspect ratio of about three to one, a leading-edge-sweep angle of about forty degrees at the trapezoidal section, and a canard dihedral of close to twenty-two degrees.

The all-important question of cross section was also narrowed down to one providing room for LD3 cargo containers in the hold and 777 “comfort upstairs. As it is a longish aircraft we can have a seven-abreast layout in premium economy, and a 777 or 747 business arrangement up front,” Roundhill said.

Crucially for the later 787 development, Boeing also revealed publicly for the first time that sample fuselage sections for the Sonic Cruiser were being designed with composite materials as well as advanced aluminum. Roundhill said, “We have a much higher application of composites than the 777, which was around eleven percent by weight, because of environmental and economic requirements. The baseline has composites in the primary structure of the tail and the wing, and we are looking at large amounts of composites in the fuselage as well.” Gillette also revealed that systems technology would be a key focus with an increased use of electric power.

In this telltale way the Sonic Cruiser was already hinting at the metamorphosis that would ultimately turn it into the 787. Part of this was also driven by timing and the technology that would realistically be available. In early 2001 Bair said a 2006 entry-into-service Sonic Cruiser would be made from aluminum and have 777-level technologies, including engines, systems, and flight deck. A 2008 version, by contrast, would have more composites, derivative engines, and advanced flight deck and engines. The advantage of waiting two more years was lower direct operating costs (DOCs). The question was whether the market would wait.
Chapter 2
SUPER EFFICIENT

From the first days of the Sonic Cruiser announcement, airline reaction had been mixed. Some, such as Air Canada, Virgin Atlantic, and Singapore Airlines (SIA), had expressed interest, particularly in the promised ability to increase long-range daily mission rotations. Others, such as Emirates, had immediately raised fuel consumption, environmental, economic, and even operational issues. While SIA thought the Sonic Cruiser could operate alongside its upcoming A380s, Emirates thought the smaller jet would take up valuable slots better occupied by the A380.

According to Gillette, “even a 15 percent increase in speed can mean an extra 20 percent to 30 percent utilization per year.” Giving the London-to-Singapore route as an example, he said, “The aircraft saves about five hours on that kind of sector [round-trip]. Not only does it go faster, but it doesn’t need to refuel. Imagine having an aircraft that you can fly 25 percent more per year, as well as at 15 percent greater speeds!”

Gillette said the high-performance Sonic Cruiser would also “climb out of congested airspace quicker. We estimate 2.5 minutes to 10,000 feet versus 5.5 minutes for a 777, and 16 minutes to 41,000 feet against 19.5 minutes to 35,000 feet for a 777.” He claimed the Cruiser would “punch out of airspace and drop back in like a space shuttle. When there are around five hundred Sonic Cruisers in service they will operate above the rest of the traffic in what we call ‘Cruiser space.’” Gillette characterized the Sonic Cruiser as “an aircraft that has the potential to radically change the way the world flies.”

Some airlines could see it; others couldn’t. Boeing’s job in 2001 was to start convincing its customers of the intrinsic value of speed. “There’s no point in Boeing creating the aircraft we think they needed,” said Gillette. “That’s why we’ve started the journey by asking the airlines what they want—but this time it’s a different paradigm. You now have a new Thoroughbred in your stable, and you have to rethink your race team. Airlines now need to think about three speed regimes: the 767, the 777, and the Sonic Cruiser.”

The curiously swept-back “shark tail” was part of Boeing’s plan was to make the 7E7 as instantly recognizable and distinctive as the humped upper-deck 747. It was therefore the first-ever Boeing jetliner outlined initially by industrial designers with aesthetics in mind. Led by Boeing’s Director of Differentiation Strategy Blake Emery, the group took inspiration from Clotaire Rapaille, a French industrial designer who helped influence the shape of Chrysler’s PT Cruiser. His cosmetic suggestions included a fish-like fuselage shape, pronounced bird-like wings, and an all-new flamboyant blue and white “house” paint scheme. The final shape would only slowly emerge after aerodynamic refinement and thorough engineering design trades. In terms of looks, Boeing admitted that the Sonic Cruiser was a hard act to follow. Mark Wagner
Following initial work in the University of Washington’s low-speed wind tunnel, the Sonic Cruiser model was tested in Boeing's transonic facility. These proved that the shape had good stability and drag characteristics right up to Mach 1.08. “When we looked at the first data we said ‘wow,’” said Walt Gillette, who added that there was no indication of “Mach tuck”—a potentially treacherous nose-down pitch change that can occur as the supersonic shock, and the center of pressure, move aft. Strain gauges also detected no onset of buffet, another danger that in some aircraft had led to in-flight breakups.

At the 2001 Paris Air Show that June, however, the Sonic Cruiser ran into its first serious trouble. The problems started when remarks by Boeing Vice Chairman Harry Stonecipher, apparently dismissing the seriousness of the possible environmental impact of the Sonic Cruiser, were published in a British newspaper. The comments attracted the attention of European Environment Commissioner Margot Wallstrom who, in an open letter, retorted angrily to Stonecipher’s alleged cavalier attitude.

Referring to Stonecipher’s remarks about there “being plenty of fuel still around” and “the environmental bandwagon,” she said, “I find it hard to believe that anyone today could afford himself the luxury of a ‘let’s not think about tomorrow’ attitude, which runs diametrically opposed to the aims of sustainable development.” Questioning the entire speed concept, Wallstrom asked “whether a one-hour time saving on a transatlantic flight is worth a significant increase in carbon dioxide emissions contributing to climate change. In my view, this environmental price is simply not worth paying.”

Completing her salvo, she said that “aircraft emissions already contribute to about 3.5 percent of man-made greenhouse gas emissions and are expected to double over the next ten to fifteen years. Instead of building even faster planes, your industry should work toward improved environmental performance, dramatically improving the efficiency of aircraft and developing aircraft powered by alternatives to fossil fuel.”

Airbus made the most of the Paris Air Show to publicly denigrate the project, and the nickname “Chronic Snoozer” was frequently overheard around the European company’s chalet. Airbus Chief Executive Noel Forgeard declared himself surprised at the interest being shown “in an aircraft that has a twenty percent increase in fuel consumption for a marginal increase in speed.”

Undeterred, Boeing continued its detailed audit with the airlines. But there were worrying signs, particularly among the U.S. majors, where the softening economy was taking its toll on yields. Business travelers were flying less, and the success of new low-cost carriers such as JetBlue, as well as the original budget airline, Southwest, was pushing the creaking legacy carriers to the brink. Many operators were in survival mode, unaware that something much worse was about to hit them: the terrorist attacks on New York and Washington, D.C., on September 11, 2001.
protocol on limiting greenhouse gases. The concept unexpectedly became the subject of a vitriolic attack by European Environment Commissioner Margot Wallstrom. In an open letter to Boeing Vice Chairman Harry Stonecipher after the Paris 2001 Air Show, she asked, “Can it be true that you have brushed aside environmental concerns around your new aircraft so nonchalantly?” Mark Wagner

**CHANGING WORLDS**

On September 12, Walt Gillette addressed a rapt audience at a conference in Seattle about the Sonic Cruiser. But even as he discussed the “time machine” and the virtues of speed and point-to-point travel, the real-world market for the Sonic Cruiser was imploding. The truth, as ugly as it seemed, was that the airlines were already on the verge of a deep crisis, which in most cases the dreadful events of September 11 merely hastened.

Although the crisis was all-consuming in North America and to a great extent in Europe, some airlines—particularly in Asia and the Middle East—were still eager for Boeing to explore Sonic Cruisers with supersonic dash capability. Boeing moved quickly to suppress these desires, although Gillette told the Seattle crowd that the model had been tested at speeds up to Mach 1.08 in the Boeing transonic eight-by-twelve-foot wind tunnel.

However, even though Boeing was avoiding the cost and risk of developing exotic technologies required for supersonic travel, the targets set for the Sonic Cruiser were no walk in the park. Pressure to meet the long-range goals, yet still carry sufficient fuel for the higher cruise speed, began to drive Boeing with a new urgency toward a series of advances that would all benefit the 787. These included the use of advanced computational fluid dynamic design tools for high- and low-speed aero design, advanced materials for lower manufacturing cost but better properties, improved systems for greater efficiency, and next-generation engines.

Although Boeing had already outlined ambitions for a much greater use of composites in primary structures, Gillette said other materials were being considered, particularly for the fuselage. He reported that “we’ve started building several sample technology fuselage barrels because there are several ways we can go at it. We’re looking for the lightest, most cost-effective ways of building it.”

To better understand the true manufacturing potential, and challenges, of large-scale composite assemblies, Boeing’s Sonic Cruiser team meanwhile made a secret visit to Kansas—the center of the world’s composite aerospace structures industry. The experience was an epiphany to Gillette. “In mid-2001, when we hadn’t even made the decision to use carbon composites, we went to Wichita and visited Raytheon. When we entered the assembly building, instead of the usual noise of a production line, it was quiet, and these big machines were silently rotating. It was almost primordial—they were like ‘beings’ being created, and once you’ve seen it you’re never the same again. It was an unforgettable image in my mind, like butterflies coming out of a chrysalis, and most importantly it gave us confidence knowing someone knew how to do it.”

Boeing’s structural inspiration included the pioneering work of Raytheon for its business aircraft. Beginning in the 1980s with the Beech Starship, a largely composite pusher design intended to replace the King Air 200, Raytheon used its hard-won experience to develop the all-composite fuselage of the Premier 1. Although retaining conventional metallic wings, the fuselage was made of graphite and epoxy laminate and honeycomb composite construction, which eliminated the need for internal frames. This increased cabin volume by nearly 15 percent and, in comparison with a conventional aluminum-made airframe, reduced weight by about 20 percent. Mark Wagner

The proposed development timescale was also coming together, and not surprisingly would end up a virtual mirror image of the schedule later adopted for the 787. Reflecting experience gained on the 777, Boeing sketched out a roughly 5 1/2-year plan for the Sonic Cruiser. Assuming launch in 2002, it looked to start major assembly in 2005, roll out the jet in the third quarter of 2006, and fly in December of that year, ideally on the 103rd anniversary of the Wright Brothers’ first flight, on the 17th of the month. FAA certification was planned for December 2007, with first deliveries set for January 2008.

“Now we need to sit down with the airlines and talk about the value of speed,” said Gillette. But this was where the impact of 9/11 was already having a profound effect. Bunkered down in survival mode, particularly in the
United States and Europe, the airlines could not spare people to work with Boeing on its studies. It therefore focused on other critical aspects, including the establishment of an entirely new production system that would prove both foundational and critically challenging for the 787 project.

Through late 2001 Boeing worked to form what it described as a “technology team” that would form the basis for its future structures and systems partnerships. By the end of January 2002, the process was making headway, with Boeing announcing that the initial rounds of team selection would be complete by the middle of that year. Within days of this statement, Boeing and Japan Aircraft Development (JADE) and its associated Japan Aircraft Industries (JAI) agreed on research and development for the Sonic Cruiser, marking the first formal deal on the project between the airframer and any third party. Jeff Luckey, then director of supplier management for the Sonic Cruiser, predicted similar deals would be struck “at a rapid pace in the months ahead.”

The JAI deal was centered on advanced composite technology, a national strength honed over the years since the 7J7 (see chapter 4), and was backed by aerospace R&D funding from Japan’s trade and industry ministry. Boeing knew that the deal’s importance went beyond technology and the downstream marketing benefits. The JAI consortium had turned to Boeing’s project in 2001, having rejected an offer from Airbus to join the A380 team, and the strategic value of tying up similar agreements with other technology-capable partners around the world was not lost on the company.

Embraer’s “E-Jet” family intrigued Boeing as it searched for game-changing improvements for the design, development, and production of its new aircraft. In 2001 product development teams were dispatched to find out how systems and structural partners helped the Brazilian manufacturer develop its highly successful new, small jet airliners, including the E170/175 and the E190/195. Here the fourth E170 development aircraft banks away from the camera ship during an air-to-air sortie over Brazil. Mark Wagner

Within the systems world, a similar process was under way, with a few added wrinkles. Although the new composites technology meant only a few specific companies around the world would even be capable of joining the Sonic Cruiser team in the first place, the wider breadth of systems expertise meant a greater choice of not only suppliers but also technology. To ease its way through this conundrum, Boeing hit on the idea of asking as many first- and second-tier companies as possible to study the various systems requirements of the new aircraft. The companies would then be asked to forge partnerships between themselves to offer optimized “system solutions.”

By April 2002 Boeing had welcomed fifteen airlines back to its studies and had completed the initial network analysis work required to put a value on speed. This, in turn, had helped define the optimum capacity of the new family at between 190 seats in mostly premium seating and mixed configurations seating up to 250. By now talks with airlines had resumed on a one-to-one basis, mostly because the 777 “working together” model did not apply so readily to the very different Sonic Cruiser. “With a new type of airplane like this, there is more competition between them on how they might use it,” said Walt Gillette. Overall performance, configuration, and specifications remained the subjects for discussions with all the airlines.

“Talks with the airlines are going very well,” reported Gillette later that summer. “We have been working with them to understand the different value that speed offers. They’ve been used to flying at 0.8 Mach for fifty years, and now they’re being offered something that goes fifteen to twenty percent faster. They have to think about how it fits within their system.”

Airlines were also by now being shown other new configurations that had emerged from a complex set of trade studies. “In late 1999 we set out with the idea that we could offer a sonic aircraft, and the best-looking configuration that could make that happen is the [aft wing] one we released to the world. However, the only bit of nervousness about it was the CFD codes. Were they really telling us the truth about the drag performance at Mach 1?” Gillette said.

Although transonic wind tunnel tests verified that the canard-configured design “sliced right through Mach 1,”
Boeing’s design team continued to explore alternatives. “As always we had to know if we’d been making the best use of the technologies for the mission. We ended up doing dozens of trade studies on wings and engine positions as well as canard locations,” said Gillette. “Clearly this would have been the largest canard aircraft ever to fly [bigger even than the Tupolev Tu-144], and was intended for extremely efficient cruise.”

Canards, or foreplanes, were designed to work with elevators and elevons to allow operation over a wide range of center-of-gravity conditions that would otherwise be virtually impossible to handle on configurations such as the Sonic Cruiser, with large, heavy engines mounted aft. Retractable canards were used on the Tupolev Tu-144 supersonic transport to increase lift at low speeds, countering the pitch-down moment effects of the elevons mounted on the trailing edge of the delta wing. The canards are displayed to good effect on the Tu-144LL, reactivated for high-speed research at Russia’s Gromov Flight Research Institute, Zhukovsky, near Moscow in August 1999. Mark Wagner

One of the basic trade studies involved removing the canards altogether, moving the wing forward, and adding a horizontal tail. “As the wing moves forward and sits near the middle of the aircraft, it needs to be wasp-waisted a bit,” said Gillette, explaining the area-ruling requirements of the transonic design. The canard-configured Cruiser, on the other hand, allowed Boeing to stick with a large aft wing, which in turn enabled a constant-section fuselage. “But canards are an unusual configuration, and you have to find ways of getting it out of the way of jetbridges [articulating covered walkways connecting the gates with the aircraft] and so on.”

Alongside the new midwing design, the original Project Yellowstone not only remained alive but also began to prosper. Although considered a true project in its own right, the Sonic Cruiser team used Yellowstone primarily as a reference configuration against which the airlines could better judge the true benefits of the proposed Sonic Cruiser technology versus a conventional 767. Roundhill recalled that “on the presentation charts we always showed the ‘reference’ aircraft, and there was a lot of debate about whether we should take it off. Of course, we didn’t know about 9/11 then, and with Alan’s approval we decided to leave that data point on there.”

The performance targets for Yellowstone were “a little more aggressive than the 787, and we did that intentionally, but it was a ‘real’ airplane,” said Roundhill, who added, “we made it a fairly big ‘dot,’ but we didn’t want to overpromise. I’m certainly glad we kept that dot on the chart!”

Slowly but surely, however, the tide was indeed turning. At presentations, the airlines listened patiently to the Sonic Cruiser briefing before asking to see more details about the reference model. Rumors of this unexpected swing in favor of Yellowstone began circulating in about May 2002 but were strongly downplayed by Boeing at the time, saying, “We talk to the airlines about the reference aircraft, but it’s not really what we’re planning on. We believe the Sonic Cruiser is the best answer for both Boeing and the airlines.”

To get around Sonic Cruiser infrastructure concerns, Boeing presented airlines with alternative configurations. One was a “midwing” design that combined fairly conventional wings and tail surfaces with a “wasp-waisted” or area-ruled fuselage. The concept was configured with two main cabin cross sections, a wide cabin section in the fore body and aft body, and a slimmer midbody section. The design resurrected a far-reaching 1972 Boeing-NASA study that evaluated area-ruling in several concepts optimized for cruise speeds in the Mach 0.9 to 0.98 range. Lia Ravelo
Gillette himself sensed the swing, and at that year’s Farnborough Air Show publicly acknowledged for the first time that change could be coming. “Never lose sight of the fact that this is a free enterprise and we build aircraft the market wants. In the end, the market could choose a conventional aircraft with Sonic Cruiser technology, but that’s not what we’re emphasizing. The conventional aircraft is quite a bit more fuel-efficient, but fuel is not the big cost number right now,” he said.

It was not only the prospect of rising fuel costs that troubled the airlines. After the initial enthusiasm, some carriers wondered how the Sonic Cruiser would fit into their complex network operations. The aircraft’s higher cruise speed meant earlier arrivals and departures, particularly on transpacific routes. Although Boeing had set up a “network analysis group” to help the carriers evaluate the benefits of Cruiser operations, and put a figure to the cost savings on crew expenses, the logistical challenges of slotting in the aircraft’s unusual timings into hub and spoke connections were proving difficult.

By early September 2002, the scene was set for the final showdown over the future course of Boeing’s product development. With airline interest in the Sonic Cruiser clearly on the wane, Boeing knew that its fourth and last prelaunch set of meetings with potential operators was to be the crucial decider.

The Sonic Cruiser gave way to the more compelling 7E7 at a time when efficiency was the key for the airlines. Battered by the global slowdown and the market fallout as a result of the devastation of 9/11, they needed to save money, not time. Efficiency was already starting to improve thanks to the development of large twins such as this 777-200ER, seen here on its final approach to London Heathrow in 2003. Mark Wagner

Held at the Bell Harbor Conference Center at Seattle’s Pier 66 in late October, Boeing hoped the meeting would help decide once and for all whether speed was valued over efficiency. The airlines were virtually unanimous, and none gave a high rating to a Mach 0.98 cruise capability, while all gave maximum points to a 20 percent cut in fuel burn relative to a 767. The bottom line was that speed and Sonic Cruiser were out, Yellowstone and efficiency were in. But for Roundhill there were few regrets. “It seems like a long process, but boy, when you make a decision on an aircraft, it stays with you for fifty years. You’ve just got to get it right,” he said.

E FOR EVERYTHING

The Sonic Cruiser was difficult to let go for Boeing, but the industry had spoken. First details of the reference aircraft, now renamed “Super Efficient,” were revealed semipublicly the following month at a Society of Automotive and Aerospace Engineers conference in Phoenix, Arizona. After once again reviewing the Sonic Cruiser options, which by now encompassed the baseline aft-wing as well as two midwing finalists, Gillette showed the expectant group what they had been waiting for: a first view of the mysterious “reference airplane.”

To the uninitiated the Super Efficient was a rather conventional-looking “tube and wing” aircraft with none of the exciting outward innovations of the Sonic Cruiser. Yet Gillette’s PowerPoint slide revealed a hybrid 767-777–like design incorporating virtually every new technology of the Sonic Cruiser, with the obvious exception of the transonic design’s unique shaping. Features included more electric systems, advanced composite primary and secondary structures, a “future flight deck,” and a distributed power system with no engine bleed-driven pneumatics.

Facing the inevitable, Boeing’s board sanctioned the Super Efficient at its next meeting early in December 2002. The decision also officially terminated the Sonic Cruiser, although the company line was that product development studies would continue at a lower level. Yet the board’s move, although precipitated by market forces, was not necessarily an easy one to make. Airlines around the world were in crisis, and the looming threat of a new war in the Middle East added more uncertainty to what was already an increasingly bleak economic outlook.

Speaking just before the holiday break on December 20, 2002, Alan Mulally spoke frankly about the parlous state
of the industry into which the Super Efficient was being born. “These are unprecedented times. I’ve never seen the combination of economic cycle and terrorist ‘overhang’ having such an impact on our industry.” Describing the airlines’ 2001 losses of $10 billion and 2002 losses of $7 billion as “staggering numbers,” the normally ebullient Mulally relayed sobering details of a 20 percent drop in revenues for U.S. airlines alone versus figures for 2000.

Boeing itself had taken drastic action after 9/11 to trim capacity to meet demand, reducing production by more than 50 percent by the end of 2002. “Every aircraft we put out that’s not needed just hurts the airlines and the bottom line. But we’ve done the right thing, and it will help us recover more quickly,” Mulally added. Boeing hoped the timing of the Super Efficient, which Mulally said would be launched “early in 2004 at the latest,” would fit well with the timing of the next economic recovery.

But faced with heavy restructuring costs and reduced demand, was the timing right for Boeing? “Can we do it now?” asked Mulally rhetorically. “Absolutely yes. With an ’08 delivery, we don’t start spending the big bucks for two to three years.” Furthermore, Mulally was convinced that the shift from speed to efficiency virtually guaranteed massive success in the prized midsize market and the burgeoning long-range point-to-point networks. “I feel more comfortable than ever over the last three or four years that this is the new aircraft Boeing ought to go ahead and make.”
Over the winter of 2002–2003, the Project Yellowstone reference model swiftly morphed into “Super Efficient” before emerging as the 7E7. This initial model, dubbed the 7E7-400X, was a traditional fallback of the baseline version called the 7E7-300X, and therefore carried at least forty more passengers but had a shorter range of seven thousand nautical miles, some eight hundred nautical miles less than the shorter version. For the 787, Boeing would significantly shrink the range gap between these two versions.

The new aircraft itself “will look more like a 777. The family will end up looking a lot like today’s aircraft, but it will be super, super efficient, and that’s why the airlines will love it,” said Mulally. The aircraft “could be” designated “787” if launched, and he acknowledged that “eight is a lucky number.”

However, as 2003 began, Boeing changed the Super Efficient designation to the 7E7, a reference to the magic word “efficiency” and a continuation of previous pre-numeric designations such as the 7N7/7X7 for the 757/767, and the abandoned Boeing-Japanese 7J7 project. Design definition work was meanwhile kicking into high gear, with major targets including finalization of the all-important fuselage cross section, engine thrust requirements, and whether or not, and how much composites to use in the primary structure of the wing and the fuselage.

At this early stage, two initial versions of the 7E7 formed the focus for discussions, both of which traced their heritage to the finalists of the Sonic Cruiser studies. These included a 210-seater and a 250-seater in three-class configurations, with a range of about 7,000 to 8,000 nautical miles and a cruise speed of Mach 0.84 to 0.85.

The big decision hinged on whether the 7E7 should have a seven- or eight-abreast economy cabin, the smaller option representing a cross section similar to that of the 767. The larger fuselage cross section, though narrower than the nine/ten-abreast seating width of the 777, would still be wider than the competing A330/340 family. Both designs could accommodate LD3 containers in the cargo hold but would be held within the contours of a double-lobe or “double-bubble” fuselage rather than the structurally efficient circular design adopted for the first time with the 777.

“Boeing has always done double-bubble fuselages, although the 777 was circular and the reason for that was the move to the nine-abreast configuration. However, we got criticized by some because of the space that created above the ceiling, so all of the Yellowstone studies were double-bubble,” said Roundhill. Boeing later devised innovative upper-lobe crew rest areas for the 777, which came into their own for the 777-200LR/300ER models, but the lower-capacity targets of Yellowstone and 7E7 also played in favor of the slimmer cross section and the double-lobe approach.

By February 2003 the airlines were being briefed on further refined offerings, dubbed the 7E7-300X.
and 7E7-400X. The 300X seated 228 passengers in a three-class arrangement and offered a design range of 7,800 nautical miles, while the stretched 400X seated 268 and could fly about 7,000 nautical miles. Crucial performance targets included more range and 23 percent better fuel burn per passenger than the A330-200, as well as cruise speeds as high as Mach 0.89—somewhat faster than those being publicly discussed just a month or so earlier.

At the end of the following month, on March 28, Boeing filed for new type and production certificates for the 7E7 with both the FAA and the European JAA. “That’s a major milestone in the program,” said newly appointed 7E7 Vice President Mike Bair. “That starts the process for the production plan of the aircraft and is a milestone we didn’t pass through on other recent derivatives.” In other words, the 7E7 was the first new Boeing model since the 777 to get this far, and events augured well for a positive “authority to offer” decision from the Boeing board, expected in December 2003.

With the 7E7, Boeing wanted to ride the wave it had begun with the Sonic Cruiser. However, the first visual impressions were significantly different from the baseline reference concept (see inset) unveiled by Walt Gillette to a gathering at the Society of Automotive and Aerospace Engineers conference, held in November 2002 at the Sheraton Crescent Hotel in Phoenix, Arizona.

Before then, however, Boeing faced a hectic year. “Most of 2003 will be spent defining what it will look like, and convincing ourselves we have a viable business case,” said Bair.

The crucial cross-section decision was also revealed in late March, the company opting for the wider eight-abreast cabin with a roughly 226-inch diameter. This made it about 28 inches wider than the 767 and 18 inches narrower than the 777, while giving it the advantage of at least few inches extra width over the A330.
fitting raked tips to the 197-foot span of the longer-range model (originally about 188 feet), and blended winglets to the 170-foot-span, gate-size-restricted short/medium-range version. The raked tips also were chosen for the stretched, longer-range model, which also was given extra wing area for a total wingspan of almost 208 feet. The elegant curve of the Korean Air–built raked tip is well illustrated on this image of ZA001. Mark Wagner

Like first-time parents dithering over names for their unborn child, Boeing once again changed the 7E7 designations. The 7E7-300X/400X disappeared, to be replaced for a short time by the 7E7 and 7E7STR (stretch). Within weeks, however, these morphed once more into two main subsets, the baseline and stretch 7E7SR (short-range) and baseline and stretch 7E7LR (long-range). The new groups came in response to what was becoming a rising flood of interest from carriers for all kinds of range and payload capability. Of almost forty airlines advising Boeing, some wanted long-range, point-to-point capability between 4,640 and 9,200 miles, while others wanted short-range to mid-range (3,450- to 4,600-mile) capacity in the 250-to-350-seat range.

The resulting matrix produced four main options: a baseline LR seating about 200 to 220 in three classes, with an 8,970-to-9,200-mile range; a stretched LR seating up to 260 with a range of up to 8,500 miles; a baseline SR seating 320 to 340 (in two classes), with a 3,450-to-3,900-mile range; and a stretched SR seating 280 to 310 with a range of up to 4,600 miles. Both baseline SR and LR aircraft had the same length, of about 190 feet, while the stretch was lengthened by almost 23 feet, to be some 213 feet long.

Despite this plethora of options, Boeing still drove to “keep things simple,” with as little variation as possible among the versions. Yet satisfying such divergent requirements at equal levels of efficiency with the same design posed several design challenges. One of the biggest and most basic was what to do with the wing. The longer the range, the better it was to have a bigger wingspan. Yet the opposite applied for shorter-range routes, where the typical mission required far less fuel and usually operated from smaller airport gates of 757/767 size rather than 777 size.

One possible solution studied was an optional wing “tip treatment,” which was essentially a large winglet to allow the SR span to be shrunk to about 164 feet, from the 187.9-foot span of the standard 7E7. Mike Bair acknowledged that solving the span issue was one of the “biggest complications” in the design process, and one that severely challenged Boeing’s one-plane-fits-all dream.

Huge production decisions also loomed in 2003, with Boeing facing the dilemma of where to actually assemble the 7E7. In March Bair said, “We are developing a list of criteria which we will use to evaluate the final assembly site, and it is in our interests to make that list as open a process as we can.”

While planning the assembly process for the 7E7, Boeing looked most closely at lessons learned on the 737. Lean assembly techniques and the implementation of a moving line had seen the assembly time of a 737 at Renton cut from twenty-two days in 2000 to just eleven days by 2008. Boeing was targeting a final cycle time of six days as it aimed to produce more than thirty 737s per month. The aircraft move along the line, complete with all the wheeled equipment around it, at about two inches per minute. Mark Wagner

Taking its cue from the Airbus production process, which involved the airborne delivery to a final production line of very large subassemblies from the partner sites around Europe, Boeing chose to evolve this for the 7E7. Parts from Boeing’s new and as yet undecided set of partners would be flown or shipped to an as yet undecided location somewhere in the continental United States, or even more astonishingly, elsewhere in the world. “It doesn’t necessarily have to be in the United States—those are the sort of things that are on our list to consider. We haven’t even ruled out multiple sites,” Bair said.

The move was a radical departure for Boeing, which had grown up around its two major commercial assembly
sites in the Puget Sound area: Renton near Seattle, and Everett. Although an increasingly large number of big parts came into Puget Sound by sea and rail, including entire 737 fuselages from Boeing’s Wichita, Kansas, site, the basic production process remained unchanged from the days of World War II.

PARADIGM SHIFT

“Final assembly will look vastly different to today’s aircraft. We’ll be taking advantage of a moving line, plus a smaller number of highly finished large pieces,” promised Bair. Boeing was already laying the foundations for much of the change at the time by outsourcing more structural work, particularly to Italy and Japan, as well as introducing an automotivelike moving-line concept to commercial aircraft assembly. The moving line had first been tried out on the 717 line at Long Beach, and later was transitioned to the much busier 737 line in Renton.

The news that outside sites were in the frame sent companies and unions across the country running to state capitals to help their bids, while unions in Seattle were equally adamant that the E in 7E7 would soon stand for “Everett.” With its recent headquarters move to Chicago, Boeing had already sent a clear signal to Washington State’s government that it was less than happy with the incentives on offer, and the local legislature was in no doubt that the 7E7 site search was in earnest.

One distinct design feature that survived from the early days of the 7E7 through to the real thing was the flush nose and nontraditional (for Boeing) flight deck windows. There was more to the shaping than simply styling, as with any design aspect that made it through the complex trade studies. The new configuration gave good aerodynamic performance, offered better bird strike resistance, and improved flight deck visibility. Mark Wagner

Kansas quickly stepped up with offers of $500 million in financial incentives if Boeing gave Wichita a role as a major development center for the 7E7. The question of site selection was becoming complex, and to help it handle the conundrum, Boeing hired the consulting firm McCallum Sweeney. Final bids were expected in by late June, coinciding with the end of that year’s Paris Air Show.

Behind the scenes, however, the marketing battle was becoming bogged down in a form of trench warfare of indifference. Airline reaction to the new twin, so strikingly ordinary after the Sonic Cruiser, was depressingly indifferent. Boeing knew the 7E7 was dramatically new beneath the skin, but the marketers wanted to make sure the aircraft conveyed the same message on the outside. The 7E7 was going to be distinctive, and while not quite the breathtaking image projected by the Sonic Cruiser, it had to be memorable and immediately distinctive.

On May 5, 2003, the world got its first look at the “official” view of the idealized 7E7 when Boeing issued an artist’s impression combined with a unique online name-the-plane contest that was virtually guaranteed to make the 7E7 a globally recognized project. The new-look 7E7 was indeed different from anything seen before. An overall impression of speed and style was conveyed from nose to tail, starting with conformally swept flight deck windows. Other changes include integrally blended winglets in place of the raked tips defined on the baseline proposal, and a “sculpted” vertical “shark” tail with a smaller area than the more conventional, narrow-chord 777-style fin previously outlined.

The marketing alliance with communications giant AOL Time Warner was equally surprising. Under the scheme people around the world were invited to vote online for the name of the 7E7. The choices were limited to eLiner, Global Cruiser, Stratoclimber, and Dreamliner, and through the power of the Internet held the potential to spread the word about the 7E7 like no new airliner in history. The initiative also specifically included children in the process, and involved the production of a special edition of Time for Kids called “A New Dream Takes Wing.”
Boeing also began a broad-based systems definition phase for the 7E7 project, which was expected to culminate sometime around August with the confirmation of both the overall firm mission requirements and the design concept itself. Specific targets included selection of materials, system options, common core architecture, airport infrastructure issues, interiors, flight deck, and commonality.

One of the biggest decisions facing the team was the engine selection (see chapter 6). The company announced plans to downselect to two engine suppliers in the third quarter, although General Electric made little secret of its intent to seek sole-source exclusivity. By now engine requirements called for thrust ratings of 63,000 and 68,000 pounds, a bypass ratio between nine and twelve, an overall engine pressure ratio of fifty to one, and fan diameters up to 115 inches.

If these targets could be achieved, Boeing planned to seek board authority to formally offer the aircraft by year’s end, and to seek customer commitments during 2004. Assuming launch later in 2004, firm configuration—the major design milestone when the aircraft was ready to be released to engineering and the companies making the parts—was expected in the second quarter of 2005. This would set the clock ticking on a production buildup that would culminate with the first flight in 2007 and initial deliveries in 2008.

But how gimmicky were the sloped cockpit windows and the other features, particularly the shark tail? Were they for real, or simply marketing? Boeing said the latest configuration changes had to be “aerodynamically positive or neutral,” but conceded they were aimed at “differentiation.” Mike Bair said, “We want to go beyond baseline to something that people will know by sight—like the way we all know a 747 when we see one.”

Aside from the marketing hype, Boeing was under no illusions about the true impact the 7E7 was already starting to have on the company, let alone the market. “It’s another transformational aircraft,” said Boeing Commercial chief executive Alan Mulally. “It’s a chance to define the future. It will mark another significant improvement in efficiency. How can we miss?”

The target was big enough according to Boeing’s analysis, which now suggested a market of two thousand to three thousand aircraft for the 7E7. “We are providing the all-time fragmenter, a point-to-point enabler,” said Mulally. “The thing that changed the world with the 767 was its economics and its range, because it could overfly hubs. The 7E7 will be like this. It will be the equivalent of a regional jet for international use.”

Yet how could Boeing be so optimistic about a new middle-market aircraft when it was in the process of shutting down the 757 line for lack of orders, and with no certainty over prospective military developments, was on the verge of committing the 767 to “death row”? To Mulally the answer was simple. The 7E7 was going to be far more than a 757/767 replacement in terms of performance, capacity, and economics. “The point is, when you look at the world, some eighty-eight percent of all the dollar value will be in this area. If you serve that with the 7E7, that’s your market,” Mulally said.

Mulally also believed that the new twin formed a “rallying call for everything we’re going to do for a better value solution. We will take partnerships to a new level. We’ll do less of the detailed work, and we’ll have shorter assembly times. The 7E7 will be the next significant improvement in production efficiency.”

But uncertainty still dogged the company, which had been rocked by scandals and big losses on the defense side of the business, culminating with the resignation of Condit and the recall of Stonecipher from retirement. Boeing workers in the Seattle area were nervous, particularly as the 7E7 production site selection was imminent, and corporate confidence appeared to be at an all-time low. A cartoon of Stonecipher and Condit did the e-mail rounds, showing the pair as the silent movie–era slapstick comedy duo Laurel and Hardy. Beneath them was a caption depicting their trademark, saying, “Here’s another fine mess.”

But Stonecipher acted quickly to dispel rumors that he was prepared to veto the 7E7 unless a rock-solid business case was proven. Rushing to Seattle early in December to be briefed by Alan Mulally and 7E7 project leader Mike Bair, Stonecipher said, “Everything we have seen about it says the airplane has the potential to be a game-changer.”

Despite the unsettling developments, Boeing’s 7E7 development team had been busy finalizing the complex work share arrangements with the newly emerging structures team. Details were announced to the world on November 20, 2003, just a week after meetings were held in Seattle to brief eighty airlines and eight financial institutions on the latest developments. These included new details about just how serious Boeing had been with its “standardized” airplane goals. Part of this was driven by the perceived growing importance of big airline groupings such as the Star Alliance—a strong team comprising major carriers such as Air China, Air New Zealand, ANA, Austrian Airlines, BMI, SAS, Singapore Airlines, TAP, Thai, South African Airways, Swissair, United Airlines, and U.S. Airways.
The 7E7 was deliberately “standardized” to cut costs for airlines, make it easier to finance and build. By making about $10 million of optional features basic, such as head-up displays and heaviest maximum takeoff option, Boeing predicted that the 7E7 would be more attractive to increasingly influential airline alliance groups such as OneWorld, Sky Team, and the Star Alliance. Customer members of the Star Alliance, whose logos are painted along the side of this BMI Airbus A321, would have around only about 150 catalog options to choose from on the 7E7 versus some 600 on the 777.

“The alliances can be a powerful instrument toward standardization,” said 7E7 Vice President for Customers John Feren. “We only have one landing gear supplier, and our current plan is for two engine suppliers. We are also looking at going from fifteen LRUs [line replaceable units] to eight in the cockpit, for example. The affordability of this aircraft will be as important as its fuel efficiency, and if we don’t price it competitively, all the innovations will be for naught.”

Speaking for one of the prospective customers, Cathay Pacific, the Hong Kong–based carrier’s U.S. Technical Vice President Peter Gardner confirmed “everything forward of the flight deck door is virtually standard. The only thing that’s left for the customers to mess with is the interior, and apart from the exterior paint and the engine selection, it is being narrowed down.” Gardner also gave one of the first public reactions to the cabin mock-up, also just unveiled. “There is a ‘wow’ factor as you go through the door. It creates a new ambience, but the concept is really good.”

But it was the structural supplier news that really hit the headlines. Although it was widely known that much more of the aircraft would be made by partners, it was the scale and the type of work that still took the outside world by surprise. Some 65 percent of the aircraft would be made by outside companies, with Japan securing the largest chunk, including the wingbox—the first Boeing wing to be made offshore. Just as surprising was the unexpected teaming of two longtime Boeing structural partners and teammates, Alenia of Italy and U.S.-based Vought. The two even formed a new company, Global Aeronautica, which would be responsible for the center and aft fuselages and aft stabilizer.

The U.S.-Italian venture was as strategic as it was unexpected. David Brigante, Alenia vice president in charge of commercial aviation accounts, believed the new relationship with Vought was vital, not only to the 7E7, but also to Alenia’s longer-term growth ambitions. Before its tie-up with the American company, Alenia had looked at opening its own U.S. site. “We always had the idea of having an assembly area near the customer,” said Brigante, who added it even considered buying a part of Vought from Northrop Grumman. “That’s how it all started.”

Across the Atlantic in Charleston, South Carolina, Alenia North America Chief Operating Officer and Global Aeronautica Board of Managers Chairman Vincenzo Caiazzo said the joint venture “combines the best of the two companies to perform activities that previously were not performed by either. The investment has also allowed a foreign company to have access to a global market—a move which is important for both Alenia and Vought. The 7E7 is all about the creation of innovative relationships in the supply chain that have never happened before—that’s why Global Aeronautica will be really remembered as a pioneer.”

Caiazzo added, “The new business model of the Dreamliner has dramatically changed the relationship in the supply chain. Today Boeing is changing itself into a large-scale integrator, and the suppliers are expected to be vertically integrated partners capable of defining, producing, and assembling complete systems and structures to deliver to the final integrator in Everett.”

To some traditionalists the scale of the outsourcing, particularly the wing, was nothing short of shocking. To Boeing, however, it was all part of the grand plan to improve production efficiency by transitioning to its new role as a large-scale systems integrator. “The wing generates lift, but the thing that makes it fly is our ability to understand the requirements of the customers, and to integrate all that into an aircraft that works,” said Bair.

With the partner team coming together, Mulally and Bair flew to Chicago for the pivotal “go/no go” board meeting on December 15, 2003. Tensions were high and the planned 1 1/2-hour board meeting lasted 4 hours. But those waiting nervously outside did not have to worry. “We could have got the vote in the first ten minutes, but the
board wanted to know about the changes,” said Stonecipher. The decision was in the bag, and the scene was now set for a historic announcement the following day in Seattle.

Passenger appeal was a key design driver from the start, with an emphasis on a better cabin environment, wider aisles and seats, larger windows, and bigger overhead baggage bins. Composites enabled cabins to be pressurized to higher levels, thereby lowering cabin altitude from about 8,000 feet to 6,000 feet, and raising humidity and comfort levels. The windows, 18.4 inches tall and 10.7 inches wide, were expected to be the largest on any commercial jet aircraft—though not quite on the never-to-be-beaten scale of the 26x19-inch windows of the Vickers Viscount turboprop! Mark Wagner
Chapter 3
DREAMTIME

Outside it was a typical gray, overcast Seattle winter’s day, but inside the Washington State Trade and Convention Center there was a carnival-like atmosphere. More than three thousand people were gathered in a party mood on December 16, 2003—one day shy of the one-hundredth anniversary of powered flight—to hear Boeing announce that the 7E7 was officially for sale.

Mulally, standing on stage with Stonecipher, had the crowd in his hands as he reflected on the timing of the announcement. “Savor this moment. This is a great way to start the second century of powered flight,” he said as the audience clapped and cheered. Indeed, the celebration was a double one for the Boeing workers, as the authority to offer (ATO) the 7E7 was accompanied by the news that Everett had won the site selection contest and would be home to the Dreamliner.

China’s interest in the 7E7 emerged after a customer conference in Beijing in May 2004. The long-term result was a $7.8 billion group deal covering sixty aircraft for Air China (fifteen), China Eastern (fifteen), China Southern (thirteen, including three for its Xiamen Airlines subsidiary), Hainan Airlines (eight), and Shanghai Airlines (nine). Each was also assured first deliveries in time for the 2008 Beijing Olympic Games. The deal, signed by the Chinese government on January 28, 2005, also closely coincided with the formal designation of the 7E7 as the 787.

More than eighty alternative sites had been reviewed, but the case for Everett had been “compelling,” said Bair. Much of the credit went to the Washington State government, which, having recently seen Boeing move its headquarters out of state to Chicago, stepped up with tax and other incentives worth about $3.2 billion to secure its bid. “Many factors weighed into the decision. But it’s clear that the best overall solution for Boeing and the 7E7 is to place final assembly in Everett,” said Bair.
In December 2003 Boeing’s Everett site was officially named as the final assembly site for the 7E7. Ending months of speculation, the decision came as a massive relief to the Boeing employees there and to Washington State, which had offered tax and other financial incentives worth more than $3 billion to keep the business. Boeing and McCallum Sweeney Consulting together evaluated bids from more than eighty alternative sites before selecting Everett, which offered existing capacity in the underused eastern end of the massive Building 40 complex.

Although the ATO was in the bag, and Everett chosen for the final assembly site, major questions remained about launch, and how many orders would be needed for Boeing to finally “push the button” on the program. Speaking at the celebrations that day, Mulally said, “We might have some major customers step up early and order the airplane.” Dropping hints that Boeing was considering closing the gap between the ATO and the full launch, a period of ten months for the 777, Mulally said, “We are conferring with fifty or so airlines,” adding that the go-ahead will be “sooner rather than later.”

With the formal launch coming up, a new set of program milestones was laid out for 2004. Major system selections were set for about March and April, with the engine finalists being decided at about the same time. “Most of it will be done by summer,” predicted Bair.

But even as the bunting and streamers were swept up in the convention center, news began leaking out that launch hopeful Japan Airlines (JAL) was expected to delay ordering the 7E7 until at least midyear. JAL had issued a request for proposals (RFP) in October 2003 for Airbus A300 and Boeing 767 replacements and, smelling blood, Boeing obtained special board approval to offer the 7E7 in November—well before the ATO. But to Boeing’s disappointment, JAL decided against placing any orders in December and let the offer expire.

Like so many Pacific Rim carriers, JAL had been badly hit by the impact of the SARS virus in 2003 and was prepared to be even more cautious than usual with its finances. ANA therefore became the next most likely launch candidate in Japan, but as of January 2004 had not issued any RFPs. To help jump-start sales, Boeing meanwhile opted to undercut Airbus in the midsize wide-body market with what seemed like a bargain price for the Dreamliner. Bair was first to announce the surprisingly low cost of the aircraft, which many industry observers had expected to come at a premium because of its expected 20 percent performance benefit. “We’re looking at it as a 767/A300/A310/A330 replacement, so because of that we’re talking $120 million plus or minus around $5 million—depending on the exact configuration,” said Bair in a matter-of-fact way.
In early 2004 Boeing’s surprising 7E7 pricing strategy revealed that it would be sold at prices similar to those of the 767 despite its extra capability. Although many, including Airbus, had forecast 7E7 prices akin to the A330 in the $145 million range (2003 dollars), Boeing pegged it “close” to the $125 million price of the 767-300ER. Mark Wagner

Speaking above the roar of portable air con units in a chalet at the Asian Aerospace Show in Singapore a few days later in February 2004, Randy Baseler, Boeing Commercial Airplanes vice president of marketing, confirmed that the 7E7 would be offered at catalog prices “in the ballpark” of the 767-300ER, listed then at $115.5 million to $127.5 million. In comparison, the A330-200, the closest Airbus type to the 7E7, had a list price of $142 million. Thomas Waggener, 7E7 director of marketing, said airlines were “pleasantly surprised” at the 767-comparable price tag. The pricing decision for the 7E7 was to find a “balance between whether to sell a few airplanes at a high price or a lot at a low price,” added Waggener, who said the move was part of a broader, albeit altruistic, strategy to help the airlines help themselves. Healthier airlines need more equipment, and so “we will sell more airplanes that way,” he said.

While the marketing push continued, the first major systems were announced that same month. Hamilton Sundstrand and Rockwell Collins were picked for the bulk of the power-related and avionics systems, respectively. (See chapter 5.) Systems selections would continue to make headlines until well into 2005, by when 99 percent of the decisions had been made. But just when everyone thought they’d heard everything there was to know about the technology on the Dreamliner, Boeing would keep the surprises coming.

One totally unexpected design feature revealed in 2004 was a novel form of a common engine attachment point that would allow a different engine type to be installed within twenty-four hours. “That could offer airlines a lot of downstream flexibility and will increase the financeability of the aircraft,” commented Bair, who added that the conventional engine-airframe designs were essentially unique to each combination, inevitably impacting on asset value later in the life of the aircraft.

Meanwhile, the engine choice itself was approaching, with GE, P&W, and Rolls all submitting final bids by the end of February. The agonizing decision over the winners was announced on April 6, when GE and Rolls were announced as the victors, leaving P&W out in the cold. “It was not an easy decision; all three manufacturers provided wonderful engines, and they all have really strong relationships with the airlines. Quite frankly it was also a very close decision, but we are happy with that this represents the best value for everyone that’s going to be involved in this aircraft, from our customers to the 7E7 team,” said Bair. (See chapter 6.)

“It was a combination of all aspects,” he added, saying that airlines “were more nervous when it wasn’t clear that they’d have a choice at all, than with this decision.” Bair also unexpectedly revealed a distinctly un-Boeing naming convention for the new jet. The 7E7SR became the 7E7-3, the baseline 7E7 the 7E7-8, and the 7E7STR stretch the 7E7-9. “It’s a simpler naming structure, and it kind of makes it easier to help us finalize the seat counts,” said Bair, who explained that the basic classification was driven by range—the 7E7-3 being a 3,500 nautical miles design, and the 7E7-8 being designed for 8,500 nautical miles. The stretch 7E7-9 designation therefore was a fallout from the 7E7-8, even though its design range would be slightly less, at 8,300 nautical miles. Seating plans at this stage saw the 7E7-3 configured in three classes for about 289 to 300, while the 7E7-8 held 200 to 217, and the 7E7-9 held 250 to 257.

Meanwhile, the battle to finally launch the 7E7 was reaching a crescendo, particularly in Japan, where ANA was still the leading candidate. Airbus was determined to head off the 7E7 at the pass by proposing a notional, new wide-body design purpose-made for the short-haul market. Dubbed the A30X, the aircraft was optimized for stage lengths of 1,000 nautical miles and would be available in 2014–2015 if launched by 2009–2010, said Airbus’s irrepressible chief commercial officer, John Leahy.

The problem for Airbus was that ANA still had not issued a formal RFP for a 767 replacement, unlike JAL, which had gone through the initial stages the previous October before delaying its decision. Instead, ANA was looking at the 7E7 without an open tender, egged on by Boeing’s performance promises for both the 7E7-3 and longer-range 7E7-8. However, with its next shareholder meeting not scheduled until June 2004, no major order announcement was expected before then.
To further boost 7E7 marketability, the aircraft was designed with a standard engine interface to allow a complete change from one engine option to another within twenty-four hours. Similar to the engine interchangeability designed into the Lockheed Martin F-35 Joint Strike Fighter, it was a first for any commercial jet airliner. In reality it proved a longer exercise than first thought, taking almost four days in initial trials. Boeing’s eventual target was a six-hour change time. Mark Wagner

**GO FOR LAUNCH**

It was with some surprise, therefore, that Boeing quietly put the word out to journalists on the evening of the April 25 to expect a big 7E7 announcement the next day. Calling in from all over the world on the twenty-sixth, the media heard the big news that the board of directors had officially launched the 7E7 on the back of firm orders for fifty aircraft from ANA in a deal worth almost $6 billion.

ANA’s $6 billion launch order for fifty 7E7s was announced on April 26, 2004, and included an unspecified mixture of short-range and baseline, longer-range versions. Earlier that month Boeing also once more revised its naming convention, the 7E7-300X or baseline, becoming the 7E7-8, to reflect the eight thousand nautical miles plus range capability. The shorter-range version, formerly dubbed the 7E7-300SRX, now became the 7E7-3 to reflect its three-thousand-nautical-mile optimized-range design as well as its three-hundred-seat capacity. The stretch, formerly the 7E7-400X, became the 7E7-9 by default. Mark Wagner

It was the largest launch order in Boeing commercial history and covered an unspecified mixture of 7E7-3s and 7E7-8s, with deliveries of the latter version beginning in 2008. The 7E7-3 variant was to be certificated about six months later, while the timeline for the 7E7-9 indicated entry into service no earlier than 2010. Crucially, ANA still had to decide on the engine supplier, but Boeing confirmed that a four-month gap would be planned between certification of whichever became lead engine and the second engine.
The expected delivery rate at this stage indicated eight per year to ANA, but already the sheer amount of market interest was giving Boeing worrying signs that it would simply not be able to keep pace with demand—at least not to start with. “There is a limited number of aircraft in the first couple of years, and we are looking at a lot more activity than we have the capacity to produce,” Bair said prophetically at the time.

Gambling on its new production system capacity to ramp up in record speed, Boeing was optimistically offering up to ninety-two delivery positions to the end of 2009. How dangerously overconfident this was, and how expensive the true ramp-up would ultimately prove to be, would only become apparent more than three years later.

By the Farnborough Air Show that year, however, Boeing’s mood was remarkably upbeat about the 7E7, which was on track for design freeze in July 2005. Media interest was intense, and even the slightest changes in the design became talking points at the event. These included a small extension of the 7E7-8 wingspan by 4 feet, to 197 feet, while the 7E7-3 wing now sported more prominent winglets. High-speed lines had also been refined to generate an overall aerodynamic efficiency improvement of about 6 percent. Boeing chose the final configuration after “literally hundreds” of iterations had been reviewed using computational fluid dynamics. Part of the gain was due to the inherent design flexibility of composites. “The span is near that of the 777, but the wing is thinner and so is the wingbox, which is fine because composites allow you to do things that you could not do with aluminum,” explained Bair.

In spite of the changes, the overall appearance was still “different” and in keeping with what Bair described as the goal of “having 99 percent of the public saying, ‘hey, that’s a 7E7.’” However, for the first time Bair acknowledged that the distinctive shark-fin tail would be “less dramatic” than the artist impressions. He still hoped traces would be visible in the rudder with what he dubbed a “hint of a reverse curve.”

The nose retained its conformal streamlining, and the flight deck also kept the four-pane windshield of the artist’s rendering in place of the more traditional Boeing six-pane design. This time the window numbers and design were driven more by potential weight savings and safety than sex appeal. “We’re not going to compromise efficiency just to make it look cool,” affirmed Bair.

Although externally identical, the composite airframe of the newly named 7E7-3 would be strengthened to handle around 2,300 cycles (each being a takeoff, cruise, and landing) per year, more than three times the duty required of the 640 cycles per year of the 7E7-8 and the 7E7-9. Spacing between the 30 percent larger windows was restricted more by provision for space for systems wiring than by the traditional structural dictates of aluminum. Mark Wagner

New details also emerged of the larger cabin windows, 30 percent bigger than conventional transparencies. These were made possible by the jump to primary structural composites, which did not require the local reinforcement around the cutouts used in conventional aluminum skins. “We’re just trying to make sure we have enough room for wire runs between the frames, but the good thing about composites is that this allows us to have large windows without penalties,” he said.

However, it was becoming obvious that composites were not necessarily the panacea they were sometimes made out to be, and the specter of weight was already raising its ugly head, as Bair admitted. “We’re a bit overweight, although less so than we were on the 777 at this point in the process. We are roughly 50 percent composite now by weight. We don’t have an actual target in terms of either weight or percent for composite, we’re just doing what makes sense,” he added.

Farnborough also was buzzing with news of 7E7 orders, and by now ANA had been joined by other carriers in announcing commitments. Unlike the usual Boeing launch order group of mainline U.S. and sometimes European flag carriers, the early 7E7 customers were quite different. The Japanese carrier was joined by Air New Zealand, U.K. leisure carrier First Choice Airways, and Italian leisure/scheduled operator Blue Panorama. Typifying the broader appeal of the Dreamliner vision, First Choice had largely opted for the jet because of its cabin features as well as its economics, said the airline’s managing director, Chris Browne. The carrier planned to replace its fleet of
767s with 7E7s from early 2009 onward, and it was “the next logical step, it allows us to offer affordable holidays to long-haul destinations,” she added.

By the late summer of 2004, Boeing was focused on freezing the final high-speed aerodynamic lines, and with that milestone Mike Bair almost apologetically acknowledged that the fin shape would not be “nearly as sharkish” as the early artists’ renditions had indicated. By this stage, however, the rudder still retained a “hint of reverse curve,” he added. Boeing later acknowledged that pure mechanics overcame aesthetics, and the fin was straightened to maximize the rudder’s sweep radius. Mark Wagner

In June 2004 Air New Zealand joined ANA as a launch customer by ordering two 7E7-8s. It selected the Rolls-Royce Trent 1000 and just over a year later doubled the order to four. In February 2007 it became the launch customer for what was now the 787-9, but at the expense of the original 787-8s, which were converted into orders for the stretch. The numbers also were doubled, to a total of eight aircraft. Boeing/Air New Zealand

Key to the decision was the appeal of a comfortable cabin environment on long-haul routes from the United Kingdom to as far afield as the U.S. West Coast, Hawaii, or South Africa. “There is no other aircraft out there to touch it,” said Browne, who had been offered the A330-200 as an option. “We believe the advantages of the 7E7 are compelling,” she added, pointing to its operating costs, low noise and emissions, and range.

By October 2004 ANA was ready to announce its long-awaited engine choice, and for most of the aerospace world the answer was unexpected. Confounding the pundits who predicted a GE victory in this first round, the Japanese carrier chose Rolls-Royce’s Trent 1000. The decision made the Trent the lead engine on the 7E7, which became the first all-new Boeing wide body to be launched into service with a Rolls-Royce engine.

The ANA decision coincided with news that Kawasaki Heavy Industries (KHI) had joined Mitsubishi Heavy Industries (MHI) as a risk-and-revenue-sharing partner in the Trent 1000 program. KHI was to assemble and supply the intermediate pressure (IP) compressor module under an 8.5 percent share, while MHI’s combustor and low-pressure (LP) turbine work represented a 7 percent share. Negotiations on the remaining partnerships were “well advanced,” said Rolls-Royce.

The following month, a “Progress Summit II,” held in Seattle with about seventy airlines, included open discussion about customer requirements, concepts for standardizing and simplifying the 7E7, as well as airplane
financing. The meeting also provided the first glimpse at the startling new maintenance interval targets that Boeing was aiming for with the new jet. These would play a pivotal role in the lower cost of ownership and operations equation that Boeing was counting on to swing the midsize market away from Airbus and over to the Dreamliner.

The first C-check interval after first flight, for example, was expected to be up to thirty-six months after delivery. Compared with the standard interval before the same milestone on a 767-300 being flown twice a day, the 7E7 “will be able to fly an extra 169 flights,” said John Feren, who presided at the event. This was mostly due to the extensive use of advanced composites, more electric systems, and sophisticated self-diagnostic systems in the aircraft, which, like a person able to monitor his own body, would be able to tell the crew if it needed a checkup.

By now the Dreamliner shape was also all but firmed up. Boeing had accomplished 75 percent of the planned wind tunnel campaigns, amassing an astonishing eleven thousand hours of tests in the process. Composite use by weight had now crept up beyond 50 percent, slightly higher than a year earlier, and “it might go up a bit more between now and final configuration,” forecast Feren.

**NEW YEAR, NEW NAME**

Boeing’s sales surge in late 2004 changed abruptly into a tsunami of orders over the busy winter. JAL, one of the earliest sales goals for the Dreamliner, quietly signaled its intent to commit to thirty aircraft plus twenty options. Although the deal would not become official for several months, Boeing was relieved at the JAL decision, which had become more protracted than anyone expected.

The new year also saw long-running negotiations with a group of Chinese carriers finally bearing fruit. The momentous deal, covering up to sixty aircraft worth about $7.2 billion, was signed with Air China, China Eastern, China Southern, Hainen, Shanghai, and Xiamen airlines at a ceremony in Washington, D.C. Alongside Mulally’s signature appeared those of U.S. Assistant Secretary of Commerce Al Frink; the Chinese Ambassador to the United States, Yang Jiechi; and China Aviation Supplies President Li Hai. Significantly and not unexpectedly, the sale also marked the milestone renaming of the 7E7 as the 787. This was not only the next number in line after the 777, the last all-new Boeing airliner launched almost fifteen years before, but it also conveniently contained the number “8,” which is considered lucky in many Asian cultures.

The agreement, which came several months later than Boeing originally hoped, followed a complex series of talks and supplier deals with Chinese aerospace companies that began as far back as a Boeing 7E7 conference in Beijing on May 25, 2004. After the conference, which was attended by the Civil Aviation Authority of China, government approval was sought to proceed, with the firm order to be placed on the airlines’ behalf by the state-run China Aviation Supplies Import & Export Group.

In line with Boeing’s optimistic delivery forecast, the negotiations also included guarantees each that carrier would receive its first aircraft before the start of the Olympic Games in Beijing in August 2008. Little did anyone realize that production delays would make this impossible and that flight tests by then would not even be under way. Allocations from the order, which, excluding options, took overall firm orders and commitments to about 186, included 15 each for Air China and China Eastern, 13 for China Southern (3 of them for its Xiamen subsidiary), 8 for Hainan, and 9 for Shanghai Airlines.

In the wake of the Chinese deal, Boeing also finalized more workshare contracts in Asia, including a contract with China’s Chengdu Aircraft Industrial for the 787’s rudder, and Korea Aerospace Industries for the fixed trailing edge. Ironically, at about the same time the rudder deal was struck, Boeing also released finalized design renditions of the 787 showing that the famous shark fin had essentially been overtaken by reality and had become conventional. To many of the old Sonic Cruiser fans still hoping for characteristic features such as a vestigial shark fin look to the tail, the latest image was slightly disappointing. “The concept vertical tail would not work,” said Bair, who seemed almost apologetic. However, he was all in favor of the final shape, which he described as having an “aggressive look.” This he believed was a result of giving the job of outlining the 7E7 concept to industrial designers before letting the aerodynamicists turn it into reality. “It caused a lot of creative solutions,” he added.

One of the most dramatic features of the finalized aircraft, however, was the unusually high upswept wing angle, or dihedral. “You are seeing this is what happens when you build a composite wing,” said Bair. The slender 197-foot wingspan of the baseline 787-8 had an aspect ratio of 10, compared with 8.68 on the 777-200. But despite the narrower chord of the wingbox, and of the wing itself, the overall stiffness would be the same as for a conventional aluminum structure.

It was also revealed that the engine nacelles would feature noise-reduction chevrons as standard features. These “cookie cutter”–like shapes had already begun to be introduced on production engines such as the GE CF34 regional jet engine and had been the subject of careful noise monitoring tests among Boeing, Rolls, and GE as part of the 777-based Quiet Technology Demonstrator project.
Behind the scenes, the 7E7 went on a diet to lose weight. The weight-saving campaign, broadcast on banners throughout the Everett design offices to press home the message to employees, had been launched in December 2004 and by mid-January 2005 had started to produce results. Alarm bells had rung when the manufacturer’s weight crept above 3 percent over target, but “was trending downward” below 2.5 percent within a few weeks of intense effort, said 7E7 chief project engineer Tom Cogan.

Maintenance cost advantages were designed as basic into the 7E7. Boeing’s aim was a 30 percent saving in airframe maintenance costs per year by the time of the first scheduled heavy structural inspection, or “D-check.” In the 7E7 this was planned for twelve years, rather than eight for the 777 and six for the 767. The advantage was expected to grow with age, and be about 60 percent by the twenty-fourth year. Line and base maintenance check intervals were similarly extended to a thousand hours and thirty-six months, respectively, compared to five hundred hours and sixteen months for the 767 and six hundred hours and twenty-four months for the 777. Here an ANA Boeing 767 undergoes a D-check at Tokyo Haneda. Mark Wagner
Digital definition played a key role in the swift rate of progress compared with previous programs. A series of Cray supercomputers racked up more than 650,000 hours of processing time on the design, more than for any other commercial jetliner, and differentiating the 7E7 from even the 777, which had pioneered digital design processes at Boeing. Unlike the 777, where digital design data had been converted into conventional drawings to be released to manufacturing, the 7E7 would remain digital throughout. “This aircraft is being digitally defined, and we will go straight from digital definition right to building the aircraft,” said Cogan.

Dassault Systèmes’ virtual design (CATIA) toolset, used on the 777 to great success, was updated for use on the 787. However, with CATIA the digital door had barely cracked open. Boeing saw endless possibilities for using an integrated digital data system to not only design the aircraft and check everything fitted together in a virtual 3-D world, but also for planning the tools that made the parts, the manufacture of the parts, and even product support. It was a radical approach that, in many ways, was the only way to achieve Boeing’s massively ambitious 787 undertaking and the shift to widely distributed global partners.

**DESIGNED FOR LIFE CYCLE**

The approach was called product life-cycle management (PLM), and was based on another software suite from the Dassault Systèmes’ arsenal called ENOVIA. This enabled enterprisewide collaboration, giving every partner access to 3-D digital models of parts, assemblies, and systems. To accompany this, the French company’s DELMIA software suite provided Boeing and its partners with a way to simulate and perfect 787 manufacturing processes before actually building tools and production facilities. With DELMIA for virtual planning and production, CATIA for virtual product design, and ENOVIA for collaboration, the digital assets Boeing would develop would be used across the 787’s entire life cycle, including sales, marketing, and even future derivatives. As the system included planning and layout of production lines using exact 3-D models of parts and assembly tooling, it was expected that the amount of rework, or tasks performed out of sequence, would be dramatically cut. But the dramatic events of 2007 were to prove that no matter how much digital support and planning were available, the unexpected was always lying in wait around the corner to upset Boeing’s plans.

But back in 2005 all this lay ahead, and the project was accelerating on track. “Right now we have about three gigabytes of the aircraft defined,” said Cogan, who added that the digital manufacturing environment created a communication “loop back” between 787 design and manufacturing engineers. This was put in to ensure that theoretically, no matter where they were, there was no risk of anybody committing to a design change only to discover it could not be manufactured, or that it needed costly changes to other components. Increased data handling capacity also dramatically speeded up the process of testing, and in most cases rejecting, different design renditions.
Whereas the 777 had pioneered the use of digital design tools, the 787 took this to a new level by using the same digital data set to design not only the baseline aircraft, but also the tools that made the parts and even the production line itself. Here a digitally derived graphic of the 787 final assembly line provides more than just a pretty picture.

This applied to both the structure and the aerodynamics, which were initially honed using CFD analysis. The result was that the design was more fine-tuned by the time large-scale wind tunnel work began. “We tested between fifty and sixty wings on the 767, and on this we will come in at about twelve wings. We aimed for 0.85 Mach and hit it right on the Mach number first time in the transonic wind tunnel tests,” Cogan said.

Systems work was meanwhile starting to ramp up significantly, and the more electric design philosophy was already taking the company in very different directions from anything developed before, recalled 787 systems chief engineer Mike Sinnett. “There has been a shift in the focus for all the teams to think about power, and power stability. We’ve all had to learn to be power engineers in some ways. In the past it was a stovepipe approach, with each looking after their own areas; but this way it is forcing a much broader view of the entire aircraft.”

Systems testing also reflected the federated development concept adopted for the 787 as a whole, with test work at locations around the world rather than just in Seattle. Tests of the aircraft’s powerful electrical generators, for example, were to take place at a laboratory set up by Hamilton Sundstrand at Rockford, Illinois. Additional power systems would be tested at labs elsewhere in the United States.

“With the 777 we did all of that integration at almost all levels, and now we’re trying to concentrate on a higher level of integration responsibility. The biggest difference is we’re linking together different labs around the world. We will still be running the systems integration lab in Seattle for the flight simulators, all avionics, the flight control system, and the Iron Bird [see chapters 5 and 8],” said Sinnett.

Definition of the 787-9 stretch, meanwhile, continued as part of attempts to satisfy the interests of Emirates, the influential Dubai-based carrier. “We still have some ‘trade space’ left on the 787-9, which could still change by a seat row or two,” said Bair, who added that size range was 259 passengers in a three-class configuration “plus ten or twenty, but even that’s kind of iffy.” Entry into service for the 787-9 was also provisionally brought forward to the end of 2010 following an important order by Air Canada.

More big-ticket wins were to follow, some strategically vital in the growing war with the Airbus A350 (see chapter 10). In April 2005 news emerged that Northwest Airlines, a major U.S. A330 operator, had selected the 787. Airbus had been optimistic of a breakthrough with Northwest with the A350, since the carrier firmed up additional A330-200/300 options. The carrier also had about sixteen A330-200/300s in service at the time of the decision and had roughly the same number due for delivery by 2007. The defeat was therefore particularly hard on Airbus, which had hoped the high degree of cockpit and systems commonality would provide a better incentive to Northwest.

By June 2005 the 787 was on a firm footing with growing airline interest and on track for firm configuration to be completed around schedule that September. “It’s been gratifying how the world is receiving the Dreamliner” said Walt Gillette, whose title had now grown to be vice president of engineering, manufacturing, and partner alignment. “Now our assignment is to deliver the goods. We have definitive agreements and proposals accepted for 261 aircraft from 21 customers. Of that 261, some 118 are firm, and we have active proposals for around 400 more aircraft out there, and that doesn’t include the possibility of options.”

By now more than eight hundred thousand hours of computing time had been amassed on the Cray supercomputers, while wind tunnel work was about 80 percent complete. Data from this latter work, mostly focused on the 787-8 variant, were used to develop initial flight control system software for the first flight simulators. The final round of wind tunnel work was scheduled for early 2006. “We will go back and do specific tune-up testing for the 787-3 and 787-9. It’s a pretty action-packed schedule, and it’s more like a continuous development,” said Gillette.
Boeing’s extensive wind tunnel test plan for the 7E7/787 covered fifteen thousand hours over three years and covered twenty different “campaigns.” These included four main high-speed tests in the Boeing transonic wind tunnel, five main low-speed test phases, four propulsion-related, and four noise-test campaigns. Powerful computational fluid dynamics design tools helped cut out a lot of preliminary work, reducing the number of final wing designs tested on the 787 to about a dozen, compared to about sixty on the 767.

Boeing set up a sophisticated and comprehensive test facility in the Integrated Aircraft Systems Laboratory for the 787. The “iron bird” at the heart of the integrated test vehicle (ITV) replicated all the flight controls of the real thing. The yellow-and-black-striped wheels in the center of this photograph represent the rudder and the left and right elevators, while to the left are hydraulic and electrically actuated flaps and spoilers. To the right are the horizontal stabilizer trim and minispoiler test rigs. Orange wiring is for test and monitoring, while white wiring is for flight hardware. Mark Wagner

Tests on the composite fuselage sections were also ramping up, with three test barrels completed, including two versions of the original aft fuselage Section 47, plus a constant diameter barrel that was representative of either a Section 43 or 46. “Now we’re working on a Section 41 (nose), and we will be doing six or seven such test barrels in total,” said Gillette, who added that the work of proving the material was essentially over. “From now on we are working on production efficiency basically. We’re through the baking process, and at the end of this we will build a big piece of barrel and an additional half a piece of barrel for certification of the mechanical join of the major sections.”

Test work also was under way on the first full-size structural wingbox, and involved tests on a representative outboard wing section, as well as a nine-foot-long center section unit. Fuji Heavy Industries (FHI) made the wing center section, while Mitsubishi Heavy Industries (MHI) provided the outboard wing, with Kawasaki Heavy Industries (KHI) adding the fixed structure.
Despite the decision to have the wing manufactured in Japan, final assembly was to be completed in Everett, with the addition of systems and Boeing-built trailing and leading edge moving surfaces. “We’ve traded on this one. Boeing traditionally did the wingbox on other wings, and the partners did the outside. This time it’s the other way around, and all the tests will happen here as well as the completion of all production wings,” said Gillette. MHI supplied ribs, stringers, and spars for the test unit, with Boeing providing the composite skins. Similar tests were also performed by Alenia in Italy on the first full-size horizontal tail structural box, and by Boeing at its Fredrickson site in Washington, where the vertical tail was being developed.

With external lines close to finalization, the development focus shifted to the cabin, flight deck, and systems. Of major significance was the flight deck, which, in keeping with the rest of the 787, was expected to be truly twenty-first-century standard. The outside world got its first formal look at the new flight deck in early September 2005 and was not disappointed. Dominated by five large flat-panel primary flight displays, the flight deck projected the look and feel of the 777 cockpit to enhance commonality and ease cross-crew familiarity and training. The most dramatic new features were dual head-up displays (HUDs) manufactured by Rockwell Collins Flight Dynamics. Using liquid crystal display technology, the HUDs were standard equipment.

Boeing banked on attracting new 787 orders as part of fleet modernization deals involving its older sibling the 777. Air Canada became one of several such multimodel contracts in November 2005 when it signed up for eighteen 777s and fourteen 787-8s, plus options for eighteen more 777s and forty-six 787-8s and 787-9s. In April 2007 Air Canada exercised half of its 787 options, taking firm orders to thirty-seven, making it the largest customer for the model in North America, and the third-largest in the world after ANA and Qantas. Originally set for 2010, planned delivery slipped as the program hit big problems in 2008.

The specially developed 787 systems integration facility at Hamilton Sundstrand’s Rockford site was meanwhile nearing completion. Engineers were testing the electronic links between the site and several suppliers that, working in conjunction with Boeing test engineers, would be able to conduct tests of the integrated systems remotely. It was through such advances that the 787 hoped to stay on track, despite the sophistication of much of the technology and the new territory being covered. “That’s how it’s balancing out,” said Gillette. “We’re doing a number of innovative things that a decade ago would have taken longer, but we’re able to compress time dramatically and essentially we’re doing more in a shorter time.”

And time was short. The first subassemblies were due “on dock” at Everett at the end of 2006 to allow flight tests to start in mid-2007. With the 787-3 and 787-9 variants hard on the heels of the 787-8, Boeing’s 787 design team knew they were in a race against time and that this was only the start of what was to become one of the most intensive and pressurized periods of development in the company’s history.
Chapter 4
GOLF, MISSILES, AND DREAMLINERS

It was a cold, bright early January day in Seattle in 2005 when the outside world got its first glimpse of a large piece of the Dreamliner’s radically new, composite fuselage structure. Gratefully exchanging the cold wind outside for the warm air inside Boeing’s Developmental Center by Boeing Field, the invited journalists stared for some seconds in silence at the blue-and-white-painted fuselage barrel sitting on its mobile tool fixture in a corner of the building.

This first view of any tangible part of the 7E7 was orchestrated by Boeing partly to prove that the new-technology twinjet and its large-scale composite materials were for real. The representative Section 47, an aft fuselage barrel, was the first all-composite one-piece development article and was to be followed by other large-scale test sections for different parts of the body.

“It’s the largest piece of pressure vessel carbon fiber ever made, and the first one like it in the world,” said Walt Gillette, standing in front of it like a proud new father. Stretching twenty-two feet long, and just over nineteen feet in diameter, it was selected for its challenging compound curvature as the best single unit to begin proving the process.

“This is a piece of aviation history,” said Walt Gillette about the first full-scale composite one-piece fuselage test section built to demonstrate the advanced production concepts that would define the 787. The twenty-two-foot-long, nineteen-foot-wide aft fuselage Section 47 incorporated advanced features such as co-cured stringers and was made from composite tape laid down by a computerized machine over a mold made from interlocking mandrels. The tape, presoaked in epoxy, was enclosed with caul plates and polymer bags and placed in the autoclave for curing. Under heat and pressure a chemical reaction transformed the composite into a toughened structure. This test specimen was later donated to Boeing’s Future of Flight Center in Everett. Mark Wagner

Based on the same fiber placement principle used by Raytheon in the manufacture of its composite-fuselage Premier I business jet, the test 7E7 fuselage sections would prove that the airliner could be successfully assembled from carbon fiber reinforced plastic (CFRP) tape laid down on a massive mold, or mandrel, by a computerized machine. The mandrel rotated as the tape was applied. Once completed, the entire structure was then wrapped, or bagged, and placed in the autoclave, a huge pressurized oven, for curing.

The piece looked huge and impressive, but despite its size Boeing deliberately played down the move to an all-composite fuselage and wing primary structure. The shift, it said, was an evolutionary, rather than a revolutionary, step. Chief Project Engineer Tom Cogan said, “It’s not really that much of a leap. We’ve been working with composite components for more than thirty years, and the reason we didn’t go for an all-composite aircraft in the past was cost.” He offered another intriguing perspective. “Think about it in reverse. If we built aircraft out of composites and wanted to go to aluminum, then we wouldn’t be able to do it. Why should you? It corrodes, it fatigues, and it needs more maintenance.”

Still, the skeptics were vocal and felt the decision to opt for an all-composite primary structure was a massive risk for a large airliner. Although predominantly composite aircraft such as the Premier 1 and Northrop Grumman B-2A had proved structurally sound, they argued that issues critical to commercial certification, such as crash-worthiness
and lightning protection, were not yet properly thought through. Airbus warned the airlines considering the 7E7 about the vulnerability of the material to accidental, everyday damage caused by collisions with baggage and catering trucks.

Ironically Airbus, which had played the technology trump card as its best way into the commercial market for the past thirty years, had itself pioneered much of the use of large-scale composite primary structure in production airliners. The A310-300 was the first commercial airliner to have a fin box made from composites, in 1985, and four years later the A320 was introduced as a composite-tail plane having an integrally stiffened carbon/epoxy laminate skin. In 1993 Airbus also introduced the A330/340, the wing of which was 13 percent composite by weight. The A380, with elements of the fuselage, wing, tail, and aft pressure bulkhead made from composites, took this even further, with more than 20 percent of its empty weight made from the material.

But modern composite materials in aerospace traced their origins well back beyond Airbus and Boeing to the late 1950s, when the Cold War was at its height. The United States was concerned that its intercontinental ballistic missiles (ICBMs) could be intercepted, and decided that higher reentry vehicle speeds were needed to guarantee delivery of their deadly nuclear payloads. However, higher reentry speeds meant higher temperatures, and a new material was needed to withstand the thermal shock. Research produced a ceramic/metal composite called Avcoite to do the job, and it was successfully tested on the U.S. Air Force’s new Minuteman ICBM. Carbon fibers also were developed at about the same period as reinforcements for high-temperature molded plastic parts on shorter-range missiles.

These first types of carbon fibers were made by heating strands of rayon until they turned into carbon. However, as the carbon content was only about 20 percent, they were relatively weak, and it was not until the 1960s, when the carbon content was boosted to about 50 percent by the use of a new raw material called polyacrylonitrile, that the first true potential of carbon fiber could be glimpsed.

A composite structure consists of fibers held together in some form of matrix, or glue. A tree, for example, is a composite structure because it is made up of cellulose fibers bonded together by lignin. A graphite or carbon composite similarly consists of carbon fibers consolidated together with a tough resin.

The individual carbon fibers are long, very thin strands about 0.0002 to 0.0004 inch (0.005 to 0.010mm) in diameter and composed mostly of carbon atoms bonded together in crystals. These turn out to be amazingly strong for their size because their microscopic structures are roughly aligned parallel to the long axis of the fiber. Twisted into a yarn, thousands of these fibers are combined to make a fabric that is then mixed with an epoxy, or glue, and wound or molded into whatever shape is required.

Although the strength and lightness of the carbon material had obvious appeal for aerospace, in these early years it was too expensive to use because of the low production volumes involved. It was the sports industry that came to the rescue, jump-starting production of carbon materials for use in golf club shafts, fishing rods, and tennis rackets. The sporting material of choice at the time was mainly graphite fiber, which has an internal structure close to that of graphite, a pure form of carbon. Boron filament reinforced epoxy also became widely used in sports equipment, although this was generally more expensive.

Although invar, an iron-nickel alloy, was the preferred material used for making large composite tools because of its controlled coefficient of thermal expansion, lighter mandrels better suited to lean manufacturing also were sought for the 787. Janicki Industries, a local yacht builder based in Seedro-Wooley, Washington, helped Boeing develop new mandrel technology. Spirit AeroSystems meanwhile selected bismaleimide (BMI), a high-temperature composite material from Cytec, for its mandrels, while others, such as Alenia, stuck with invar. Here the end of an invar mandrel is glimpsed inside the newly formed Section 46 center fuselage at Alenia’s Grottaglie site. Mark Wagner

The later 1960s also saw the introduction of higher-strength carbon and aramid fibers, as well as better
“prepregs,” a term for the fabric or tape made from the fibers already impregnated with glue. Unlike the high-cost boron-filament–based materials, this newer material could be cut with traditional steel tools and was cheaper to make (down to about $10 a pound versus $90 a pound for boron in 1960s dollars) and easier to use.

Although glass fiber-reinforced composites, mostly in the form of thin sheets sandwiching a honeycomb core, had found their way into secondary structures on commercial aircraft in 1960s in such areas as wing-to-body fairings and secondary control surfaces, it was not until the 1970s that things really began to take off as improved CFRP was developed. As with the push for more efficient engines, the first fuel crisis of the 1970s prompted NASA, among others, to begin a more serious look at structural composites for aerospace. Thanks to the sports industry, the commercial availability of carbon and aramid fibers also meant that the raw materials were more affordable.

Early civil uses included aramid/epoxy underwing fairings of the Lockheed L-1011 in the 1970s, and a carbon/epoxy aileron on late-production TriStars. McDonnell Douglas also introduced a carbon/epoxy upper rudder into the DC-10 as well as an aft engine pylon skin made from boron and aluminum.

Boeing initially used glass fiber/epoxy in the control surfaces, fairings, and trailing edge panels in the 747, and from the late 1970s, in the Kawasaki Heavy Industries (KHI)–made flap on the 747SP. Demonstrating considerable foresight, Boeing also developed and certificated a carbon/epoxy stabilizer for the 737-200 as part of the NASA Aircraft Energy Efficiency (ACEE) program, initiated in 1975.

Under this effort 5 1/2 shipsets were installed on the 737, and the modification received FAA type certification in August 1982. The composite design, which was 21.6 percent lighter than the equivalent aluminum structure, went into service in 1984 and was later analyzed by Wichita State University’s National Institute for Aviation Research (NIAR). Encouragingly, the analysis revealed few changes in strength and other characteristics after eighteen years and fifty-two thousand flight hours in service.

CFRP composites also were used for the elevator in later 727s and for spoilers on 737s from about 1973 onward. Composites featured more extensively on the 757/767 family of the late 1970s and early 1980s, particularly on the wing-to-body fairing, main landing gear doors, engine cowlings, trailing edge panels, spoilers, ailerons, rudder, elevators, and stabilizer fins. In most cases the materials used included CFRP, aramid/epoxy, and aramid-carbon/epoxy and glass-carbon/epoxy hybrid composites, similar to those being used by Airbus and by McDonnell Douglas on its MD-80 series. Almost all of these the parts were made up of sheets of composite co-cured or secondarily bonded to a composite honeycomb core.

Airbus had pioneered the use of large-scale composites for primary structure when it introduced a carbon-fiber-reinforced plastic fin and tailplane into the A310-300. The innovative design also ushered in the use of the tailplane trim fuel tanks for center-of-gravity control. Here an Air Transat A310-300 sweeps low over the beach seconds from touchdown at Sint Maarten in the Caribbean. Mark Wagner

**COMPOSITE FUTURE**

Boeing’s biggest move toward embracing composites on a more dramatic scale, however, came with the 7J7, which was a short-to-medium-range, low-operating-cost project aimed at replacing the 727. Begun in the 1980s against a background of steadily rising fuel prices, Boeing pumped every new technological innovation into the project, including GE36 propfan engines, new avionics, a fly-by-wire flight control system, and advanced structures. The 7J7 was therefore in some ways a bellwether for Project Yellowstone and the 7E7, particularly since the 7J7 had large-scale international involvement from Japanese aerospace (hence the “J”).
The 7J7 had an unprecedented 25 percent industrial workshare allotted to the Japanese group and was to have entered service in 1992. A key product of the 7J7 experience was the teaming arrangement between Boeing and Fuji Heavy Industries, which fabricated a full-size horizontal stabilizer test unit for the project. This was later tested for fatigue, static, and damage tolerance characteristics by Japan Aircraft Development Corporation (JADC).

A stepping-stone toward composites on the 787 was the Boeing-NASA ACEE program in 1975. Under this effort five 737-200s were fitted with an experimental composite horizontal stabilizer and placed into regular service in 1984. Composite NARMCO T300/5208 replaced standard aluminum in a co-cured, stiffened-skin structural box arrangement with I-section stiffener panels. The unit incorporated two titanium spar lugs bonded externally to a precured graphite-epoxy chord. Although one, a MarkAir-operated aircraft, crashed in bad weather in Alaska in 1990, all the others flew until retired. On inspection all the stabilizers were found to be in virtually perfect condition. Here the second test airframe, a Delta Express aircraft, taxies at Orlando International, Florida, in 1996. Mark Wagner

However, it was the FS-X, a Japanese fighter project, that helped both Mitsubishi and Fuji boost their composite wing structure and building experience. The FS-X was developed as a semi-indigenous replacement to the aging McDonnell Douglas F-4. The FS-X, which was later called the F-2, was led by Mitsubishi and based heavily on the General Dynamics (later Lockheed Martin) F-16 design but with several advancements, including use of co-cured composite structures in a larger wing. In this process, the wingbox and skin could be cured and bonded in a single process, a production breakthrough that would have massive implications for the 787 more than a decade later.

The 7J7 was meanwhile terminated by Boeing in 1987 amid airline concerns over propfan noise and other technical challenges, and the company refocused instead on further developments of the 737 and the 757 to counter the growing threat from the A320. But the legacy of the 7J7 lingered, and in some cases provided a technology bridge to the 777, which benefited from the early development work.

Experience gained on the 7J7 empennage, which represented the first significant use of a toughened-resin CFRP material, plus test results from an experimental Boeing-built, 767-size composite horizontal stabilizer, encouraged the company to go in this direction for the 777. The march of time also meant carbon fibers with improved strength and stiffness, such as Hercules IM7 and Toray T-800H, were now available as well as tougher matrix polymers.

In addition, Boeing had gained valuable experience with large-scale composite structure work under NASA’s 1989 Advanced Composites Technology (ACT) program, which aimed to improve the efficiency of composite structures and to reduce their manufacturing costs. The program aimed, very simply, to reduce air travel costs through the use of composite materials on commercial aircraft. Targets included a 20 percent cut in production costs and a 25 percent cut in weight compared to conventional aluminum structures.

Early on, Boeing’s research involvement was tied to the advanced composite fuselage side of the $130 million effort, while McDonnell Douglas focused on the wing. Long Beach, California–based Douglas Aircraft was interested in using the ACT-derived wing on several future projects, including a new-generation twinjet dubbed the MD-XX. However, Boeing assumed the wing work through the 1997 merger with McDonnell Douglas.

Buoyed by ACT and 717 work, Boeing homed in on a 777 design in the early 1990s that overall was 12 percent composite by weight. Most of this was in the tail, where the stabilizers (vertical and horizontal) were designed with composite main and auxiliary torque boxes. The main boxes were made from CFRP, with solid laminate front and rear spars, honeycomb sandwich ribs, and integrally stiffened laminate skin panels.

The main box spars and panels used a toughened-matrix CFRP material from Toray called T800H/3900-2, a direct forerunner of material that would later be featured on the 787. The auxiliary torque box and fixed trailing edges were GFRP or a hybrid glass/CFRP sandwich panel with aluminum ribs. In-service experience of the CFRP empennage plus that of the 777’s composite floor beams quickly proved that the widespread use of the material should not be a showstopper for the 7E7.

Following the game-changing moves during the buildup to Y-2 and the intervention of the Phantom Works (see chapter 1), the stage was set for the use of composites on the 7E7. The questions were how much, and what they
would be used for. The answers, when they first emerged at the Paris Air Show in June 2003, shocked the outside world. Not just the empennage but also the whole primary fuselage and wing structure was to be made of composites, representing a staggering 50 percent of the new jet by weight. Depending on the 7E7 version, Boeing said this would make it twenty thousand to forty thousand pounds lighter than its nearest rival, the A330-200. Yet the 7E7 would still be able to fly 1,700 nautical miles farther with the same load of about 250 passengers.

Originally Boeing intended assembling the structure in a conventional way, but using composite panels in place of metal sheets—the “black aluminum” approach. Gillette said that instead Boeing “took the challenge of understanding the properties of composites and decided to make the fuselage in one piece. It’s what composites really want.” The ovoid cross section of the new airliner was well suited to the use of the new material, he said. Unlike former Boeing 7-series designs, in which the intersections between the ellipses were contoured out with aluminum, composites allowed the entire one-piece section to be completed without any additional strengthening or filleting. “It’s fifteen to twenty percent lighter than aluminum, doesn’t fatigue and doesn’t corrode, and will require a lot less maintenance over the life of the program,” said Gillette. Stringers would be co-cured into the structure in the autoclave, and mechanically fastened composite circumferential frames, floor beams, and panels would run the length of the fuselage.

Mitsubishi’s composite wing know-how was perfected on the Japan Air Self-Defense Force F-2 attack fighter, a growth derivative of the Lockheed Martin F-16. The Mitsubishi-designed, graphite-epoxy composite lower-wing box structure included lower skin, spars, ribs, and cap, and was co-cured together in an autoclave. The wing, which had a Fuji-made upper skin, was the first use of co-cured technology in a production tactical fighter, and paved the way for the 787.

The 777 was the first production Boeing jetliner to use large-scale composite materials in the primary structure. The main torque box of the vertical stabilizer was a graphite-reinforced unit made up of front and rear spars, while the whole box was covered with composite skins. For reinsurance the
The company made the gutsy commitment to go to a single-piece barrel in late 2003, thanks to the “instrumental” influence of Frank Statkus, the former Joint Strike Fighter program vice president, who had recently been appointed vice president of advanced technology, tools, and processes. “We knew we would one day figure it out: the question was could we make it in time to meet the delivery schedule,” said Gillette. “The challenge was to understand a manufacturing plan that allows you to build them at a commercial rate,” he added.

By May 2004 Boeing announced that Tokyo-based Toray Industries, one of its main suppliers for composite materials on the 777, had been selected to provide its 3900-series toughened carbon fiber–reinforced epoxy prepreg material for the 7E7. Based on Boeing’s BMS8-276 specifications—regarded industrywide as one of the most exacting material standards—Toray planned to produce an array of toughened polyacrylonitrile-based fibers for the job. T800S was selected because of its applicability to high-rate manufacturing and its tensile strength of 853,000 pounds per square inch.

Toray had established a prepreg production facility in Tacoma, south of Seattle, in 1992 to support the large amount of composites needed for the 777, and immediately began to gear up to produce much more material to support all the global 7E7 partners. In all, it predicted a need for up to 35 tonnes of composite per aircraft, and began planning to set up new production sites around the world. Although Boeing’s buildup largely required a massive expansion in its prepreg production, the overall increase in composite use in aerospace and other fields prompted Toray to commit to boosting fiber production capacity to 30.65 million pounds by August 2007, up from 19.4 million pounds at the end of 2005.

In February 2007, as demand for the 787 continued unabated, Toray knew this would not be enough and announced plans to spend ¥55 billion ($450 million) over the next two years to expand the fiber production capacity at plants in Japan, the United States, and France. This effectively increased its production commitment to 39.46 million pounds per year, while prepreg production was to more than double, from approximately 125 million square feet per year to almost 363 million square feet per year.

New production lines were planned at its U.S. subsidiary Toray Carbon Fibers America, in Decatur, Alabama, and at its European subsidiary Société des Fibres de Carbone, in Abidos, France. New lines also were planned at its Ehime plant in Japan, while an additional prepreg production line with an annual capacity of 62.43 million square feet was announced for its Tacoma site. A new line with similar capacity also was planned at its Ishikawa, Japan, plant to support the 787 suppliers in Japan.

While structurally pushing the envelope with composites, the 7E7 system’s heritage owed much to the 7J7. Although dating to the 1980s, 7J7 technology included integrated electrical power generation and distribution, fiber-optic data links, fly-by-wire flight controls, an integrated flight management system, flat-panel cockpit displays, and the use of Ada standardized “high order” software. Named for Ada Lovelace, the daughter of the poet Lord Byron, credited with being the world’s first programmer by assisting British inventor Charles Babbage in the 1820s with his early “analytical machine,” Ada software was used in the 777 flight control system.

As Toray was being announced, other composite and metals suppliers were being selected. These included other
well-known names in the aerospace composites world, such as Cytec and Hexcel, as well as Alcoa and Russian titanium supplier VSMPO-AVISMA. Cytec was to supply a prepreg combining carbon fiber and a high-temperature bismaleimide (BMI) resin that could withstand the heat generated by the electrothermal wing anti-icing system. The material was to be laid on large preformed honeycomb sub-assemblies provided by Hexcel, and formed into movable leading-edge slats by Spirit AeroSystems at its Tulsa, Oklahoma, site. In the same midwestern city, Hexcel was to work with interiors specialist Nordam on codevelopment of the first composite window frame for any civil airliner using a new material dubbed HexMC. Hexcel also was to provide a myriad of smaller parts such as clips and brackets that, in former Boeing aircraft, were made from metal. It also supplied Goodrich, the selected engine nacelle maker, with HexPly 8552/AS4 prepregs and a new noise-reducing material called Acousti-Cap.

Cytec and Hexcel’s involvement in the 787 extended into other areas as well. Cytec, for example, provided a BMI-based composite mandrel for Spirit’s Section 41 barrel tooling, while Hexcel’s HexTool, a combination of carbon fiber and BMI resin, also was selected for several fabrication tools. Cytec’s toughened composite material, applied using the company’s resin-infusion system, became a key element in a vacuum-assisted resin transfer molding (VARTM) process used by EADS to make the aft-pressure bulkhead. The first all-composite component of its type ever used on a Boeing commercial aircraft, it was similar to the domed composite bulkhead EADS provided for the A380, and measured fourteen by fifteen feet. The VARTM process also was used by Australia’s Hawker de Havilland, part of Boeing, to produce the trailing-edge control surfaces, including ailerons, flaperons, flaps, spoilers, and fairings made from Hexcel structural carbon fabrics and resins.

Cytec was also to supply the fuselage assembly partners with a surfacing film that was spread over the skin after molding to reduce the amount of sanding needed before painting. As an intermediate barrier coating, it also meant that airlines could change the colors of the paint without necessarily having to sand all the way down to the composite.

**METALS FIGHT BACK**

Although most of the news about the Dreamliner put the limelight on the composite industry, the traditional aerospace metals suppliers also had reason for cheer. Although the switch to composites for much of the primary structure, previously the sole domain of aluminum, was an obvious concern to the metals industry, the 787 still contained 20 percent aluminum by weight, and the sheer production volumes would guarantee big business for suppliers such as Alcoa. The aluminum specialist was picked to supply its proprietary 7085 alloy, mostly used in areas such as wing spars and engine pylons, and the estimated content value on the 787 was close to that on the 767.
Titanium makes up to 15 percent of the 787, the biggest share after composite (50 percent) and aluminum (20 percent). It is the first major aerospace application of a new, stronger type of titanium alloy called 5553. To feed its increased appetite for this important metal, which is 60 percent heavier than aluminum but twice as strong, Boeing and Russian supplier VSMPO-AVISMA announced a joint venture in 2006 to machine titanium forgings for the 787. Under the 50:50 deal rough machining of forgings was performed in Verkhnaya Salda, Russia. Final machining and processing of the forgings were completed at Boeing’s Portland, Oregon, fabrication facility and by other machining subcontractors.

However, aware of the squeeze from composites and the growing use of titanium, Alcoa wanted to protect its turf and continued to study a higher-strength, lightweight aluminum-lithium (Al-Li) alloy as a potential future material. By 2007 it was working on Al-Li alloys for plate, rather than sheet, products designed to be machined to produce lighter, simpler monolithic parts. Alcoa believed this could provide Boeing with a weight-saving alternative to the strategically vulnerable titanium.

Alcoa also developed other crucial components for the 787 such as a titanium hydraulic adapter for the aircraft’s 5,000 psi system. Alcoa said the system provided 49 percent weight savings over previous designs. With a 15 percent share of the structure by weight, the new twin was easily the biggest user of titanium of any airliner. Compared to the larger 777, which required 139,000 pounds of titanium, and even the far bigger A380, which consumed 150,000 pounds per aircraft, the 787 would require about 250,000 pounds of the raw material per aircraft. The material had the advantage of being lighter than aluminum and more compatible with composites than aluminum, sharing a similar coefficient of expansion. Additionally, it did not corrode when in contact with composites.

A new grade of titanium, named 5553, was developed for the 787. To support the Dreamliner and ensure an uninterrupted supply of this important metal over the lifetime of the program, Boeing signed up with VSMPO-AVISMA to supply machined titanium forgings as part of a thirty-year commitment worth a staggering $18 billion.

**PREPARING FOR PRODUCTION**

By mid-2004 Boeing prepared to start transitioning all its preproduction and test work to its manufacturing partners. “We are now focusing on how to transfer all that into the 7E7 configuration, and how we translate it into specific parts of the wing and fuselage in manufacturing,” said Al Miller, who at the time was Boeing’s 7E7 director of technology integration and later became director of advanced technology.

The first one-piece contoured barrel (OPCB) test section was completed at the end of 2004, after which it was used to develop and test techniques for cutting out windows and doors, as well as painting processes. The structure also was used to verify overall integrity and featured several new design aspects, such as integral frames, stringers, and shear ties. Other test barrels were used to prove out production techniques, in particular, the potentially difficult process of detaching the cured fuselage structure from its supporting mandrel. Despite several issues (see chapter 9), the test sections more than proved their worth.

A similar test piece for the wing was meanwhile being made by a joint team from Boeing, Fuji, and Mitsubishi. Measuring approximately seventeen feet from the front to rear spar and fifty feet from the aircraft centerline to the tip, the half-span box section represented a portion of a representative full-scale wing. Four feet deep at the thickest section, the unit weighed 55,000 pounds, including test-only hardware and instrumentation. Mike Bair said the tests would help determine the basic strength of the structure. He added, “the tests we are running will help us to verify the analytical methods we have used to calculate the loads that the structure will have to carry.”

While tests continued through 2005 and early 2006, frantic building activity took place at the global partner sites as they hurried to get into position to meet Boeing’s production plan. A huge focus for activity was around the Japanese port city of Nagoya, where Fuji, Kawasaki, and Mitsubishi were all investing heavily in 787 production facilities.

Fuji’s new West Handa plant housed composite fabrication for its 787 wing center box work, while assembly was
performed in a newly erected 48,000-square-foot building in nearby Handa. “We decided to make a new plant here at Handa closer to the final shipping port,” said Fuji 787 Program Manager Yasuhiro Toi. The composite fabrication site, covering a floor area of about 29,500 square feet, housed a French-made Forest Line high-speed automated layup machine, water jet trimming and drilling machine, and nondestructive inspection (NDI) machines.

To verify the analytical models used to design the composite wing box, Boeing planned a special full-scale structural test in addition to the standard series of structural evaluations, culminating in the static and fatigue rig tests. Together with Fuji and Mitsubishi, engineers created a portion of the wing weighing 55,000 pounds and measuring 50 feet long and 18 feet wide at its broadest chord point near the root. The wing was all composite, with the exception of monolithic aluminum ribs, and a test of the wing to 150-percent ultimate load (completed in November 2008) revealed the need for design tweaks.

Aluminum side-of-body ribs are prepared at Fuji for integration with composite front and rear spars, skins, and spanwise stiffening members in the wing center box. The completed unit, known as Section 11, measured 17.4 feet long (fore to aft) by 19 feet wide by 4 feet deep. Mark Wagner

Sophisticated robotic automatic guided vehicles (AGV) chimed favorite Japanese karaoke tunes as they glided across the factory floor carrying immense sections from stage to stage. In the relatively quiet atmosphere of a composite factory (as opposed to the deafening rivet-gun cacophony of a conventional aircraft factory), these sounds were an important safety feature, warning workers of their otherwise silent approach.

The AGVs transported parts to and from the autoclave which, at twenty-three by twenty-three feet in length and diameter, was one of the largest of its type in the world.

Although an automated layup machine was eventually installed, the first six shipsets were manually laid up. “We plan to finish work on putting in this machine around July, and will have it producing the first automated parts in the September time frame,” said Fuji Boeing Project General Manager Hideyuku Sano in June 2006. “We also completed a [subscale] half box in early manufacturing trials at Utsunomiya [another Fuji site], which we sent to Everett for EME [electromagnetic effects] testing in September–October 2005.”

Fuji, like the other partners, was discovering that the major challenge was not making individual composite components, but developing processes to make them consistently and at a rapid rate. Toi admitted that during the buildup and testing of the skins “we have had a few problems, as usual, but no showstoppers. The most difficult part is making it a stable product for large-scale manufacturing.”
The cavernous mouth of Kawasaki’s huge autoclave awaits its next load. Measuring 65 feet 6 inches in length and 26 feet in width, the “oven’s” pressurized interior is sealed tight with a vast interlocking, sliding door. Mark Wagner

The completed wing center box had “a lower part count and fewer holes in it than a conventional article. It also does not need the extra strengthening usually required to fight fatigue,” he added, unaware that weight-saving redesigns had already introduced potential weaknesses that would only later be revealed during structural tests. Fuji also had to deal with the added pressure of being first to manufacture any of the major structural parts—the wing center box being at the very heart of the airframe.

“Our part is the first and has the highest loads,” said Toi, who added that the wing box was “similar overall” to conventional metal alloy structures but that “the detail is more sophisticated” to take advantage of composite materials with tailor-made thicknesses to provide strength where needed. Measuring 17.4 by 19 feet, the initial lower skin, completed in about early June 2006, was followed within a week by the upper skin. Compared with the 9.8-foot-long main landing-gear door that Fuji made for the 777, “this is also the biggest [composite] piece for us,” he said.

A few miles away, Kawasaki was busy preparing its new fuselage Section 43 manufacturing sites for the 787. “We are working night and day preparing the factory with the first delivery near at hand,” said Hirokazu Komaki, Kawasaki 787 program manager in mid-2006. “The most remarkable thing is the development of the OPB [one-piece barrel] section. In terms of manufacturing concept and scale, this has never been seen here before—it is a big event for Kawasaki.” The OPB effort was also challenging in terms of time, he added, saying a formal agreement was not signed with Boeing until as recently as May 2005.

Kawasaki was responsible for the main landing-gear wheel-well assembly (Section 45), and the fixed trailing edge, which was assembled from sections supplied by subcontractors throughout Asia. The first of these mostly metallic subassemblies was completed over the July–August 2006 period. The large assembly site, which formally opened in early July 2006, was completed by February 28 that year and contained a 26-by-65-foot autoclave, a shear tie fastening machine, and a panel fastening device for OPB assembly.

Mitsubishi meanwhile underwent a similar site expansion, with several plants across Japan contributing to the 787 wingbox effort. The bulk of the work was undertaken at a newly expanded part of the Oye site, a section of which by the Nagoya dockside was formerly occupied by the Mitsubishi Motors group. The site also was adjacent to the original design offices and assembly site that produced the A6M5 Reisen or “Zero” fighter during World War II. Here stringers longer than seventy-two feet were fabricated and co-cured with skins made in the same facility that also had responsibility for the final assembly of the complete wingbox. Mitsubishi’s Shimon Oseki site made all remaining wing stringers, while the company’s Hiroshima plant contributed parts for the autoclave. Shinmaywa, better known for its flying boats, was subcontracted to produce composite spars.

The 154,200-square-foot composite fabrication factory was completed in mid-April 2006, and incorporated a 26-by-131-foot autoclave to cure the 787’s long wing-box. Also including NDI, waterjet, and automated layup machines, the site was used to complete a成功的 fuel and seal test on a representative wingbox section in April of that year. Earlier tests, running back over two years, included tension/shear evaluations conducted in Mitsubishi’s Nagasaki site, and main landing-gear fitting strength tests at the company’s Kobe plant. To accommodate the higher loads, skins around the landing gear area were thickened to about 1.5 inches, compared to about 0.5 inch for most of
the remaining wing.

A few yards away, down by the brown waters of the Nagoya Harbor complex, Mitsubishi’s wharfside composite assembly factory was completed by the end of August 2006. From here completed ship-sets were loaded directly onto barges at the dock and transported downriver to the nearby Centair airport at Nagoya for shipment by 747 Large Cargo Freighter (LCF)—or Dreamlifter—to Everett. The site was sized to house up to ten assembly bays as well as four predelivery bays and a split-level area housing a moving production line on the upper floor for systems installation. Each wing consisted of main composite spars, skins, and up to eighteen composite stringers. The structure also included thirty-seven aluminum ribs, the largest of which were fitted to the wing center box.

The enormous traveling Mitsubishi mandrel for the lower skin of the right wing glides smoothly along, rolling so silently that it plays tunes as it goes to warn of its approach. The invar mandrel, weighing around 40 tons, was designed to be 102 feet long to accommodate the 787 wing and deposit the uncured skin directly in the 131-foot-long autoclave. Once cured, solid laminate wing skins were cut to shape using a powerful waterjet cutter built in the United States by Washington-based Flow International at its facility in Jeffersonville, Indiana. Waterjets were used because of their ability to cut thick laminates quickly without overheating the material. Mark Wagner

The upper center fuselage Section 44, undergoes assembly in Alenia’s Grottaglie site. Together with the Section 46 made alongside in the same facility, the 28-foot-long section would later be joined to the Kawasaki-made main landing gear wheel well and the Fuji-made center wing box at Global Aeronautica’s Charleston facility. Mark Wagner

ITALIAN JOB

A similar mammoth effort was meanwhile under way in southern Italy, where Alenia Aeronautica was gearing up to make large sections of the fuselage at its Grottaglie site, near Taranto. Here the company was to produce the center-aft fuselage Section 46 and mid-Section 44, which together made up about 60 percent of the fuselage. Section 44, the midfuselage section over the wings, measured 28 feet long, while the adjacent Section 46, farther aft, measured 33 feet long for the 787-8 family. The facility was sized to handle future stretches including the 787-9 and the later 787-10.

By mid-2006 Alenia was completing assembly of a massive main manufacturing building measuring 1,310 by 570 feet and about 79 feet tall. Covering 230,000 square feet, the stylish building included a 56-by-118 foot automated fiber placement machine made by Rockford, Illinois–based Ingersoll Machine Tools, and a 28-by-64-foot
autoclave described by the company as the largest in Europe. The cavernous site was completed later in the year as it prepared to begin work on a preproduction fuselage before starting assembly of the first production unit in the first quarter of 2007.

Outside the site, which required 20,000 tons of structural steel and 1.76 million cubic feet of concrete, the main runway at Grottaglie was being almost doubled in length, to 9,800 feet, to handle the Dreamlifter. Work on this project was originally due for completion in December 2006, with the first landing of the Dreamlifter expected in the middle of that month, but progress was briefly held up over the uprooting of ancient olive groves at the end of the runway. The majority of the old trees were later replanted around the Taranto region.

Workers at Grottaglie complete the 33-foot-long center fuselage Section 46, which contains about four thousand pounds of carbon-fiber material. In March 2007 Alenia shipped the first complete fuselage center Sections 44 and 46 to Global Aeronautica. Note the longitudinal “top hat” stringers, which were comolded with the fuselage skins, and the frames, which were connected to the skins with mechanically fastened shear ties. Frames and shear ties were supplied from Alenia’s Pomigliano site, while some machined parts came from a plant at Nola. Mark Wagner

Building on skills developed for the 777, which involves the routine assembly of the 46-foot-long composite flap section at Alenia’s Foggia plant, the company produced a fully co-cured solid laminate monolithic part for the horizontal stabilizer some 33 feet long—the largest monolithic structure ever produced for a commercial aircraft. Initial preproduction units were completed in the third quarter of 2006, and assembly of the first production horizontal stabilizer followed by the start of December 2006, with initial deliveries set to start in early 2007.

Work was also well under way at Spirit Aerosystems, a former Boeing facility responsible for producing the Section 41 nose in an all-new facility in Wichita, Kansas. Describing the 113,000-square-foot site as “one of the most advanced in the world,” Spirit 787 Section 41 Facility Director Forrest Urban added in April 2007 that “there were a lot of skeptics in the world who didn’t believe this could be done.”

Ingersoll double-headed fiber placement machines applied composite plies over the Section 41 barrel mounted on a rotating mandrel made from interlocking segments. The 42-by-21-foot barrels were cured in a 70-by-30-foot autoclave built and installed by California-based Thermal Equipment. Following baking in the autoclave, sections were removed for nondestructive testing using an automated ultrasonic scanning system before passing to the next bay position for the cutting of door frames and windows, and the addition of frames for the support of cockpit windows, as well as the floor and nose gear.

Unlike previous Section 41s, all built at what was Boeing’s Wichita division until the commercial operations were sold to become Spirit in 2005, the 787 worked involved a lot more completion in Kansas. As well as the nose undercarriage, Spirit also was responsible for the installation of the full flight deck, including controls, wiring, displays, and the avionics in the electronics bay—all items previously installed during final assembly either at Renton or Everett. John Pilla, Spirit’s 787 vice president and general manager, said, “we’ve been ‘stuffing’ planes for more than ten years, but this is a first for us.”
A Brotje automated frame riveter drilling machine at Spirit AeroSystems is guided by sensors to within plus or minus 0.002 inch for drilling holes for frames, sheer ties, and door and flight deck window surround structures. Each Section 41 is rotated twice using the blue fixture that holds the barrels in place. Mark Wagner

The pace was just as frantic at Charleston, South Carolina, where Vought and its joint venture with Alenia, Global Aeronautica, had set up shop for the 787 program. The site was first selected in September 2004, and clearing of the dense wetland area began in March 2005 with the removal of vegetation and its associated banana spiders, snakes, and alligators, said “Newt” Newton, the company’s vice president and deputy general manager.

The site was built to integrate, align, drill, and join together the bulk of the fuselage, including the aft Sections 47/48 from the adjacent Vought site, as well as the Kawasaki-built Sections 43 and Fuji-built Section 11/45 fuselage parts from Japan, the Alenia-built Sections 44/46, and the Boeing Winnipeg-built wing-to-body fairings from Canada.

All were to be put together in the new 106,000-square-foot assembly and integration building, which involved the pouring of more than 1.21 million cubic feet of concrete and the use of 5,380 tons of steel.

Including workers in Dallas, Seattle, and Texas, the Global Aeronautica workforce was expected to reach about four hundred “as we reach rate,” said Newton. Initial preproduction units, using simulated dummy sections, were test-fitted together in the fourth quarter of 2006, with the first of the real fuselages due to start passing through in the second quarter of 2007.

“The biggest concern is that we’re able to orchestrate the ‘dance’ of all the parts arriving for the first aircraft, and not letting them get out of sequence. Traditionally, it has taken us several aircraft to get it right, but we need to get it right pretty early,” said Newton, who was cautioning in mid-2006 that delays and hiccups were possible. “We’re all victims of human nature and sometimes you have got to expect delays.” Newton’s words were to prove prophetic in the year to come.

Vought installed Cincinnati Machine automatic fiber placement devices such as this to robotically apply layers of graphite epoxy to contoured surfaces on Sections 47 and 48. Reinforcing fibers are oriented in specific directions in the resin prepreg to deliver maximum strength only in the direction needed. Mark Wagner

A few yards away, the new Vought site also was gearing up to begin assembling the all-composite, and reasonably complex, aft fuselage sections in its new 108,000-square-foot building. Some 21,300 square feet of the site were dedicated to a composites manufacturing clean room, while the California-based ASC Process Systems autoclave was one of the world’s largest by volume, measuring 76 feet by 30 feet in diameter. The site also included Cincinnati Machine automatic tape layers, PAR Systems trim and drill machines, and Brotje-supplied automatic
riveters. As with the other main 787 composite structure suppliers, a MTorres-built numerically controlled ultrasonic NDI machine checked for voids, porosity, and delaminations.

Production of the first articles began in the summer of 2006, with the first set of fuselage sections completed in the first quarter of 2007. To ease the transition, the first seven shipsets were joined in the Vought site (rather than the adjacent Global Aeronautica site) to reduce to duplicate training.

The scene was set, therefore, for one of the most remarkable industrial collaborative ventures in the history of aerospace. As the reels of composite tape began to unwind, and autoclaves were heated up around the world, the biggest question of all was whether these parts could really come together in Everett ready for final assembly in time, in the right configuration, and in the right order.
Chapter 5
SYSTEMS ADVANTAGE

New jetliners, particularly game-changing designs, always take advantage of the very latest systems technology to further their competitive edge. The 747 introduced new navigation sensors and unprecedented levels of systems redundancy, while the A320 ushered in fly-by-wire flight controls for commercial airliners. The 777 meanwhile introduced an unparalleled suite of integrated avionics.

The 787 was to introduce more new systems technology in one go than any Boeing since the 747, not simply because the time was right, but also because every part had to play its part in the battle for efficiency. From Sonic Cruiser days onward, what went on inside the new design was just as important as the shape of the design or the operation of the engines.

Systems work transcended the shift from Sonic Cruiser to Super Efficient and 7E7 like no other aspect of the project. Both aircraft required twenty-first-century technology, and both needed the very latest ideas to improve efficiency: the Sonic Cruiser to maintain parity with the 767, and the Super Efficient to minimize operating costs. In recognition of the potential savings, Boeing’s 7E7 systems design group was empowered like none before it. “We tried to approach it without regard to functions, and asked ourselves how we could do it more efficiently,” said 787 systems director Mike Sinnett.

Third-generation flight deck displays, 50 percent larger than those on a 777, were perfected in Boeing’s E-CAB 1 (engineering cab). Like other elements of the elaborate test setup, the E-CAB was more than just a simulator and could operate in two test modes: one with actual aircraft equipment and the other with flight control software. New flight deck features included an LCD tuning panel for several systems, including VHF/UHF radios, transponders, the enhanced ground proximity warning system, and the weather radar.

“...In the past, systems have kind of come along for the ride. We’ve never really made big functional improvements in systems over the past forty years. They’ve gotten better, but they’ve not made big leaps. This time we’ve looked around for revolutionary leaps.” The bottom line, added Sinnett, was “solely based on would it mean more economic energy extraction at cruise, where you spend most time? That’s how to dictate the architecture of the aircraft, because that’s how you become more efficient.”

Starting from scratch, the team turned its back on convention. “Typically we’d approach the aircraft from an ATA (Air Transport Association) chapter perspective (a traditional industry-adopted breakdown of the aircraft into component systems). But from a first-principles perspective we were able to set aside all our more typical prejudices,” he added.

The first clues to just how different this approach would be came in June 2003, when Boeing announced the 7E7 Systems Technology Team, which involved partnering with more than twenty international suppliers to develop technologies and design concepts for the new twinjet. The twist was that simply winning a place on the team did not automatically qualify the company for a place on the aircraft, and all would have to compete to become ongoing...
Just as we brought the world’s best materials and aircraft structures experts together to help evolve materials and aircraft structures technologies, we have assembled a team of systems experts to help us understand the possibilities and best choices for systems on the 7E7,” said Walt Gillette, vice president of engineering, manufacturing, and partner alignment for the 7E7 program.

Members of the Systems Technology Team included ECE Zodiac, Messier-Bugatti, and Thales from France; Diehl and Liebherr-Aerospace Lindenberg from Germany; Teijin Seiki from Japan; FR-HiTemp, Smiths Aerospace (later part of General Electric), and BAE Systems from the United Kingdom; and Connexion by Boeing, Crane Aerospace, Fairchild Controls, Goodrich, General Dynamics, Hamilton Sundstrand, Honeywell, Matsushita Avionics Systems, Moog, Parker Hannifin, Rockwell Collins, and Triumph Group from the United States.

The team was tasked with creating systems approaches that were “open and elegant.” An open-systems approach would allow systems to stay in lockstep with the latest technological advances. “We expect to deliver 7E7s well into the 2030s and 2040s,” Gillette said. “The pace of technology improvements is increasing year after year. Anticipating the need to incorporate improvements, even if we don’t know specifically what they will be, means we design the airplane to be flexible and adaptable. This will make it a more valuable asset.”
Sundstrand’s APSIF site, the AEM exercised the aircraft’s full and complex power system—probing it primarily for power quality and seeking out potential problems. Mark Wagner

In the end, after competitive bids and several down-selects, a team of just over thirty major (Tier 1) companies was created to develop the systems and structures for the 787, compared to hundreds on previous efforts. Under the new system the partners performed far more of their own design, development, and manufacturing while working closely with Boeing’s Life Cycle Product Team (LCPT) organization.

A total of eight major LCPTs were created covering the fuselage, propulsion, services, interiors, production, integration, and systems, and one for the wing, empennage, and landing gear. “Each is responsible for the entire life of that part in the aircraft,” said Sinnett who led the systems LCPT. “In previous programs I’d have had responsibility for the engineering design, then I’d have turned it over to production.” Beneath each Tier 1 name was a subset of suppliers to the particular part or system being provided by that team. This fundamentally different approach made Boeing more of a product integrator, and allowed it to focus on its prime role of final assembly while permitting its partners to focus on their expertise in developing subassemblies and systems. In another departure from the past, the LCPTs also formed a Partner Council, which held meetings to share progress and expertise to help overcome problems.

**ELECTRIC JET**

By far the most radical step in the 787 systems story was the decision to make it the most “all-electric” jet ever developed. “It’s probably the biggest change to the systems architecture of any aircraft,” said Sinnett, who explained that the move was made mainly to improve engine efficiency. A myriad of systems normally powered by air bled from the engines were instead electrically powered.

“Our aircraft does not draw as much horsepower off the engine in cruise so it doesn’t burn as much fuel. If you look at the extraction profile you see the amount of power you pull off is just what you need, so the engine isn’t working any harder than it needs to. We’re only getting what we need, and we only use what we generate,” said Sinnett. This was no easy trick to pull off. Even the highly sophisticated “more electric” systems on the Lockheed Martin F-35 Joint Strike Fighter, the first new-build Western fighter design of the twenty-first century, could not do this and instead dumped excess energy into its fuel, which acted as a heat sink.

In keeping with the more-electric-systems theme, an electrically based deicing system developed for the rotor blades of the Bell-Boeing V-22 Osprey as well as for the AgustaWestland AW101 was selected for the 787. Here a V-22 dazzles the crowds at the 2006 Farnborough Air Show. Mark Wagner
Gear actuation was software-controlled rather than mechanically linked, enabling faster extension and retraction sequencing. This also helped cut drag and therefore could be factored in as a weight benefit. The landing gear actuation package includes an emergency, 3,000 psi alternative landing gear deployment system that opens the doors, releases various actuators, and then locks into position, all within seconds. The gear actuation system, along with the rest of the main landing gear, also was later tested in the landing gear actuation system (LGAS) test rig at Everett. Mark Wagner

Although the 787 main gear uses Boeing’s classic double-brace design, the braces themselves are made from composite materials—another first for a commercial jetliner. Together the two-part drag brace and side brace help spread the impact loads at the gear anchorage points where they attach to the composite wingbox. Based on a Messier-Dowty–developed woven fiber composite manufacturing process, the parts are made by U.S.-based Albany Engineered Composites using Hexcel IM-7 fibers and resin infusion by Aircelle in Le Havre, France. Mark Wagner

Conventional pneumatic systems on commercial aircraft also had this problem and frequently dumped spare power overboard. Boeing therefore reasonably assumed that the more-electric systems would extract as much as 35 percent less power from the engines. It also expected lots of weight saving, as the pressurized air ducted around the aircraft through valves and precoolers weighed hundreds of pounds.

But the savings were in more than just weight. In the no-bleed architecture, electrically driven compressors provide cabin pressurization, with fresh air brought on board via dedicated cabin air inlets. Boeing predicted that this
approach would be significantly more efficient because it avoided excessive energy extraction from engines with the
associated energy waste by precilters and regulating valves. Instead, the compressed air was produced by adjustable
speed compressors at the required pressure without significant energy waste. That resulted in significant
improvements in engine fuel consumption. The engines also would be started electrically rather than pneumaticly. “We have a unique way to tailor torque for the starter motors, and use it for the power that the engines want to see,” said Sinnett. “Each needs a different torque profile, and with conventional engine starting coming from the high-pressure bleed valve we just give the engine everything we’ve got. This way the torque can be softer, quicker, and will also require less maintenance.”

But if this was such a great idea, why hadn’t it been done before? The answer largely lay in the state of the art of
the generators that extracted power from the engines. Previously these were relatively big, cumbersome devices, but
improvements in “power density” over twenty years had changed that. The two 250kVA generators fitted to each
787 engine, for instance, took up only slightly more room than the single 120kVA unit installed on a 767 engine.

As well as being used to start the engines, electrical power on the 787 replaced virtually all the traditional
pneumatic system and drove the environmental and cooling systems, moved the undercarriage legs, controlled the
brakes, and ran the anti-icing system. Power sources for the electrical system were engine-driven and APU-driven
generators, while the power sources for the hydraulic system were engine-driven and electric-motor-driven hydraulic
pumps similar to those in previous aircraft. A small amount of engine bleed air survived, however, and was used for
engine cowl anti-ice and nacelle heating as well as to help maintain operational stability in the engine.

Because it had to perform so many tasks, the 787’s hybrid electrical system was designed to handle several
voltage types: 235 volts alternating current (VAC), 115 VAC, 28 volts direct current (VDC), and ±270 VDC. All
Boeing’s conventional aircraft had 115 VAC and 28 VDC electrical systems, but the company was going into
relatively new territory with 235 VAC and ±270 VDC. Both were the consequence of the decision to go to the “no
bleed” electrical architecture.

Overall, the 787 generated twice as much electricity as previous Boeing airliners, including the 747. It did this
using a gang of six generators: two per engine and two on the tail-mounted APU. Although the four engine-mounted
were rated at 250kVA and the two APU-mounted at 225kVA, all operated at 235 VAC for reduced weight. The
generators were directly connected to the engine gearboxes and, to cope with the widely varying engine speeds on
the ground and in flight, operated at a variable frequency (360 to 800 Hz). Variable frequency was chosen over the
traditional integrated drive generator (IDG) concept because it was simpler, and therefore likely to be less of a
maintenance burden on the airlines that had pressed Boeing on the point.

With so much electrical power to share, the electrical system was split between two electrical/electronics (E/E)
bays, one forward and one aft. Just as importantly, it also included remote power distribution units (RPDU), which
acted like substations on a power grid to support various electric systems. The RPDU themselves represented a step
into the future and were based on solid-state power controllers (SSPC) instead of the traditional thermal circuit
breakers and relays.

The “smart” electrical distribution system, for which Boeing was awarded a patent in December 2003, comprised
a data communication network, power distribution panels, and the RPDU themselves. Throughout the flight the
RPDU were designed to “read” load connectivity from the power distribution panel. This was programmed to
memorize how much power particular systems required for each phase of the flight, which enabled the RPDU to
directly control electrical power to individual loads.
The true brains of the 787 reside in dual common computing resource cabinets that together form the common computing system (CCS). Developed by the former Smiths Aerospace before its takeover by GE, the CCS often is described as the 787’s central nervous system. The cabinets host processing and power control modules, along with network switches. Application specific modules, provided by third parties specified by Boeing, are installed in the cabinets. A second element of CCS is Rockwell Collins’s common data network (CDN), a fiber-optic Ethernet that connects all the systems that communicate with the CCS and with each other. The CCS also includes remote data concentrators (RDCs) that concentrates analog and digital signals from the remote sensors and effectors and put them onto the network. Mark Wagner

While some of the 235 VAC electrical system was supplied from the aft E/E bay, the bulk came from the forward E/E bay and RPDUs. Power for many of the systems previously operated by pneumatics came from a ±270 VDC system, which fed several large-rated adjustable-speed motors. These controlled the cabin pressurization compressor motors, the ram air fan motors, the nitrogen-generation-system compressor used for fuel-tank inerting, and large hydraulic pump motors. The system was supplied by four auto-transformer-rectifier units that converted 235 VAC power to ±270 VDC. The electrical system also included two 115 VAC external power receptacles to keep the 787 powered up on the ground if the APU was not running. Another two 115 VAC external power receptacles aft also were provided for any maintenance activities that needed the large high-speed motors.

Given the unprecedented importance of the electrical system to the entire program, it was among the first to be put out to competition. Hamilton Sundstrand was named as the main winner, with responsibility for three of the four main work packages, including the electrical power generation and start system; the remote power distribution system; and, in partnership with Zodiac, the primary power distribution system. The remaining package, the power conversion system, was awarded to Thales.

Integrated into the Hamilton Sundstrand’s electrical power generation and start system were electrical load control units (ELCUs) developed by Zodiac Group member Intertechnique. The ELCUs optimized the load to suit the power demands, and were controlled by a software and hardware system that worked at predefined microsecond intervals using a concept called time-triggered protocol (TTP). Developed by Austria-based TTTech, this involved a continuous communication between all connected nodes via redundant data buses to ensure that overloads in the bus system were prevented even if several demands occurred at once.

Honeywell flight control software was tested on a leased American Airlines 777-200ER under the controls validation and risk-reduction (CV/RR) program. “We found problems we hadn’t expected, and some we did expect,” said Systems Vice President Mike Sinnett. Trailing edges were varied to mimic the
drooped aileron and trailing-edge variable camber (TEVC) system, the first practical commercial application of an in-flight variable camber concept that operated by deflecting the trailing-edge flaps in 0.5-degree increments while in cruise. The TEVC was meant to reduce cruise drag, saving the equivalent of almost 1,000 pounds. Tests also helped simulate the increased wing twist angle of the 787.

Mark Wagner

Boeing tested a “smooth ride” vertical and lateral gust suppression system using the M-CAB multipurpose generic motion flight cockpit simulator. A set of static air data sensors detected pressure differentials created by the onset of turbulence and fed flight control system commands to the ailerons, spoilers, and elevons that compensated for the motion. The goal was to avoid inertial, roller coaster responses and instead to ride through the turbulence by damping out the motion. The result, said Boeing, was a ride that felt more like riding in a fast car over cobblestones than the large amplitude, lurching upheavals normally encountered.

Mark Wagner

The GE Aviation high-lift actuation system powered, actuated, and monitored the flap and slat system, as well as repositioned the trailing edge surfaces during operation of the Variable Camber system during flight, to reduce drag. Moog provided the primary flight control actuation system on all of the flight control surfaces, as well the spoilers and horizontal stabilizers. Each wing packed nine electrohydraulic servo-actuators with integral control electronics, as well as two simplex electromechanical actuators and two motor-drive controllers. An electrical backup for actuation system for both the leading edge slats and the trailing-edge flaps was developed by Sweden’s Saab Avitronics.

Mark Wagner

Boeing’s determination to embrace a more electric architecture became clear in 2004, when it awarded the U.K.-based companies Ultra Electronics and GKN Aerospace the role of developing an electrically powered wing ice protection system. This traditionally had been performed using hot bleed air from the engines that was ducted along
the wing’s leading edge via a “piccolo” tube.

In these conventional systems, the spent bleed air was exhausted through holes in the lower surface of the wing or slat. However, the 787 became the first commercial aircraft application of an electrothermal system originally used on the blades of military rotorcraft such as the AgustaWestland AW101 and the Bell Boeing V-22 Osprey. The system was made up of several electrically heated elements contained within a sprayed metal matrix bonded to the inside of the leading edges by a polymer composite material. The heating blankets were designed to be energized simultaneously for anti-icing protection or sequentially for deicing to heat the wing’s leading edge.

Boeing predicted that this method was significantly more efficient than the traditional system because no excess energy was exhausted. As a result, the required ice protection power usage was approximately half that of pneumatic systems. Moreover, because there were no bleed air exhaust holes, airplane drag and noise reduction were also expected to improve. “It turned out to be a good system for us, mostly because it protects the efficiency of the aerofoil shape with high integrity,” said Sinnett. “There are multiple zones for each leading edge section, and in case of a failure, we’d only lose coverage of around one sixth of one slat.” An added benefit is “we can also do this with around half the power that we’d need to deice pneumatically.”

Early trials of the concept in Boeing’s own research anti-icing tunnel in Seattle led to some tweaks in the configuration but otherwise confirmed the baseline design. “We altered the design a bit on the heating blanket, which has now been moved further aft on the underside of the leading edge of the slat. We ended up extending the coverage on the slat by around two inches to reduce the ‘run-back’ ice, so we are basically carrying the heat back farther,” Sinnett said.

**BRAKE-BY-WIRE**

Just a month before the electric ice protection news broke, Boeing awarded contracts for another radical electrically based system, brake-by-wire. The 787 became the first ever commercial jetliner to have electric brakes in place of the conventional hydraulically actuated brakes. Two suppliers, Goodrich and Messier-Bugatti, were set up to compete for the digitally controlled system, which included the aircraft’s eight main wheels, electromechanically actuated carbon brakes, and the controlling electronics package.

Although potentially a risky development, electric brakes offered weight and efficiency savings, as well as fitting better with the company’s modular assembly plans. In particular, by helping dispense with the need for installation and test of hydraulic systems, Boeing believed electric brakes would save time during assembly and test.

Being digital, the system also offered operators the benefit of inherent monitoring and self-checking capabilities. Better reliability was expected because it had fewer parts than a similar hydraulic brake system. If something did break, its modular design meant specific parts could be replaced on the ramp without necessarily having to remove an entire brake assembly.

Although new to the jetliner world, brake-by-wire technology had been tested in the 1990s on a USAF-led program involving an F-16 test aircraft. Goodrich developed the first fully integrated electrically actuated brake system for later versions of Northrop Grumman’s RQ-4B Global Hawk unmanned air vehicle. For the 787, Goodrich’s Troy site in Ohio supplied wheels and brakes, with its actuation systems unit in Cedar Knolls, New Jersey, providing the electromechanical actuators (EMAs). These replaced the hydraulic pistons used to supply clamping loads to the aircraft’s brake discs. Goodrich’s fuel and utility systems unit developed control software.

Messier-Bugatti, in association with Sagem, developed a brake-by-wire system that the company believed marked “as much of a breakthrough for airlines as was the advent of carbon brakes some twenty years ago.” The Messier-Bugatti system involved a power supply, brake control, and the electric brake itself, all of which are connected to an electric brake actuation control (EBAC). The unit comprised an electric motor, reduction gear, ball screw and nut, and rotor and stator carbon discs, and converted electrical signals into commands and drove the brakes. Tests were performed at Villeurbanne, the center near Lyon, France, responsible for R&D and carbon disc production for aircraft as well as for Formula 1 racing cars.

GE Aerospace was responsible for the brake control and monitoring system, one of three main work packages under an integrated landing gear system contract awarded in 2004. The brake control was a wireless-based system that picked up wheel speed and pressure information, and combined it with rudder pedal, throttle positions, and other sensor data to instruct the brakes what to do. GE also developed the nose gear steering and landing gear actuation systems as well as high-lift actuation systems. Gear actuation was software-controlled rather than mechanically interlinked, reducing closing and opening times.

The landing gear actuation package included an emergency, 3,000 psi alternative deployment system. The high-lift actuation system powered, actuated, and monitored the flap and slat system and included power drive units, a transmission system, and rotary actuation and braking devices.
The nose and main landing gear were developed by Messier-Dowty, the win being its first prime contract with Boeing on a commercial program. The design was the first of its type to make extensive use of titanium and composite. The inner cylinder of the main landing gear was made from titanium, “and that’s a first,” said the company’s vice president, Grant Skinner. The main gear’s side and drag braces were made from composite, also an industry first. “It was something we proposed to Boeing up front, though on our original design it wasn’t composite,” he explained, saying that Boeing’s search for additional weight savings led to the subsequent design revision. The braces, although far lighter than conventional metallic equivalents, were slightly bulkier. “It’s a bit like the difference between a steel and a composite mountain bike. The tubes are thicker on the nonsteel version because of the different strength-to-diameter ratio,” Skinner said.

The inner landing gear cylinders were to be made in Bidos, France, while in Gloucester, United Kingdom, the truck beam or bogie would come together; and in Montreal, Canada, the outer cylinder of the main gear fitting took place. Titanium brake rods for the main landing gear were built at Messier-Dowty’s Suzhou site in China. First metal for the inner cylinders was cut in France in November 2005, and machining of the first truck beams took place through 2006 in Gloucester, and of the main fitting in Montreal. Initial shipsets were assembled in Gloucester, but eventually transitioned to a final integration facility by the Everett site, where all the actuators, wheels, brakes, and other parts would be added before it was “rolled” as a complete subassembly to the production line.

Japanese manufacturer Bridgestone was picked to supply nose and main landing gear radial tires incorporating a new belt structure with “a high-elasticity, high-strength cord that is weight-efficient and wear-resistant,” said Boeing. A second tire supplier also was expected to be certified.

While much of the advanced technology focus was on the electrical systems, significant improvements also were made in more traditional areas, such as hydraulics and fuel. The Parker-developed 787 hydraulics operated at a high pressure of 5,000 psi, compared to the 3,000 psi of most previous systems.

It was made up of three independent systems—left, center, and right, with the center powered by a pair of large electrically driven hydraulic pumps in place of the usual air turbines. The pumps on the center system had capacity for 30 gallons per minute at 5,000 psi and were designed to split duties, with one running constantly and the other kicking in just for peak demands, such as landing-gear or high-lift-system actuation.

Among them the three systems collectively powered the primary flight control actuators, as well as landing gear actuation, nose gear steering, thrust reversers, and the leading and trailing edge flaps. Power for the left and right systems was mostly provided by engine-driven pumps mounted on the engine gearbox, backed up by an electric-motor-driven hydraulic pump for peak demands and for ground operations. As with the A380, A350XWB, and Concorde, the higher-pressure system saved both space and weight on the 787, as it allowed the use of smaller hydraulic components.

In early 2006 Parker ran the first production configuration hydraulic pump at its design ratings of 5,000 psi with zero load, and 4,750 psi at full flow, marking a crucial step toward full-up testing and production go-ahead. Parker supplied the entire hydraulic subsystem through its Kalamazoo, Michigan–based Hydraulic Systems Division. The
The company’s Nichols Airborne Division supplied liquid-cooling pumps and reservoirs for Hamilton Sundstrand’s primary electronics cooling air management system and “smart pumps” for the Hamilton Sundstrand APU.

The 787-8 fuel system was designed to have a maximum usable fuel volume of some 33,530 U.S. gallons, and a maximum weight at takeoff of 480,000 pounds. Goodrich provided the fuel quantity indicating system (FQIS), which sensed the density and level of the fuel in wing and center tanks. It also developed software for the fuel system as well as for the proximity sensing system, which monitored the position of the landing gear, fuselage doors, cargo doors, and thrust reversers. The system included 136 proximity sensors located throughout the aircraft, 6 data concentrators that digitized the sensor data, and a software package that provided position status and health information to the flight deck displays.

Meanwhile, Eaton-owned FR-HiTemp provided pumps and valves for the fuel system to FHI and MHI in Japan for installation in the center and wing tanks, respectively. The fuel system pump and valves package included 47 different part numbers and 216 components, and included electrically driven pumps using twice the voltage of previous commercial aircraft. The company’s HiTemp team also teamed with Hamilton Sundstrand and Carleton on the nitrogen generating system.

COMMON CORE

The thinking brain of the 787 was the common core system (CCS). Developed by GE Aerospace, the CCS concentrated the processing functions of many different systems in one spot, saving weight, cost, and power. The CCS concept allowed the avionics system to be upgraded almost as easily as a modern personal computer and embodied the goals of Boeing’s original open-systems architecture concept.

“Boeing has chosen to design the 787 a little bit differently by using the CCS,” said GE Aerospace 787 CCS Program Director Mike Madden. “It is a scalable and a modular system, which means you can add elements of the system without having to redesign the entire thing, and its modularity means these elements are all common.”

The CCS followed the growing trend for integrated modular architectures (IMAs), in which more and more functions are tied together. Boeing’s open-standards computing “platform” combined more than eighty functions into one computer system and built upon foundations laid by the C-130 Aircraft Modernization Program (AMP) upgrade and the 777’s Aircraft Information Management System (AIMS). The 777 had about eighty separate computer systems with about a hundred different devices, versus thirty computer systems on the 787.

The CCS consisted of three main elements: a common computing resource (CCR), a cabinet that housed general processing and application-specific modules; a Rockwell Collins–developed common data network (CDN), which used the deterministic Ethernet 664/AFDX (Avionics Full Duplex) standard; and a series of remote data concentrators (RDCs). The massively capable network supported both copper and fiber-optic interfaces with connection speeds of 10 and 100 Mbps, or up to a thousand times faster than the ARINC 429 data buses used in existing generation avionics.

Each 787 had two CCR cabinets, with eight general processing modules, network switches, and two fiber-optic translator modules in each cabinet. The CDN was made up of network switches inside the CCR cabinets as well as throughout the aircraft. Provided by GE Aerospace’s Cheltenham site in the United Kingdom, the RDCs replaced dedicated wiring and concentrated signals from the aircraft’s twenty-one remote sensors and effectors, feeding them into the network. The effectors sent signals to make units such as actuators move.

The 787 used COTS (commercial off-the-shelf) operating system software by Green Hills Software and Wind River Systems in the core avionics systems. “Wind River is for the CCS in particular, while Green Hills is more for the flight control system,” said Sinnett, who added that the benefits of adopting the COTS approach would be felt throughout the long lifetime of the 787. “Rather than having everyone develop their own interface and operating system, they can plug directly in using these. When something has to be changed and updated, you can change the operating system without having to recertificate the codes.”

GE Aerospace selected Wind River Systems’ VxWorks 653 real-time operating system (RTOS) for the CCS. “We needed a partitioned operating environment which allowed us to share processing resources amongst a number of applications. That maximizes the utility of the processors and means you can certificate applications independently of the both the platform and one another,” said Madden.

Boeing was able to take advantage of the 787’s Honeywell-developed fly-by-wire (FBW) flight control system (FCS) to make the aircraft thousands of pounds lighter as well as to reduce cruise drag and improve safety. Electrically signaled in the pitch axis like the 777, the 787 was also fly-by-wire in the roll and yaw axis, giving control in three axes. The 787 system was therefore more sophisticated and integrated, and gave designers more flexibility to tailor the aircraft’s structure and flight control responses.

“We’ve taken all the lessons learned from the 777 and applied them to the new aircraft, as well as taken advantage
of the FBW technology we didn’t fully do with the 777,” said Sinnett.

The 787 FCS combined a control law called P-Beta (P being the aerodynamic term for roll rate), with the 777 flight control law called C*u (pronounced Cee star u), which governed speed stability rather than pitch—or pointing—stability. This meant that if the speed of the trimmed aircraft changed, the pitch would change, to return it to the set speed. In roll (wing down/up) and in yaw (nose left/right), control was via direct electronic signals to the control surfaces.

Boeing 787 chief test pilot Mike Carriker said “sideslip angle β [beta] is the angle between the direction the wind is coming from and the direction the nose is pointed. Generally P, roll rate, is controlled by the rotating of the control wheel, and β is created by stepping on a rudder pedal. When the pilot ‘rolls’ the airplane, a command is sent to the flight control computers for a roll rate, and the computers figure out how much control surface is used to meet the command. When the pedal is pressed, it is a command to establish an angle of sideslip. The hard part is that these two terms have an effect on each other. Get some β, and you get some roll. Create some roll, create some β. Sometimes you really want β, like a crosswind landing, but most of the time you don’t want any. Getting this part correct is the hard part.”

Flight tests of the new control laws were made as early as 2006 in a leased American Airlines 777-200ER in which the FCS could be switched on and off in flight. More authority, or “gain” in the P-Beta laws was gradually introduced to evaluate the interplay between the control inputs. Dubbed the CV/RR (control verification/risk-reduction) test bed, the flight tests also included simulation of the 787’s drooped ailerons as well as a drag-reducing feature called the trailing edge variable camber (TEVC) function.

Boeing expected that the TEVC could cut cruise drag and save the equivalent of 750 to 1,000 pounds in weight, and took advantage of the all-new wing and flight control surface design. The fully automatic system, which was the first practical commercial application of in-flight variable camber, operated by deflecting the trailing edge flaps in 0.5-degree increments while in cruise. The system could be moved through a 3-degree arc, with the trailing edge being set up and down by as much as 1.5 degrees on either side of a neutral position.

As the 787 fly-by-wire system was “full authority,” acting in the longitudinal as well as the lateral axis, it also was used to help reduce the structural weight of the outboard wing by shifting the lift distribution inboard. This was achieved by the basic shape and twist of the wing itself, as well as by using maneuver load alleviation control laws to move ailerons, spoilers, and flaperons (multi-function control surfaces that acted as both flaps and ailerons). “We lower the weight by bringing down the loads on the structure and we get a four-thousand-pound weight reduction out of the box. Overall we’ve taken several thousand pounds out of the fuselage and tail by reducing the maneuver loads they’ll see in service,” said Sinnett.

For the FBW system Honeywell chose the Green Hills Integrity-178B RTOS for the flight control system (FCS) modules, which were distributed among the four FCS electronic cabinets in each aircraft. Outputs from these flight control modules drove Honeywell actuator control electronics units. Moog provided actuation for the primary FCS as well as the control system for the spoilers and horizontal stabilizer. Every 787 would use thirty actuators and control electronics, as well as rotary actuation components for the GE-supplied high-lift system.
The control system was designed to provide vertical as well as lateral gust suppression, helping smooth the ride quality in turbulence. “The bottom line is the aircraft will move two feet up and down instead of six feet, and that will improve how you feel because motion like that is at the same frequencies that cause airsickness,” said Sinnett.

TWENTY-FIRST-CENTURY FLIGHT DECK

The flight deck was configured with the largest flight displays ever developed, dual head-up displays (HUDs) and dual electronic flight bag displays (EFBs). Unlike in any previous commercial airliner, “all of these will be basic,” said Sinnett. “We just provide more display real estate for situational awareness, and behind that provide capability for even more of that situational awareness all of the time.”

Distinguished by much larger display screens than any previously used in commercial jetliners, the 787 flight deck sported five 12x9.1-inch screens with 546 square inches of display space, double that of the Boeing 777. Standard to all were dual head-up displays (HUDs) and dual electronic flight bags, both formerly option-only items. Electronic flight bags stored digital maps, charts, manuals, and other data, and could be adapted to provide moving ground maps for ground taxiing. Mark Wagner

In addition, key safety systems such as weather radar, terrain awareness warning (TAWS), and traffic collision avoidance (TCAS) were also made as “dual basic” to all aircraft. “So the airline never has to make a choice, and there’s always a hot spare,” Sinnett said. Boeing’s decision to standardize on these systems for safety and economy-of-scale reasons initially sparked controversy. “Some pilots like them, some don’t. Some chief executives think they’re just pilot’s toys, but we believe in our hearts the more awareness the pilot has, the better it is,” said Sinnett.

“We had tough cost targets and we thought long and hard about offering less than what we did. In the end we decided that as this approach basically doubles the size of the market, the unit cost drops and it becomes a more efficient way of managing options. Now everyone will have two HUDs, and it is just the way it will be.” Rockwell Collins provided the package, which included the HPC/HCU-2200 dual head-up-display system on the left and right sides of the flight deck.

The HUDs formed an adjunct to the Rockwell Collins–developed integrated surveillance system (ISS), which warned about turbulence and extreme weather as well as about potential collisions with other aircraft and high ground. At its heart was the WXR-2100 MultiScan weather radar. Housed in two identical cabinets for redundancy, the ISS also hosted the TCAS, Mode S transponders as well as the Honeywell-supplied TAWS. Green Hill’s Integrity-178B also was used on the “traffic module” element of the ISS. A PowerPC-based processor at the core of the system was backed up by a support ASIC for the “traffic” functionality of the TCAS.

The human “Mk 1” eyeball also got a chance to play a bigger part in the safety of the 787, which had far larger flight deck windows than the traditional narrow Boeing front and side direct-vision windows. Total flight deck window space for the 787 grew to 33.5 square feet, compared to 26.9 square feet for the 767/777. Flight deck displays were also far larger. Immediately below the windows and glare shield, other major parts of the Rockwell Collins package included 9x12-inch primary flight liquid crystal displays (LCD), five of which dominated the flight deck. Four were arranged in a horizontal bank across the instrument panel and one below on the center pedestal, and each measured 15 inches diagonally. The screens were designed to be able to display large-format maps with a 1,280 nautical miles range, giving the crew clear data on long-distance waypoints.
Specially developed features include the capability to overlay weather data without obscuring navigation information, dedicated sections for displaying air traffic control communications, and aircrew advisories. Working with individual airlines, a series of menu-driven software and features also were created to guard against incorrect data entry to the flight-management system, which was accessed via an “ABC” format keyboard rather than the “QWERTY” layout adopted by Airbus.

Rockwell Collins also provided the display control panels, multifunction keypads, and cursor control devices (CCD) that performed the same role as a computer’s mouse pad, helping the pilot to select what was to be shown on the displays. The keypads and CCD were designed with ARINC 429 ASICs embedded to reduce the complexity of the interface with the aircraft. Rockwell also provided the display software applications that ran on the GE general-purpose processor module in the CCS.

Backup displays were supplied by Thales and consisted of independently powered and connected integrated standby flight displays (ISFD), which showed pitch and roll attitude, air speed, altitude, heading, and landing approach deviation data.

The navigation suite was supplied by Honeywell and included the flight management system, air data system, dual integrated navigation receivers (INRs), and inertial reference system (IRS). Backup systems included attitude heading reference systems for the IRS, as well as standby mini-IRS units derived from products used in regional jets. The suite also included DME receivers, optional ADF radios, and dual radar altimeters, while the INRs included a fully integrated package consisting of a Cat IIIb-capable ILS (instrument landing system) or Cat I GLS (global landing system).

Despite all the changes, Boeing wanted to retain as much commonality with the Boeing 777 to meet a target training conversion time of five days between the 777 and the 787. Pilots of 757s and 767s were to be able to convert to the 787 in eight days, while 737 pilots would have eleven days of conversion training. Integrated approach navigation systems allowed pilots conducting approaches with VOR, NDB, and localizer navigation aids to use the same procedures employed during ILS precision approaches. This saved simulator training time by reducing different approach procedures to a single, common one. Pilots were presented with navigation scales displaying required performance levels supporting RNP 0.1 capability, ensuring lateral track accuracy of 0.1 nautical mile as well as vertical situation displays.

Rockwell Collins also provided the communications system based on the VHF 2100 radio, which was software upgradeable to VDL Mode 3. Providing room for future growth to accommodate future CNS/ATM (communications, navigation, surveillance/air traffic management) applications, the radio system was designed to use 20 percent less power and weighed around 30 percent less than contemporary systems. The communications suite also included the SAT 2100 satellite communications and integrated HIST 2100 high-speed data terminal, enabling data rates of up to 432 Kbps. The system accommodated up to three voice and two data channels simultaneously.
ON FEBRUARY 14, 2006, THE FIRST OF A NEW GENERATION OF TURBOFANS for the 787 hummed quietly into life at Rolls-Royce’s Hucknall test site near Derby in the heart of England. Named the Trent 1000, the powerplant was the first engine to be electrically started, and the first major mechanical piece of the Dreamliner to run.

Just a few weeks later, in the United States on March 19, a new sound filtered through the cedar, oak, and maple trees on the rolling tops of the Allegheny plateau in southern Ohio. Barely audible at idle thrust beyond the immediate area of Stand 6A on General Electric’s remote seven-thousand-acre engine test site in Peebles, this was the first run of the GEnx turbofan for the 787.

The two engines were the most technologically advanced commercial powerplants since the first generation of high-bypass turbofans of the 1960s, and their first runs marked pivotal moments for the emerging strategy of both companies. Coming just under two years after GE had been selected by Boeing as the second engine for the 787, the GEnx was emerging as a popular option and had won its way on to both the recently announced Boeing 747-8 and Airbus A350. For Rolls-Royce, its selection as the launch engine on the 787 marked the first time a non-U.S. engine maker had won pole position on a new Boeing twin-aisle and crowned its decades-long battle to beat Pratt & Whitney into the number-two slot in the big-engine world.

But this outcome was far from clear in 2000, when Boeing asked all three engine makers for Sonic Cruiser propulsion proposals as part of its wide-ranging “20XX” future airliner project. At first these tended toward 777-based derivative engines, as the requirements were a good match in terms of thrust and compressor efficiency, and also because Boeing hoped the derivative route would help keep it more affordable.

However, through the fall of 2001, continuing analysis of the Sonic Cruiser’s performance profile, wind tunnel tests, and customer studies began to show that derivative engines would not work. Sonic Cruiser Marketing Vice President John Roundhill said the studies argued “for a major change, if not a brand-new engine.” The main reason was the higher thrust needs of the Sonic Cruiser at higher altitudes, plus emissions and noise targets that pushed the edges of the envelope beyond the 777.

“This aircraft has a different relationship of climb thrust to takeoff thrust, and we found the optimal core size was smaller than the 777,” said Roundhill. GE, Pratt, and Rolls immediately responded with hybrid solutions that combined the takeoff performance of the 100,000-pound-thrust class 777 engines with the cruise performance of the standard 777-200ER/300 engines. However, Roundhill reported that “we gave them some explicit criteria in terms of inlet diameter because of drag, and exhaust velocity because of noise. The results showed us we required a new engine.”
By early November 2001 the revised requirements called for a 90,000-pound takeoff thrust-class engine giving a 10,500-foot runway roll at a maximum weight, coupled with a high subsonic cruise capability. Here was a key difference between the Sonic Cruiser and anything that went before it. A propulsion engineer seeing these first two figures would have punched the numbers into a calculator and come up with a 100,000-pound-plus-thrust engine, not one with around 10,000 pounds less thrust. The Sonic Cruiser, however, had to be a good neighbor on the ground yet cruise close to the sound barrier for most of its mission.

Boeing’s late 2001 course correction to seek all-new engines for the Sonic Cruiser dovetailed well with GE’s developing next-generation-engine plan, which the company originally called GEN X. This was aimed at prospective power demands in the lower-thrust CF6-size bracket for a range of new studies under way by Airbus and Boeing. In 1999/2000 these were focused on a 67,000-to-70,000-pound-thrust growth version of the CF6-80 dubbed the CF6-80G2, which was aimed at prospective long-range versions of the 747 and 767, respectively called the 747X and the 767-400ERX.

But these projects remained nebulous, and 2000 saw the focus shift to Airbus, which was studying a potential 250-seat, medium-range “shrink” version of the A330, variously dubbed the A330-100 and the A306. The new aircraft would have required a 55,000-to-60,000-pound-thrust range, which, although significantly below the Boeing study thrust sizes, was enough to pump new life back into the CF6-80G2, which was outlined with a hybrid titanium fan.

However, the Airbus performance targets were extremely aggressive, and GE began to be pushed inexorably in the direction of a new centerline design. It was a tough decision for GE to turn its back on the long-serving CF6, as well as the considerable investments in future growth studies such as the -80G2. But the company had the massive benefit of the GE90 and its new core at its disposal, and was determined to use this as the springboard for a whole new family. This was particularly so since GE’s momentous 1997 “U-turn” decision not to write off the GE90 and pursue further growth to support the 777.

The GE90 was a solid foundation for new growth because it used a raft of technology derived from a long series of successful GE and NASA research programs. These included the 9:1 bypass ratio; a wide-chord, composite fan blade that evolved from the GE36 unducted fan (UDF) program; low-noise and low-weight composite nacelle technology from the quiet, clean, short-cycle, energy-efficient (QCSEE) program; and a rugged dual-dome, low-emissions combustor design from the efficient, clean combustor (ECCP) program.

One of the most critical efforts, however, was the joint NASA/GE “E3” (energy-efficient engine) program, which proved the design benefits of a ten-stage high-pressure compressor (HPC) with radically advanced aerodynamics. The E3 spawned the advanced 23:1 pressure-ratio HPC at the heart of the GE90 and formed the basis for a whole new set of derivative cores, including a nine-stage HPC for the higher-thrust GE90-115B and the Engine Alliance GP7200.
In November 2001, GE revealed that its GEN X concept would be based on a scaled-down compressor from the GE90-115B, by then in initial tests. Admitting it was “very early days,” GE90 Advanced Program General Manager Mike Benzakein said the GEN X would be more integrated with the airframe than previous engines.

“On GEN X we are looking at a thrust requirement of around 90,000 pounds, assuming a Mach 0.98 cruise speed and a capacity of 250 passengers. This means we’re looking at around an 80 percent scale of the GE90 core in terms of flow scale,” he said. GE “always expected” Boeing to favor an all-new engine for the Sonic Cruiser over simpler derivatives of 777 engines such as the baseline GE90, and GEN X satisfied this requirement, he added.

The GEN X concept study rested on the evolved nine-stage HPC tested in the eighth of a series of GE90 test cores. Previous tests included the fourth core, which focused on three-dimensional (3-D) aerodynamic improvements, while the fifth was used to test a nine-stage configuration. The sixth core, tested as part of GE90-115B development, further refined this configuration, while core seven, which ran in late 2002, formed the basis for a 72 percent scaled version for the GP7200.

The Sonic Cruiser engine contest moved up a notch when detailed analysis revealed that simple derivatives of existing 777 engines would not work. The call for an all-new engine set manufacturers on the path to what would become the world’s most efficient turbofans. Mark Wagner

A big part of the study was trying to squeeze the large fan and its engine into the unusual design limits of the Sonic Cruiser imposed by Boeing. Because the engine was buried inside the wing, the fan was limited to about 110 inches in diameter, with a fan-pressure ratio of approximately 8:1. Although GE traditionally maintained a relatively low pressure ratio to help reduce fan noise, it believed that the long inlet duct of the Sonic Cruiser would compensate for this.

CHANGING PICTURE

With hindsight it is curious to see how the evolution of the engine requirements somehow became a distant warning signal for the whole Sonic Cruiser/Yellowstone effort. Almost overnight in late 2001 the landscape changed for the engine makers, who suddenly faced more difficult and expensive decisions. The simple derivative approach was gone, and the course was set for make-or-break verdicts that would decide the destiny of the big fan engine for a generation to come—but not in the way anybody could have anticipated. Having already begun to revise their designs for the Sonic Cruiser engines, the big three manufacturers were arguably better prepared to deal with the shift to the 7E7. Thrust requirements were cut by around 20 percent, and the operating cycle was far more conventional. However, while power and cycle were more familiar, the efficiency targets were definitely not. Battle lines were drawn up through late 2002 and early 2003 as the engine makers worked feverishly on design concepts that embraced technology that was sufficiently advanced to meet Boeing’s tough outline requirements yet mature enough to be considered low-risk.

The first major milestone event came in February 2003, when Boeing called all three to Seattle to be issued the initial set of 7E7 propulsion system requirements. Based around specific targets for takeoff, climb, and cruise thrust performance—as well as fuel consumption, emissions, noise, and installed weight—the “Phase 1” briefing also included details of the tough schedule, which called for entry into service in mid-2008, less than 5 1/2 years later. Key targets included a 60,000-to-75,000-pound-thrust family, with options for derated lower-thrust variants, 17 percent better fuel consumption per seat, and 10 percent lower operating costs than the 767-300ER. They also called for reduced installed weight that would contribute to a lower gross weight than the A330-200. Overall, much was required of the engine makers, which were expected to contribute about 80 percent of the 7E7’s overall performance
improvements.

Boeing planned at this stage to make its final engine selection by the end of 2003, though this would later slide into 2004 as the company revised its plans for the 7E7SR (short-range). The stakes were huge for winners and losers alike. Boeing wasn’t saying so, but given the obvious cost benefits of the exclusive 737/CFM and 777LR/GE relationships, all believed its preferred solution tended toward a sole-source partnership. GE naturally backed this to the hilt, while both Rolls and P&W more realistically supported dual-source scenarios.

Of the three, P&W had the most to lose. This suspicion was telegraphed by the urgent tone of the company’s commercial engine president, Bob Leduc, who said in February 2003, “We do believe Boeing is going to do the program and we are going to be there. It’s that simple and come hell or high water we’re going to win!” In the early 2000s, Pratt’s position in the big-fan commercial world was slowly but surely becoming marginalized, with slowing sales of the PW4000 in traditional A330 and 777 markets, and greater emphasis on partnership programs such as the Engine Alliance GP7200 with GE on the A380, and International Aero Engines V2500 on the A320 family. The company, once the world’s leading commercial jet engine maker with the incredibly successful JT3D, JT8D, and JT9D series, was looking for ways back in. To regain its single-aisle greatness, it harbored ambitions for the future with its geared turbofan technology development. But for a guaranteed presence in the mid- and far-term twin-aisle market, Pratt & Whitney needed to be on the 7E7.

Having evolved various new concepts for the Sonic Cruiser, many of them based around the PW4000 core and technology from its armory of military engines, Pratt & Whitney saw that the only way to meet the 7E7 goals was with an all-new engine. “We recognize what we have today will not meet Boeing’s goals,” said P&W Commercial Engine Marketing General Manager March Young.

General Electric’s GE90-115B, a twin-shaft, high-bypass, geared turbofan engine, was developed as the basis for the Boeing 777's propulsion system. It was designed to be more efficient and powerful than previous engines, enabling the 777 to fly further and faster than its competitors.

General Electric’s composite fan blade technology was first developed for the GE36 unducted fan and perfected for the GE90 before evolving yet again for the 787’s GEnx engine. Fitted with a titanium leading-edge cuff, the composite is less dense, and therefore lighter, but as strong as equivalent metallic blades. The GEnx-1B has only eighteen blades, compared to twenty-two on the GE90-115B and thirty-six on the CF6-80C2.
If there was one advanced technology development program that paid constant dividends to GE it was the joint NASA-GE Energy Efficient Engine (E3).
The ten-stage high-pressure compressor formed the heart of the GE90 and, with its 23:1 pressure ratio, was scaled for the GEnx. *Mark Wagner*

Pratt& Whitney’s PW-EXX concept wrapped a PW4000-derived, counter-rotating low-pressure spool around an all-new high-pressure core. The engine had the same 112-inch-diameter fan as the PW4000 version on the 777, but had a smaller core to increase bypass ratio to about 10:1, versus 6:1 on the previous engine. The new core, based on the F119 engine developed for the supercruising Lockheed Martin F-22 Raptor, was configured with a ten-stage HP compressor and two-stage HP turbine, while specific fuel consumption was reduced by boosting overall pressure ratio to 50:1, compared to just under 43:1 for the PW4000 on the 777.

The PW-EXX’s “dual arc” wide-chord fan blades, based on the GP7200 design, were to be from hollow titanium, and were contained within an aluminum isogrid fan case. The case also supported integrated fan exit guide vanes, which doubled as struts. The four-stage LP compressor rotated on a special frangible support that was designed to allow the fan stage to mechanically detach in case of a major failure. Other distinguishing features of the EXX included integrally bladed rotors in the compressor, the low-emissions Talon X combustor, axially leaned airfoils in the seven-stage low-pressure turbine, and “super-cooled” high-pressure turbine blades.

Rolls-Royce’s proposal was the RB262, a three-shaft design evolved from its RB211 heritage and based around a scaled and improved version of its Trent 900, developed for the A380. The engine also incorporated technology from the company’s Vision 10 research program, which encompassed the affordable near-term low-emissions (ANTLE) demonstrator engine. To cut noise and fuel burn, the new powerplant also was designed with a higher bypass ratio, provisionally set between 10.5:1 and 11.1, making it the largest ever developed by Rolls-Royce.

The U.K. company also planned to take maximum advantage of Boeing’s goal of having a “no bleed” systems architecture. “By not taking the bleed off the core of the engine, it allows us to change the matching of the HP and LP compressors, and we are now almost certain to make the IP [intermediate compressor] contrarotating,” said Rolls-Royce Director of Engineering and Technology Mike Howse. This was a departure from the Trent 900, which had been the first contrarotating Trent engine, but which rotated the HP in the opposite direction to the LP and IP systems. The principle was still the same, and essentially improved performance and efficiency by getting more energy out of the flow passing through the core.

Although not immediately apparent, one of the clever design features of the Trent 1000, as the RB262 was to become, was its method of increasing overall bypass ratio without making the fan diameter any larger. The design originally helped solve a conundrum facing engineers who were trying to meet the tough Sonic Cruiser engine performance goals by making the bypass as large as possible within the tight confines of the design space inside the Cruiser’s wing.

Once freed from high subsonic targets and the cramped dimensions of the Cruiser’s inlet duct, Rolls-Royce swiftly adapted the same baseline design—already tailored as part of propulsion studies for Boeing’s “reference design”—to meet the needs of the 7E7. The trick, as always with turbofans, was to find the right ratio of bypass. Too little, and the engine fails to meet its noise targets; too large, and the fan diameter is so big that it creates excess drag, which drives up fuel burn.
Judged by some to be technically ahead of its competitors, Pratt & Whitney’s proposed PW-EXX was based around the core of the F119 developed for the F-22 Raptor and later F-35 Lightning II. Incorporating integrally bladed rotors, the engine would have had a core-mounted gearbox for electrical power generation, and a compressor pressure ratio of 20:1 versus 11:1 on the PW4000. Pratt & Whitney

The answer was to insert a series of highly swept fan blades into a smaller-radius hub. Not only did this satisfy the airflow requirements, but it also kept the dimensions of the nacelle small enough to enable the engine to be transported in a 747 freighter in one piece.

Behind the new fan, the Trent 1000 incorporated an eight-stage IP compressor; a six-stage counterrotating HP compressor; an advanced low-emissions combustor; and HP, IP, and LP turbines, each with six stages.

The unique three-shaft configuration gave Rolls-Royce a new design opportunity for the increased electrical load requirements of the 787. Unlike its predecessors, the Trent 1000 power off-take was from the aft of the IP compressor rather than the usual front of the HP compressor, allowing a greater stability margin and lower flight and ground idle thrust.

The design evolution of the 7E7 was meanwhile set to throw more challenges at the engine companies. As they prepared to submit “Phase 3” proposals toward the end of 2003, Boeing revealed that the payload/range performance spread of the 7E7SR, base model, and stretch was too great for a single engine to handle in an optimum way. Boeing was anxious to avoid compromising the performance of the 7E7SR by tying its structural weight to the other longer-range and stretch versions just for production commonality. It therefore made the crucial decision to take significant weight out of the design by reducing wingspan, and other structural tweaks.

The fallout was a potential six-month slip in the engine decision, and the first major schedule hiccup for the 7E7. Senior Vice President Mike Bair said the concerns of the engine manufacturers drove the decision. “They were getting a bit nervous with the timing in front of us,” he commented in November 2003. The slide bought the company “a bit of time at the front end of the program” and enabled more options to be considered. These ranged from simple derating to more fundamental solutions, such as different fan sizes, or even common fans paired with scaled core sizes. Bair remarked that studies also included “one engine more specialized for the SR marketplace, or maybe one for the SR and base and another for the stretch.”

Tests on a modified Trent 500 under the affordable near-term low-emissions (ANTLE) technology program helped pave the way for several technology features of the Trent 1000. Royce’s proprietary powder nickel alloy, RR1000, was tested in the ANI LE compressor and was later used in the last two stages of the Trent 1000 HPC drum and HP turbine disk for benefits in cycle operating temperature and component life. Here the ANTLE is seen at the Inta test bed in Spain. Rolls-Royce

Boeing’s Phase 4 engine requirements issued at the start of 2004 outlined different engine builds covering the 55,000-to-60,000-pound-thrust range for the 7E7SR and baseline 7E7, and 70,000-pound-thrust for the 7E7STR.
This unusual “1 1/2” engine need confused and confounded the industry, and out of nowhere seemed to suddenly challenge the basic simplicity of the original 7E7 family design goals. But Boeing was optimistic that the design refinements of the SR at the lower end and the STR at the top were allowing the thrust range to contract once more, and said the Phase 4 call did not signal that any “sort of decision has been made in terms of both the family members we have outlined. We still don’t know if it’s going to be one or two engine types, or one or two engine manufacturers.”

In fact, progress on define refinements was faster than expected, and by February 2004 Boeing decided to drop its exploratory “1 1/2” engine studies and revert to a single type instead. “The logic to stay with our original plan is overwhelming,” said Engineering and Manufacturing Vice President Walt Gillette. “When we began we had one engine build across the fleet, and that’s been our mainstay. We spent six to eight weeks looking at ‘what if?’ and we had a sort of engine-and-a-half family with a common core and two fan sizes. In the end we saw the value and simplicity of one engine build is somewhat better.”

The good news from Boeing’s perspective was that thrust requirements were indeed converging. “Part of that is because when we looked at the short-range version we saw it needs plenty of climb power, and the more we looked at the stretch, the more we saw it was a really efficient airplane that needed slightly less power than we thought,” explained Gillette.

The result was a simpler, quicker final round of engine selection evaluations. Engine makers were asked to submit best and final proposals at the end of March 2004, with the verdict due to be announced about a week later. It was a nerve-racking time for all concerned. Speculation mounted of it being an all-U.S. affair, with GE’s industrial might and Pratt’s clean sheet design winning through, while others foresaw GE securing its long-dreamed-of sole-source deal. To others, the aggressive technical and marketing stance of Rolls and the highly international aspect of the entire 7E7 venture dictated an almost natural place for the U.K. engine maker at the expense of one of the U.S. giants. There would be winners and a loser, but which would be which?

Rolls-Royce designed the Trent 1000 with a smaller hub diameter to achieve an inlet mass flow level as high as 2,670 pounds per second, yet still keep fan diameter to 112 inches. The force on each fan blade at takeoff is roughly equivalent to a load of almost 100 tons. Mark Wagner

The industry got its biggest clue that there would be only one loser, not two, in late March, when Boeing revealed that it would be offering an engine swap-out capability, allowing seamless interchangeability between aircraft. “This could be an attractive feature to the financing community,” said Bair. “One of the reasons we can do this is the capability of today’s avionics; we can make it all software-programmable.”

Bair was talking about the adaptability of the open-architecture-system philosophy being planned for the new jetliner, a massive step beyond the current state of the art in which engines and their controls were essentially “hardwired” into the design. Until the 7E7, specific airframe-engine combinations were generally for life; even if alternative engine choices were available, conversions were too long and too expensive to be worthwhile.

Finally, on April 6, 2004, the winners and loser were announced. GE and Rolls were selected, and P&W was out. The stunning news was greeted with jubilation in Evendale and Derby, respectively, and with obvious dismay in East Hartford, the Connecticut headquarters of P&W. As the only engine maker to submit an all-new design, P&W clearly held the potential advantage technically, but when the dust settled later that day, it emerged that business decisions had played a key role in the final outcome.
P&W’s owners, United Technologies Corp. (UTC) and one of its major partners, MTU of Germany, had balked at the massive “buy-in” costs associated with the business case. Reflecting on the decision, P&W said, “We’re going to go after commercial programs that we think make long-term business sense, but we won’t damage the company financially to win. We may be third in the commercial business for a while; so be it.” In a message to employees, P&W President Louis Chenervert said, “While we are disappointed, we should thank the entire PW-EXX team for their outstanding efforts in this hard-fought competition.”

Bair said it had been “a very close decision, but we are happy this represents the best value for everyone who is going to be involved in this aircraft. Technically all three had very robust offerings that met or exceeded our technical requirements.”

While taking nothing for granted, for GE the GEnx decision was business as usual. For Rolls, it was all-new territory. “We did our best with Boeing, and we’ve never had a more close working relationship than this,” said Rolls Civil Aerospace President Mike Terrett. Trent 1000 Assistant Chief Engineer Gary Cutts added, “We feel we’ve been doing a program per year for the past ten years, and we feel we’re match fit for this.”

By late 2003 7E7 thrust requirements were diverging so dramatically that Boeing wrestled with the prospect of covering the range with two engine variants—one with a smaller fan diameter for the short-range version, and another for the baseline and stretched models. Further analysis showed that the gap could be closed because the short-range variant needed high power for climb, while the longer-range variant did not require as much thrust as originally believed.

THE GAME BEGINS

More surprising news soon followed in October 2004, when Rolls-Royce’s Trent 1000 became the lead engine on the 7E7 following its selection by All Nippon Airways (ANA). Proving that the old world of brand loyalties was giving way to a new world of harsh business realities, the decision made the 7E7 the first all-new Boeing wide-body to be launched into service with a Rolls-Royce engine.

General Electric pushed for exclusivity on the 787, having reaped the rewards with Snecma on the Boeing 737 and its CFM56 engine. Here British Airways engineers gawk at the sheer size of the first GE90 engine and its 123-inch-diameter fan mounted on a 777, while a closely positioned CFM56-powered 737 provides some scale. Mark Wagner

Not including the stretched 777-300, which was led by the Trent 800, it also marked only the second time a new Boeing airliner had been launched with a powerplant from the U.K. manufacturer, the first being the 757. In a twist
of irony, the last 757 was being assembled when news of the ANA decision filtered through.

General Electric’s case for exclusivity on the 787 appeared stronger than ever when it was selected as sole engine provider to Boeing for the longer-range 777-200LR/300ER models with the GE90-110/115B. The combination was a happy one for both airframe and engine maker, and set the scene for a record-breaking long-distance flight on November 10, 2005, when a test aircraft flew nonstop 11,664 nautical miles from Hong Kong to London in twenty-two hours and forty-two minutes. The distance was farther than any previous commercial jetliner had flown and exceeded a distance of more than halfway around the world. Here the weary passengers and crew disembark after landing at London Heathrow. Mark Wagner

The ANA breakthrough came hard on the heels of news that Kawasaki Heavy Industries had joined Mitsubishi Heavy Industries as a risk-and-revenue-sharing partner in the Trent 1000. Kawasaki was to provide the IP compressor module under an 8.5 percent share, while Mitsubishi acquired a 7 percent share involving the combustor and LP turbine.

The GEnx-1B undergoes a hail test at Site 4D on the Peebles test site in Ohio as part of the initial certification effort. Ice accretion testing was conducted at Mirabel Icing Facility in Montreal, Canada, where tests simulated the sort of severe icing conditions in which slabs of ice would form in the inlet cowl and engine face after a two-minute delay in activating anti-icing systems. GE
For the first time in any wide-body engine development program, Rolls-Royce felt the need to use a dedicated flying test bed for the Trent 1000. The ex-Air Atlanta Icelandic 747-200 was converted for the role by L-3 in Waco, Texas, and commanded during its initial test runs by Rolls-Royce Chief Test Pilot Phill O’Dell. The aircraft is pictured taking off at Boeing Field with the test engine at idle. Mark Wagner

Trent 1000 Chief Engineer Andy Geer described the ANA decision as a “great vote of confidence” that gave Rolls-Royce a good “leg up” in the battle to power the initial 7E7. The engine was to be built as a single bill of material across all three versions despite a broad thrust range covering certification at about 70,000 pounds of thrust for the 7E7-9, and derates to 63,000 and 64,000 pounds of thrust on the initial 7E7-3 and 7E7-8 variants, respectively.

Bolstered by the addition of a new commitment from Air New Zealand, which became only the second 7E7 customer to select an engine, Rolls revealed further details about its development plan. By now defined with a 10:1 bypass ratio and 50:1 overall compression ratio, the final design of the Trent 1000 was due to be frozen by February 2005, with first engine to test scheduled for mid-February 2006. The basic test, development, and certification effort was to involve seven sea-level engines and a flight test engine, requiring Rolls to operate its own dedicated flying test bed for the first time since the 1970s.

In late December 2004, L-3 Communications Integrated Systems was given the job of modifying and operating a 747-200 selected for the purpose. An RB211-524C2-powered aircraft acquired from Air Atlanta Icelandic was reregistered N787RR and flown to L-3’s modification site in Waco, Texas. The 747 was a far cry from the ex-RAF Vickers VC10 last used to test the original RB211.

Just as Rolls was securing its deal with L-3, GE signed an agreement the same month with Airbus to use the GEnx as lead engine on the European company’s newly announced A350, at this stage an advanced A330 derivative aimed at countering the 7E7 (see chapter 10). The Airbus deal slotted perfectly into GE’s strategy of developing the GEnx into its twenty-first-century CF6 successor, a policy that would be further reinforced with the engine’s sole-source selection the following April for the newly announced 747-8.

The GEnx development by now was accelerating, with teaming arrangements and the design firming up. Japan’s Ishikawajima and Mitsubishi, Italy’s Avio and Sweden’s Volvo Aero, and Belgium’s Techspace Aero all became partners, with a combined share of 36 percent of the program.

Fuel is injected into the GEnx engine’s TAPS combustor and thoroughly mixed with the swirling airstream to create a leaner air/fuel mixture. As this burns at a lower temperature in this combustor, the formation of nitrous oxides and other greenhouse gases is reduced. GE
In something of a landmark moment for big engine design, GE also announced that the GEnx would feature a composite fan case to save weight and improve strength and containment performance. Having been the first to introduce large-scale composites in the fan of the GE90, GE was better prepared than any to replace the conventional metallic fan case with the newer material, which it said would save close to 350 pounds per engine.

By March 2005 GE froze detailed design, clearing the way for the start of manufacturing of the first GEnx parts. Assembly of the first GEnx was now scheduled to start in October, with the first engine to test in March 2006. Tests on GE’s 747-100 flying test bed were set for the third quarter of 2006, with first flight on the 787 expected about a year later.

Seven engines were assigned to the 787 certification program, which encompassed three variants: the GEnx-54B for the 787-3, the GEnx-64B for the 787-8, and the GEnx-70B for the 787-9.

“It’s execution time. We’re cutting metal on all components and working the build process. We are even looking at ways to build them differently,” said GE Commercial Marketing General Manager Mike Wilking, who emphasized that despite the innovative use of more composites in the structure, as well as the blades, the GEnx was more evolutionary than revolutionary. “All the technologies in these engines are advanced and proven; there’s really
nothing new in here,” he said. The final design included a fan with just eighteen blades, as opposed to twenty-two on the GE90. “Just having eighteen blades cuts the scrubbing losses [aerodynamic interaction with the wake of the preceding blade], cuts weight, and improves noise reduction,” said Wilking. Despite the extensive use of composites, GE acknowledged that the engine was likely to be a “bit heavier” than the rival Trent 1000. “But we’re okay with that because we’re backing fuel burn and long-term performance retention,” he said.

The final configuration included a four-stage LP compressor, a ten-stage HP compressor, a two-stage HP turbine, and a seven-stage LP turbine, one more than in the GE90-94 from which it was derived. Other innovations include “endwall effects” or contouring to reduce pressure losses in the interstage areas between individual turbine and compressor stages.

Aside from extensive composites, the engine also included an array of advanced superalloys such as niobium silicide (NbSi) in the HP turbine, and intermetallic compounds such as titanium aluminide (TiAl), which, for the first time in any civil engine, was used in the sixth and seventh LP turbine stages. The GEnx also was designed with a scaled-up version of the twin annular preswirl (TAPS) combustor, developed for the CFM International Tech 56 technology program.

By mid-2005 Rolls-Royce had meanwhile begun construction work on a U.K. £30 million “58 bed” test site for the Trent 1000, and was getting ready to receive a flood of parts for the start of assembly of the first engine in November and the buildup to the beginning of test runs in February 2006.

Easily distinguished by its size compared to the 747-100’s standard Pratt & Whitney JT9Ds, General Electric’s GEnx-1B gets airborne for the first time, on February 23, 2006, on the company test bed at Victorville, California. In a twist of irony, the new engine became airborne within hours of the death of Brian Rowe, a former GE president who led the pivotal launch of the GE90, predecessor to the GEnx. Considered a risky move in its day, the GE90 go-ahead was described as “the gutsiest call I’ve ever seen at GE” by David Calhoun, a former GE vice chairman and formerly head of the aviation unit.

“General Electric

“It’s beginning to be very real,” said Rolls-Royce Director of Boeing Programs Dominic Horwood. “The design of the engine is essentially complete—there are still a few things to do on the external systems, but the propulsion configuration is firm with Boeing and we are on plan and on time.” An additional $42 million was allocated to development of an engine noise testing facility at NASA’s Stennis Space Center in Mississippi that was aimed at “mapping” the acoustics of the engine in 2007. Altitude tests were scheduled for mid-2006 at the Arnold Engineering Development Center in Tullahoma, Tennessee.

The overall Trent 1000 program was to involve sixteen engines plus at least two spares. Seven were destined for ground tests, most of which were to undergo multiple rebuilds, while a further engine was destined for the flying test bed. A further eight were destined for the first four 787 test aircraft plus a further two for spares.

Rolls-Royce also completed the selection of its risk-and-revenue-sharing partners on the Trent 1000 with the addition of Spain’s Industria de Turbo Propulsores, S.A. (ITP), as the sixth member. The announcement took partner shares to 35 percent. As with previous Trent programs, ITP was responsible for assembly of the LP turbine module. Other Trent 1000 partners by now included Goodrich, Hamilton Sundstrand, Kawasaki, Mitsubishi, and Carlton Forge Works. “Beyond that we’ve finished sourcing the rest of the engine, and we’re now driving it hard to get parts in for the November start of assembly of the first engine,” said Horwood.

POWERING UP
Assembly of the first Trent 1000 officially commenced in Derby on November 7, 2005, just eleven days ahead of GE beginning the buildup of the first GEnx in the United States. “We’re starting with the assembly of the IP compressor and HP compressor, and we will have all the modules built up by the end of the year,” said Horwood later that month. In December Rolls “dressed” the fan case, and in January it “stacked” the core before mating it with the fan case prior to the start of engine tests in February. The first engine in the test effort was used primarily for LP system evaluation. Engine number two was aimed at IP system work, while the third engine formed the focus for HP system work. A fourth engine also went to the AEDC in Tullahoma, for altitude and icing tests. Although originally set to go there earlier in 2006, Rolls-Royce rescheduled it for later in the year “due to availability constraints.” This suited the program better, said Horwood. “So when an opportunity arose to send the engine to AEDC a little later in the program, we took it: the benefit of sending it later is that we’ll have that much more development running under our belt, allowing us to really focus on the testing we perform at this facility.”

General Electric’s GEnx test effort was as much about convincing airlines as it was the certification authorities that the advanced features were safe and reliable. By March 2006, with the first engine running, GE sensed that the tide was turning. GEnx Program General Manager Tom Brisken said, “Operators are getting more confident. At first when we started telling them about the composite fan case, the TAPS and Ti-Al some were quite concerned—but after two and one-half years of technology demonstration maturation programs, we have satisfied them. We have performed more than seven thousand hours of technology component testing on fifty different maturation tests.”

Overall the original plan involved a dedicated core, engine 000, plus seven full test powerplants. Engine 000 was used for HP turbine stress and HP compressor performance measurement, while the first engine to test, 001, was set to assess performance, crosswind work, and vibration. This engine was later sacrificed in the destructive “blade-out” test in 2007. Engine 002, distinguished by noise-reducing chevrons, was the first to be fitted with all the production hardware and was used for emissions, LP turbine stress work, and endurance running. This latter task made it one of the longest-serving engines in the certification program. Engine 003 was used for endurance work as well as vibration, bird strike, ice, and water ingestion tests. Engine 004 was to perform the all-important 150-hour “triple redline” block test in which the engine ran for sustained periods of simulated flight cycles of up to 6 hours, at operating limits well beyond normal. Engine 005 was destined for flight tests. The seventh engine was set to undergo emissions and full-icing testing.

For the all-important 787 flight tests, GE planned to have the first shipset of compliance engines “on dock” at Peebles in September 2007 to coincide with the anticipated award of U.S. FAA Part 33 engine certification. Flight tests on the 787 were due to begin in about October 2007, with European EASA engine certification due in the first quarter of 2008 and U.S. FAR Part 25 aircraft certification for the GE-powered 787 due at about the mid–second quarter of 2008.

General Electric’s GEnx engine 965-005 became the first of the competing powerplants for the Boeing 787 to take to the air, on February 22, 2007, when it flew under the left wing of the company’s Boeing 747 flying test bed at Victorville, California. By a strange twist of fate, the engine flew within minutes of the death of former GE
Aircraft Engines President Brian Rowe, the pioneer of the high-bypass turbofan and a key figure behind the go-ahead of the GE90 on which the GEnx was based. Rowe, who was seventy-five, died that day at the University of Pennsylvania Medical Center in Philadelphia following surgery.

Rowe would have been proud of the engine’s initial performance. During the three-hour flight, the GEnx-1B64 version for the initial 787-8 model “demonstrated aircraft systems and instrumentation functionality, climbed to more than forty-three thousand feet, and established engine performance baseline for flight testing,” said GE. The initial test phase would focus on “steady-state and transient performance of the engine, verify air re-starting capability, determine the combustor operability margins, validate throttle response, and assess the nacelle and undercowl cooling characteristics.” A second flight test phase, at about midyear, would focus on the engine control system. Most tests would be based out of Victorville, with hot-weather work at Yuma, Arizona, and high-altitude takeoff work in Colorado Springs, Colorado.

The flying test bed was extensively modified to manage the electrical load from the engine’s two starter generators and to provide the power necessary for electrical ground and air starts. The GEnx would produce more than 1 megawatt compared to about 60 kilowatts for current engines of equivalent power. The modifications were completed in January 2007, and the GEnx-1B engine was installed in the inboard pylon on the left wing of the aircraft in just one day.

By May 2007, Rolls was yet to fly its engine but was able to report it had nine engines in testing, “some of which are already into their second or even third rebuild,” said Horwood. Other key milestones passed or in the final stages were the engine type test and the 1,000-cycle initial maintenance interval (IMI) and bird ingestion tests, while total test hours and cycles now exceeded 1,000 and 2,000, respectively.

“We completed the fan blade-off test in the middle of April and we’re very pleased with the results of that,” said Horwood. This was the most severe of all the certification tests and involved explosively releasing a fan blade while the engine operated at full thrust. Further tests included water ingestion, operability, bird ingestion, altitude testing, and the completion of the 150-hour type test. Following completion of the IMI work, the sixth test engine was sent to Waco, Texas, to help with commissioning of the test bed itself.

Although the first flight on the 747 was originally set for about February, Horwood said Rolls-Royce elected to complete the majority of engine altitude testing at AEDC, “where we have a very good controlled environment. We wanted to complete our work at the altitude test facility, and we have chosen to make sure we’re flying on the FTB with a build standard as close as possible to the actual flight test standard.”

The Trent 1000 ultimately made its first flight on the test bed at Waco on June 19, 2007. By this point there were now two 787 engines flying successfully, and all the signs looked good for the successful start of Dreamliner flight tests the following August. However, events were to prove dramatically different.
Chapter 7
DREAMLIFTER

For more than twenty years, a fleet of converted Boeing 377 Stratocruisers formed the backbone of Airbus Industrie’s production system. These bizarrely modified transports, known as Super Guppies, droned across Europe’s skies carrying sections of aircraft, connecting the dispersed Airbus partner factories with the principal assembly sites, in Toulouse and Hamburg. The irony of the Super Guppy’s heritage gave rise to one of the oldest jokes in aerospace, namely that every Airbus jetliner began life in the belly of a Boeing.

The saga of the Guppy family, named after a bulbous species of tropical Caribbean fish, started when the second former Pan American World Airways Stratocruiser was bought by California-based Aero Space Lines Corporation for use in transporting large Apollo space rocket subassemblies from factories on the West Coast to Florida. Using a parallel fuselage section from another scrapped Stratocruiser, the transporter was stretched by 16 feet 8 inches. Then the upper fuselage was removed and a new 20-foot-high cargo area was built around a new lightweight roof structure. The outlandish-looking aircraft was christened the Pregnant Guppy, and it was officially designated the 377-PG. The empty weight rose from the standard aircraft’s 78,920 pounds to 91,000 pounds, but payload capability increased to 34,000 pounds.

The Pregnant Guppy was followed by new and weirder variants, dubbed the Super Guppy and the Mini Guppy. The SG was 31 feet longer than the standard 377 and had a new center section that added an extra 15 feet to the wingspan. Unlike the first conversion, which hinged in the rear fuselage, the Super Guppy hinged at the nose and could carry cargo of up to 25 feet 6 inches in diameter for more than 30 feet of its length. The Mini Guppy conversions, on the other hand, hinged simply at the tail. The later modified SP versions of the aircraft also were re-engined, with 4,912-shaft-horsepower Allison 501-D22C turboprops.

Boeing’s extraordinary 747-400LCF concept was first unveiled in late 2003 after two rounds of wind tunnel tests had confirmed the suitability of the baseline concept. As originally conceived, the transport had two large cargo doors in the aft left side, and a “strongback” dorsal fairing for structural reinforcement and improved lateral stability. The difficult door configuration was later dropped in favor of a hinging tail.

In another ironic twist, the Super Guppy was not developed originally for Airbus but was created for the first two U.S. widebody trijet programs, the DC-10 and the L-1011 TriStar. The aircraft entered service in the early 1970s carrying the first few DC-10 fuselage sections up the California coast, from Convair to Douglas’s Long Beach site, and TriStar wings from Avco in Nashville, Tennessee, to Palmdale, California.

But it was most ideal for Airbus Industrie, which desperately needed an efficient outsized freighter to connect its production sites. Seizing on the Super Guppy, it used the original pair of aircraft to shuttle subassemblies such as wings, tails, and fuselage sections between its European partner companies.

The workload eventually grew to the extent that Airbus contracted Aeromaritime of France to convert two more aircraft, for a fleet of four. The last of these was finally retired in 1997, when Airbus introduced a new, purpose-designed, jet-powered A300-600 transporter derivative called the Beluga. In the world of aerospace, one of the most startling ironies will always be that a derivative of Boeing’s last piston-engined product was vital to the birth of
Airbus Industries’ first jet, the A300, and to every subsequent member of the Airbus family until 1997.

The lessons of Airbus’s Skylink concept were not lost on Boeing when it started planning for its global logistics system. Although all the main 787 production sites have access to deepwater ports for seagoing vessels, air transport is the only means by which Boeing could hope to realize its global partnership vision for the unprecedented production rate envisioned for the 787. The move also paralleled the massive production process shake-up planned for the 787, and represented big changes for the delivery system, which to date had relied on ships, trucks, and trains.

Shimmering in the California sunshine, NASA’s Super Guppy departs from Edwards AFB after undercarriage replacement in 2005. Betraying Boeing 377 Stratocruiser/KC-97 heritage with its “levitating” shallow climb angle, the Super Guppy became the backbone of the Airbus production system before replacement with the purpose-built Beluga. NASA’s aircraft, the last of four to be used by Airbus, incorporated some original parts from the first Pregnant Guppy, which, in turn, used parts of the prototype Stratocruiser dating from 1948. Loads entered through the nose, which pivots 200 degrees to the left to give access to the 111-foot-long cargo area.

Walt Gillette recalled that the choice to opt for an airborne-based logistics network was “strictly an economics-based decision. Sometimes the world forgets Boeing was contracted to build the Stage 1B of the Saturn rockets for the Apollo program, and KC-97/Stratocruisers were converted to make that happen. It is simply the time value of money, and ocean shipping is getting to be more and more specialized, which makes it harder to find shippers who will take these odd-sized pallets.”

Mike Bair, then 7E7 senior vice president, said the plan would hopefully save the company up to 20 to 40 percent in production costs against current methods. “Transporting large pieces by air will allow us to dramatically reduce flow time,” though he added a note of caution, saying that “this is a tool built for the 7E7, and their fates are clearly linked.” Problems with the new freighter could spell problems for the 7E7, and vice versa. But while the risks were high, so were the rewards. Delivery times for the large subassemblies would be reduced from about thirty days to just one.

Boeing also briefly considered other outsize transports for the Dreamlifter role, including Antonov’s enormous An-124. With a 330,000-pound payload, greater even than that of the mighty Lockheed Martin C-5 Galaxy, and an overall length of 226 feet, it came close to what Boeing needed but came with too many maintenance and certification challenges. Here a mighty An-124 is pictured on the ramp at the Dubai Air Show. Mark Wagner
Based on the A300-600R airframe, the Beluga flew for the first time in 1994. Capable of carrying about ninety-eight thousand pounds—or almost double that of the Super Guppy—it has a usable length of almost 124 feet and can carry entire fuselage sections for every member of the Airbus family apart from the A380. Mark Wagner

So what to do? What could provide the best platform to carry the 787 sub-assemblies around, some of which—such as the combined fuselage sections or wings—would be huge? To get the right answer, Boeing undertook an exhaustive analysis of every current large freighter type in service, ranging from the 747-400F to the Antonov An-124, and decided fairly quickly that there was nothing out there to do the job it was looking for. It would have to develop its own twenty-first-century Super Guppy.

Fittingly, the company selected the legendary 747 as the most suitable candidate to create a transport that would help give birth to the latest member of the Boeing dynasty. In mid-2003, Boeing’s product development team began sketching out a concept that ballooned the existing 747 outline to remarkable proportions and, for the first time since the 747 was designed in the mid-1960s, stretched the airframe. Although having grown massively in terms of weight, range, payload, and capacity, the 747 had previously never been stretched beyond the length of the original -100 version.

In October 2003 Boeing revealed outline details of the outsize conversion, together with news that the bluff-sided transport had already undergone two major wind tunnel test campaigns. Configured with a hugely extended upper lobe, the original concept was aimed at being able to load 7E7 assemblies without the need for a hinging fuselage. Although the yawning gap of the 136-inch-by-98-inch nose door of the 747 freighter was large enough to swallow big loads, it was nowhere near large enough to take the completed fuselage sections, wings, and other large 7E7 subassemblies. Instead, the cavernous interior was to be accessed via two extremely large cargo doors installed on the left aft fuselage, about midway between the wing and the horizontal stabilizer.

Rising aft from around the Section 41 (nose section) production break line, the extended upper fuselage line ran back at such a height above the standard body that it would have easily accommodated a third deck had it been a passenger aircraft. As it was, the modification increased the interior height by up to ten feet as far back as the middle of Section 46 (aft fuselage), where it tapered into the Section 48 tail area. The extra bulge also increased the girth sufficiently to make the LCF about twenty inches wider than the Airbus A380.

Concerned about the effect of the bulging fuselage on directional stability, Boeing also studied extending the horizontal stabilizer as well as even putting large end plates on its tips, similar to the Space Shuttle carrier. However, wind tunnel tests showed that none of these changes was needed when lateral stability was augmented with a large dorsal fin and a connecting “strong back” reinforcement beam that extended forward from the leading edge of the fin.

The upper fuselage extension created a wider constant cross section that was big enough to take the “full 7E7 cross section,” said Boeing at the time. Design range was expected to match “747-400 capabilities, but the additional structural weight will reduce payload to between roughly 220,000 and 249,700 pounds,” it added. All the while, the basic aim was to keep the modification simple with a minimum of change, although the company acknowledged that the conversion was inevitably going to involve a “large statement of work,” no matter how final configuration was
defined.

**SWINGING THE TAIL**

By the end of 2003 it had, however, become clear that some changes were needed. The side-loading door, for example, simply would not provide adequate clearance for the loading vehicles, so the decision was made to develop a swing-tail cargo door instead. Various options were considered before Boeing engineers eventually settled on a simple double-hinge design similar to that developed for the Canadair CL-44D4, a Canadian-developed freighter variant of the Bristol Britannia turboprop.

The Canadian design team hit upon the unique swing-tail concept in the late 1950s as a way of meeting a tight sixty-minute turnaround time specified by potential freight customers such as Seaboard World Airlines and Flying Tigers. It also developed the “high loader” scissor-lift loading tool to operate with the CL-44, and which subsequently went on to widespread use at airfields around the world. Boeing would ultimately use distant cousins of both design concepts on the 747, which by early 2004 was known as the large cargo freighter, or LCF.

The dramatic extent of the rebuild required for the Dreamlifter is clearly seen in this December 2005 view of the first conversion underway at Evergreen Aviation Technologies Corporation’s modification facility in Taipei’s Chiang Kai-Shek International Airport. Rebuilding from the “waterline” upward, the new green pressure bulkhead at the rear of Section 41 can be seen at the top of the picture.

LCF firm configuration was achieved in October 2004, and the Boeing design team in Washington kicked off detailed design work on the new upper fuselage, transition zone, and main deck cargo floor as well as the Section 47 tail part with partners at the Boeing Design Center in Moscow, Russia. Responsibility for the revised Section 41, the only pressurized part of the LCF, went to Boeing’s Rocketdyne offices in Canoga Park, California, despite this unit having just been sold to engine maker Pratt & Whitney. The design work on the new forward pressure bulkhead, which butted up against the rear of the distinctive “brow” fairing, went to Stork Fokker of the Netherlands.

One of the most significant work packages, the design of the unique swing zone, went to Spanish aero structures company Gamesa Aeronautica, later renamed Aeronova following the 2006 buyout by a consortium led by the Caja Castilla La Mancha Corporation.

Consisting of a massive strengthened barrel section divided into two and connected with two massive hinges on the port side of the aircraft, the hinged swing zone section measured 10 feet in length and extended the overall fuselage length to 236 feet.

While doing design work, Boeing busied itself searching for someone to operate what would be an initial fleet of three LCFs. Scott Strode, manufacturing and quality vice president, said at the end of February 2005 that “we’re going on the streets with proposals, and we are primarily looking at operators with an existing experience base flying 747s.” The first aircraft for conversion had also by now been selected, all of them about midway through their service lives. The first selected, N747BC, serial number 904, had been flown by Air Algerie, while N780BA, serial number 778, had belonged to China Airlines, along with its sister aircraft.
The same month Boeing also formally announced the selection of Evergreen Aviation Technologies Corporation (EGAT), a joint venture of EVA Air and General Electric, to modify the aircraft. Work was to be undertaken in EGAT’s 127,440-square-foot hanger opened the previous December at Taipei’s Chiang Kai-shek International Airport. Meanwhile, veteran cargo 747 user Evergreen International Airlines of McMinnville, Oregon (no connection to EGAT of Taiwan), was selected as one of the LCF operators. Other LCF partners selected included Cargolux for European operations and Sojitz Corporation for Japan.

All was set, therefore, for the start of drastic modifications that involved dismantling each aircraft down to its “waterline,” or just at main deck level. The aircraft also was split aft of the trailing edge to accommodate the swing zone, and strengthened to support this large machined component and its stainless-steel main hinges.

By mid-2006 the second 747 had entered modification to be converted into an LCF, while a third was parked at Taipei, awaiting its turn. A decision over the acquisition and conversion of more 747s was still dependent on the outcome of Boeing’s studies into a possible second phase of its planned production rate increase beyond 2011–2012, but it looked increasingly likely as 787 orders soared toward the five-hundred mark.
The cathedral-like interior of the Dreamlifter has a main cargo deck volume of 65,000 cubic feet, some 300 percent more than the 747-400 freighter.

The second conversion was accomplished in less time, much to the relief of Boeing and Mike Bunney, director of Global Logistics for the 787 program. The acceleration was expected, and planned, largely because the initial conversion also included “proving out all the tooling,” said Bunney. “One of the big challenges was the sheer size of the subassemblies. Due to the size of the parts, we had to ship them all in, and the skins are so enormous that we had to build them all up on-site. We also had to build up the tooling and do some real precision work on hinges and the swing zone.” Bunney attributed the on-time success to the EGAT team. “We’ve got to give them a lot of credit, they’re a quick study.”

Finally the first LCF, soon to be officially dubbed Dreamlifter in place of a host of more colorful unofficial nicknames, was ready for its first flight. On September 9, 2006, the Dreamlifter launched off the runway in Taiwan for its two-hour, four-minute maiden flight, with Boeing test pilots Joe MacDonald and Randy Wyatt at the controls. Using the Boeing test call sign RT876, the crew first flew the curious-looking Dreamlifter north, and then 150 nautical miles south along the eastern side of the island before heading north again. The modified aircraft handled well according to the crew, and MacDonald commented that “quite often during the flight, it was easy to forget you were in an LCF rather than a regular 747-400.”

Boeing, which successfully ferried the first LCF to Seattle on September 16, went into the test effort confidently expecting to devote about 250 hours to flight tests and a similar amount to ground tests, most of which were to be concentrated on loading/unloading, maneuvering, and interaction with the ground vehicles. The reality, as it turned out, was very different, and instead of getting a supplementary type certificate as expected by year-end, it was not to be until June 2, 2007, that U.S. FAA approval was granted.
Like virtually everything else concerned with the 787 development, even the development of the cargo loaders broke new ground. Designed and built by Canadian company TLD of Sherbrooke, Quebec, the world’s longest cargo loaders were 118 feet 1 inch long and 27 feet 6 inches wide, and could carry up to 150,000 pounds or 68 tons. Driving on 32 tires attached to 16 steerable axles, the loader had a maximum speed of 10 mph.

Early on in the flight tests, the team encountered vibration issues that delayed the start of crucial flutter tests and that ultimately led to the removal of the standard 747-400 winglets. With other issues creeping up on it, Boeing reshuffled its flight test and certification plan, and worked with the FAA to allow it to begin using the first aircraft, LCF1, to start delivering parts as part of the certification effort. The arrangement, which Boeing said “allowed the FAA to validate the overall delivery process and tools,” enabled the manufacturer to complete initial deliveries of subassemblies to Everett for the first 787, ZA001, as well as the subsequent static test airframe, ZY997 (see chapter 8).

Eventually the Dreamlifter, which was not certified to carry passengers beyond essential crew, was cleared for operations after completing 437 flight-test hours and 639 hours of ground testing.

Given the role of the Dreamlifter and its pivotal role in the 787, Boeing had to have absolute faith in its newest transport and the host of “unique” ground vehicles that went with it. These included a special vehicle to swing open the tail as well as support it, and the TLD-built cargo loader. Measuring 118 feet in length, the Canadian-built loaders were dispatched to all the key sites in the United States, Japan, and Italy, where all were tested as part of the Dreamlifter certification effort.

With certification achieved, operation of the Dreamlifter fleet was soon assumed by Evergreen International Airlines, with LCF2 the first to be heard using the telltale Evergreen call sign, on July 17, 2007 during a training flight. It seemed that this ungainly behemoth, which Mike Bair once described as the type of aircraft “only a mother would love,” was about to begin earning its keep as a massive cog in the 787 production wheel.

Day-to-day operation of the Dreamlifter flight was handled by Oregon-based Evergreen International Airlines, no relation to the Taiwanese EVA modification group responsible for the conversion.
LONG BEFORE THE FIRST PARTS AND SYSTEMS FOR THE 787 WERE EVEN DESIGNED, let alone being built, Boeing was pondering the equally massive challenge of test and certification. The large amounts of composites and advanced, more-electric systems demanded an unprecedented number of new tests and, in some cases, adherence to whole new standards of certification.

Boeing began the process when it applied to the FAA for type certification of the 787-8 on March 28, 2003. “When you make the application to the FAA, that freezes the rules at that point, except for special conditions,” said Jeff Hawk, the 787 director of government, environment, and certification. Boeing’s plan was to get as much of a head start as possible on testing and preparing for certification, particularly “special conditions.”

These were issued by U.S. or European air-worthiness authorities in cases where the new aircraft was so different, or had some particular design feature, that it was not covered by the existing regulations. Boeing did not want any surprises and did not want to find itself in the position that Airbus was in 2005 with the A380, of still receiving notification of special conditions in the midst of flight tests.

Boeing met with FAA and EASA officials on a more or less continuous basis from 2003 onward to clear its certification plan by early 2006. But no matter how many meetings, Boeing knew it still would have to contend with a series of special conditions. However, even by mid-2005 Hawk believed there would be no “showstoppers” among them. “We may see one for lightning strike associated with composites, and perhaps others to do with the use of composites and electric systems,” he said at the time.

Structure around passenger and cargo doors was given additional plies of composite to help protect against “ramp rash,” the day-to-day damage from inadvertent collisions with service vehicles that all jetliners experience in airline operation.

Concurrently with preparing for tests of all the novel elements, Boeing also was developing the design to meet all the usual safety standards. “Is the design criteria different because of composites? Yes,” said 787 Engineering and Technology Vice President Randy Harley. “But we still have to define internal and external loads, static strength, crash-worthiness, and producibility as well as make it fail-safe, maintainable, repairable, and inspectable.”

Boeing’s priorities for testing composites focused on fatigue and corrosion, damage tolerance, crashworthiness, and producibility. All of these issues were generally well understood with conventional aluminum, “but with a composite they get more emphasis,” said Harley. Damage tolerance, for example, demanded new tests for hail and bird strikes as well as lightning protection.

Building on experience gained with certification of the 777’s largely composite empennage, and working closely with their military counterparts who had composite technology experience through involvement with the B-2, F-22, and X-32, among others, the Boeing 787 team developed a pyramid approach to testing and proving the airliner’s composite materials and structure. The base of the pyramid was formed with a broad set of small coupon tests of the
materials, most of them only two to three inches wide by ten inches long. Next was a series of element tests that covered slightly larger pieces, such as shear panels, representative of those to be used in the structural makeup of the airframe. On top of this were tests of a number of larger-scale subcomponents, such as complete wing skin panels. Above this were tests of even bigger components, such as complete fuselage barrel sections and tail units. Finally, on the top of the pyramid were full-scale static and fatigue ground tests as well as flight tests themselves.

The good in-service performance of the composite parts on the 777 gave Boeing confidence that the 787 would be able to stand up to day-to-day punishment, and that a wide range of repairs could be developed for airlines to quickly put damaged aircraft back into service. Repairs as basic as bolting on titanium sheet metal had been used to fix damage on a number of 777 horizontal stabilizers hit by maintenance stands and service trucks. Similar bolt-on patches, as well as bonded repair techniques using composite, also were being developed specifically for the 787.

One of the biggest worries of the airlines, however, was that composites could sustain potentially serious damage internally and yet look perfectly fine on the outside. Airlines, most completely unfamiliar with composite materials, had become particularly alarmed when Airbus said at a safety conference in late 2005 that the Dreamliner could be “grounded because of a scratch in the paint.” The problem, according to the European manufacturer, was that Boeing’s certification basis for the 787 called for inspections for visible damage only, without the need for nondestructive tests.

The claims infuriated Boeing. Justin Hale, then 787 chief mechanic, said, “We all know composites can hide damage, and so right up front we decided we’d certify for visible damage only.”

But what did this mean exactly? Boeing adopted design criteria for the static strength of the 787 that were related to barely visible impact damage (BVID), and for damage tolerance that were related to visible impact damage (VID). BVID was defined as small damage, such as dents of 0.01 to 0.02 inch deep, which could be caused by dropping a tool on the wing or fuselage, and which may not be found during heavy maintenance by general visual inspections using typical lighting conditions from a distance of five feet.

Anything designed to sustain BVID would have to prove, through rigorous testing, that it would maintain ultimate design strength and would not quietly grow into bigger, potentially dangerous structural damage inside the laminated skins. For VID, which included typical damage sustained by airframes from runway debris kicked up by tires, or from balls of hail, the requirements were to carry design limit loads without failure, and to carry residual strength loads until the damage was spotted and repaired. The design for VID also included the requirement that damage would not grow over time for the equivalent of an entire structural inspection interval, the first of which was not due for up to six years after service entry.

By March 2008 Alenia completed the ultimate load testing of the horizontal stabilizer at the Laboratory of Structural Tests in its Pomigliano plant in Naples. The tests, the first of their type to be conducted on a Boeing tail outside North America, proved the unit was more than capable of withstanding 150 percent of the design limit load it expected to see in its lifetime, eventually failing at 210 percent. The three-month test phase included repeated up-and-down movements as well as asymmetry at maximum load, simulating three critical design conditions for the stabilizer. Made of two monolithic co-cured side pieces and one central element, the sixty-five-foot-wide unit was cleverly manufactured in a one-shot autoclave cure cycle starting from twenty-seven uncured components. Alenia

The bottom line was that cracks did not grow, or propagate, in solid laminate composites, and neither would they weaken the overall structure. Small areas of damage would be acceptable for the entire life of the aircraft in most cases. “We have to demonstrate we’re good for these sorts of damage to the ultimate load for the life of the aircraft,” said Hale. Other damage tolerance requirements included continued safe flight following impact with an 8-pound
bird hitting the tail at Mach 0.85 and 8,000 feet, safe flight after being sliced by a scything, loose fan blade, and even the ability to survive a sudden decompression caused by the opening of holes in the skin of up to 20 square feet.

Another key focus was demonstrating tolerance to lightning strikes—a relatively frequent occurrence, which on average hits every commercial aircraft at least once per year. The concern with composites is that they are very poor conductors, usually a thousand times more resistive than aluminum. So bad are composites that thousands of lightning-induced volts would build up between different points on a 787-size composite airframe without special treatment, resulting in high levels of electrical current surging through cables, lines, tubes, and wire bundles—possibly with disastrous results.

Boeing debated long and hard over the best ways to counter the lightning threat. In early 2006 the Seattle Times published a leaked internal review showing that concerns over wing-lightning protection existed as late as the previous November. In particular, a safety team argued that with the existing design, sparks still could occur in the fuel tank, potentially blowing up the aircraft. Despite a startling one hundred lightning strikes per second on average around the world, safety features on modern airliners had ensured no lightning-induced commercial disasters since 1963, when a Pan Am 707 had exploded in flight over Maryland. Although an Iranian Air Force 747 was also brought down by a suspected lightning strike in 1976, the safety record was otherwise startlingly good.

Boeing’s first bump in the road to the 787 was a structural issue with the ninth one-piece test barrel that failed inspection following porosity problems in April 2006. This was caused by attempts to use a defective mandrel. The rejected barrel, thought to be this section sitting outside Boeing’s Developmental Center by Boeing Field in May that year, was part of the early certification process for the 787 and taught valuable lessons before final manufacturing began for the real aircraft. Guy Norris

Boeing ultimately overcame the safety concerns by taking a multilayered approach to countering the lightning threat. The first layer of defense was an embedded bronze-copper alloy mesh in the outer ply of the composite wing skin where fasteners joined it to the underlying ribs, stringers, and spars. This conducted the electrical charge around the fuselage, creating the same sort of “Faraday cage” effect as found on aluminum aircraft. Fasteners that were exposed to the fuel tanks were also sealed, brackets and fuel tubes were insulated, and the connections between the tanks and structure were electrically bonded. Nonconductive sealant also was applied to prevent sparks and arcs from happening inside the edges of the fuel tanks, where skin fasteners and joints could have direct lightning attachment and ignite vapors.

Messier-Bugatti used a large dynamometer to test and certificate its 787 electric brake system. Along with the alternative option offered by Goodrich, these were the first-ever commercial applications of electric braking in place of the more conventional hydraulically actuated brakes. The aircraft’s eight main wheels were fitted with electromechanically actuated carbon brakes driving digitally through four controller units. Tests on Messier-Bugatti’s brakes were run in France to obtain technical standard order certification, with work being performed at Villeurbanne, near Lyon. This was also responsible for research and development as well as carbon disc production for Formula 1 racing cars. Messier-Bugatti
Last, a nitrogen-generating system (NGS) was added as standard to fill the space above the fuel in the tank with inert gas. NGS (see chapter 5) was adopted as an added safety measure throughout the industry following the 1996 loss of a TWA 747-200 due to an explosion caused by a suspected short circuit in the center fuel tank.

Similar protection also was given to the fuselage structure to prevent lightning from gouging holes in the composite and to protect the myriad electrical and avionics systems inside. Dedicated metal conductors and bonding straps were added to safely conduct electricity through the additional metallic conduits. All the electrical systems within the fuselage were similarly “earthed” to prevent short-circuiting by being connected to a current-return network. Formed by a latticework of gray wiring, the network replaced the natural return path provided by a metal airframe.

SPECIAL CONDITIONS

The first of the FAA’s long-awaited special conditions were issued in March 2007 and focused on the aeroelastic interaction between the airframe structure and the fly-by-wire flight control system (FCS). The condition reflected the expansion of the 787 FCS into an all-axis system to handle lateral maneuvers and gust load alleviation. Another special condition stipulated that “suitable annunciation be provided to the flight crew when a flight condition exists in which nearly full control surface deflection occurs.” The FAA said this was required because, under certain conditions, the crew might not be aware of “excessive deflection or impending control surface deflection limiting,” with a resulting danger of loss of control.

The following month saw special crashworthiness conditions issued that required the composite wing and fuel-tank structure to withstand a post-crash fire long enough for passengers to evacuate safely. This was prompted by the dramatic difference in thermal conductivity between composites and aluminum, the latter being highly conductive and able to readily transmit the heat of a ground fire to fuel still in the tank. Far from being as bad as it sounds, this spread the heat over the wing surface and prevented localized hot spots, delaying structural collapse or burn-through beyond the time needed for evacuation. As carbon fiber had low thermal conductivity, the FAA called for additional tests and analyses to show that the 787 fuel tanks could resist a postcrash fire for at least five minutes.

Testing on the first experimental composite fuselage sections began in 2004 and paved the way for later development testing and assembly process work conducted by the structural partners. “They have not only been involved in the design, manufacturing, and assembly—but also in the structural tests,” said Randy Harley. The leading-edge slat structure was tested by Spirit in Kansas, and the trailing edge by Hawker de Havilland in Australia. The horizontal stabilizer was designed, built, and tested by Alenia in Italy, while the U.K.-designed landing gear was tested in Toronto, Canada.

By mid-2005 fuselage test work was ramping up, with three test barrels completed, including two versions of the original tail and aft fuselage Section 47, plus a constant-diameter barrel representing equally either a Section 43 or 46. “Now we’re working on a Section 41, and we will be doing around seven such test barrels in total,” said Walt Gillette, adding that by then the work of proving the material was essentially over. “From now on, we’re working on production efficiency, basically. At the end of this we will build a big piece of barrel and an additional half a piece of barrel for certification of the mechanical join of the major sections.”

It was not all plain sailing, however, and in May 2006 Boeing hit an unexpected bump in the development road when what was intended to be the ninth and final test specimen failed quality inspections. Porosity, or air spaces in the composite layers, was revealed by nondestructive inspection (NDI) of the thirty-three-foot-long constant-diameter test section. Built to assess a different mandrel tool and production process, the ninth test section had been added to check “improvements,” said Boeing.

Two extra barrels were added to conduct separate testing concurrently and to try to stay on schedule. Analysis revealed that the revised mandrel caused trapped gases to bubble when the lengthened section was being baked in the autoclave at the company’s developmental center site at Boeing Field. “While this was a pop-up for sure, this is exactly why we are doing it. It’s all about proving the technology at the development stage. If this was the first production barrel, then we’d be very upset,” said Boeing.

Tests also were under way on a first full-size structural wingbox involving a sixty-foot-long representative Mitsubishi-built outboard wing section and a ten-foot-long Fuji-made center-section unit. Mitsubishi supplied ribs, stringers, and spars for the test unit, with Boeing providing the composite skins. In the production version, the entire complete wingbox along with skins would arrive from Japan in a single piece.

For the full-scale tests, Boeing planned two airframes: a static test unit designated ZY997, and a fatigue airframe, ZY998. Although structurally complete, neither would ever fly, and both were doomed to a life of torture. In the case of ZY997, destined to be enclosed in a metallic prison made up of 1.5 million pounds of steel in the 40-23 Building, the static airframe would ultimately be flexed and stretched to destruction.
The static test airframe ZY997, enclosed within 1.5 million pounds of steel beams, was used initially to clear three preconditions needed for first flight, including a "high blow" overpressurization of the fuselage to 14.9 pounds per square inch, and dynamic actuation tests of the leading edge slats and trailing edge flaps. Mark Wagner

Although structurally complete, ZY997 did not incorporate simulated payloads or systems installations. The wings supported some representative control surfaces and high-lift devices, as well as engine pylons and weights, while a welded steel structure in the aft fuselage simulated the horizontal stabilizer. The static airframe was used to test eleven design-limit load conditions before the ultimate load testing, which was expected to see the wing bent upward by twenty-six feet. The airframe is pictured surrounded by towers and reaction fixtures, and was tested as a free-floating body with a ballasted load system to compensate for the deadweight. Mark Wagner

Pictured at Hamilton Sundstrand’s APSIF test facility, the company’s APUs APS5000 goes through its paces. The 787 APU was designed solely with the intent of generating electrical rather than pneumatic power and therefore did not have either a load compressor or a bleed system. Rated at 1,100shp and driving dual 225kVA generators through a large gearbox, the APU was started electrically using a starter/generator for the first time on October 31, 2005, at Hamilton Sundstrand’s power systems facility in San Diego, California. The APU used an electrical control system similar to that developed for the APS2300 used on the Embraer 170, and incorporated a single-stage centrifugal compressor with a pressure ratio in excess of 8:1, and a two-stage power turbine section. Hamilton Sundstrand
Static tests were designed to validate that internal and external stresses matched design predictions as well as to demonstrate the 787’s ultimate load capability. They included taking the airframe to the design limit load, the highest possible load expected to be experienced under extreme flight or ground conditions, without sustaining permanent structural deformation. Strain and stress test data also would be key to determining the growth potential of the structure for future versions of the 787, particularly the proposed “double-stretch” 787-10 variant.

Described by Harley as the “graduation event for the 787,” the static test program gradually ramped up in intensity. “We will test eleven conditions to design limit load, and then do the ultimate load testing when we expect a twenty-six-foot vertical displacement of the wing,” he said. Ultimate load tests took the structure to 150 percent max load or beyond, and was vital not only to determine the strength of the basic structure but also to discover if the airframe was overdesigned or had previously unknown areas of weakness.

The closer the final point of destruction came to 150 percent load, the better. During static tests on the 777, for example, the twinjet’s wing deflected twenty-four feet, reaching 154 percent maximum load point, before finally breaking with explosive force in January 1995. A final test to take the 787 wing to the point of failure was due at the completion of static work in 2009.

The static airframe was surrounded by towers and fixtures and raised to allow room for landing gear load reaction systems. The airframe was tested as a free-floating body with a ballasted load system to compensate for the deadweight, while the test-load control system provided programmable control of 182 hydraulic actuators attached to the structure. “These vary from small ones to larger ones capable of more than 400,000 pounds [force],” said 787 static test director Raymond Clark. Up to 8,000 strain gauges measured stresses that were transmitted to the data acquisition system by almost 10,000 channels, compared to about 1,500 in the original 777 static tests.

Fatigue tests on ZY998 started in the first half of 2009 and were due to run for three years, with a goal of demonstrating 165,000 simulated flight cycles by 2012. Design life for the 787 was 44,000 cycles, with the target of achieving 88,000 cycles—two lifetimes—by certification.

SYSTEMS TESTS

The greater level of systems sophistication and integration on the 787 gave extra urgency to testing and ironing out the inevitable bugs, particularly in view of the tight development schedule.

To test the 787 systems to the full, Boeing equipped a series of laboratories within the existing integrated aircraft systems test facility by the Duwarmish River, west of Boeing Field. The facility had proved highly effective during the development of the software-intensive 777, and this time its role was expanded to work directly with several off-site test and development labs established by system partners around the world.

The integrated test vehicle formed a vital part of the 787 development and was designed jointly by Boeing and the suppliers. The seventy-five-ton hybrid test rig was made up of actual flight control and hydraulic system components, all of which were linked to three test benches of system software. Mark Wagner

The largest of these was the Hamilton Sundstrand aircraft power system integration facility (APSIF) in Rockford, Illinois. Hamilton was the largest single systems supplier on the 787, with eight major packages comprising 1,300 major components and requiring 1.5 million lines of software code. The APSIF was conceived as part of the company’s original proposal for the various systems, and ended up becoming a complete representation of the 787’s electrical systems, from generators to motors, laid out as they are in the aircraft, with all the actual cabling.
Set up on two floors occupying fifteen thousand square feet, the power generation, conversion, and consumption machinery was on the ground floor, while the avionics and data acquisition systems were upstairs. The lab was so realistic that a 787 APU was housed in a container just outside the lab to provide power. The lab also could run off ground power or generators mounted to 1,500-horsepower dynamometers simulating the engines. These were programmed with the assist/resist curves of the real engines to fool the starter/generators into thinking they were connected to GEnx or Trent 1000s.

Power sources for the systems also were aircraft-identical and included four 250-kilowatt engine-mounted starter/generators and two 225-kilowatt starter/generators on the APU. Together they provided 1.45 megawatts of available electrical capacity via four main power buses. Two dual-redundant bus power control units managed the power distribution, directly as 235V variable-frequency AC or converted to 115VAC, 270VDC, or 28VDC. A bank of eight high-power motor controllers converted the high-voltage DC to the waveforms and frequencies required to drive the seventeen large motors.

Power consumers included four 75-kilowatt cabin compressors to provide air conditioning and cabin pressurization, plus two ram fans to move air through the environmental control system when “the aircraft” was stationary. Four 75-kilowatt motor-driven hydraulic pumps powered the flight controls and landing gear. On the upper floor were the overhead panels and flight displays required to power up the aircraft.

The site was electronically linked to Boeing, where test engineers were able to conduct tests of the integrated systems remotely. Similar labs, though on a smaller scale than the APSIF, were established by Honeywell, Rockwell Collins, and GE Aerospace, among others. Boeing believed that the array of labs would help keep the 787 development on track, despite the sophistication of the technology and the new territory covered. “That’s how it’s balancing out,” said Gillette. “We’re doing a number of innovative things that a decade ago would have taken longer, but we’re able to compress time dramatically, and essentially we’re doing more in a shorter time.”

Flight deck development was undertaken in the avionics integration lab as well as in the ITV, which used a full-up cockpit to “fly” the “Iron Bird” test rig. The cockpit was designed to enable full transition training from an Airbus model to the 787 in twenty-one days, and shortened transition and rating training for pilots qualified on other Boeing models to about thirteen days. For 777 pilots, the flight deck was designed to be so familiar that a mere five days would be needed for “differences” training, while 757/767 pilots would require eight days, and 737 pilots up to eleven days. Mark Wagner

Initial integration facility tests in Seattle started in October 2006, while the first wire bundle arrived at the labs the following month. The facility was made up of several distinct yet fundamentally interrelated labs. These included the avionics integration lab (AIL), the integrated test vehicle (ITV), aircraft energy management (AEM), engineering cabs, landing gear/brakes test labs, propulsion integration lab (PIL), lightning lab, and hydraulics and electrics test rooms.

The main focus for all the labs was the ITV, the “Iron Bird” hybrid test rig that combined actual flight control and hydraulic systems with system software to ensure that everything worked together as it was designed. The ITV was similar to the 777 flight control test rig, which it succeeded, but was a whole generation ahead in terms of capability and ability to run three tests simultaneously. The ITV incorporated a flight deck, which was used to “fly” a series of moving flight control surfaces using equivalent aircraft-level power from the propulsion lab, and all controlled with aircraft software running simultaneously in the AIL.
Fuji Heavy Industries completed the first production composite lower-skin section in June in preparation for the start of final assembly of the center wingbox. Although it was similar to conventional metallic alloy–based structures, Fuji tailored the box with varying thicknesses to suit local load requirements. Tests would later show that some subsequent strengthening would be needed. Measuring 17.4 feet by 19 feet, the lower skin was later mated with the upper skin, spars, and ribs before being combined with the Kawasaki Heavy Industries–built main landing gear wheelwell unit to make the first Section 11/45.

Mark Wagner

Under the “Lean Plus” manufacturing goals adopted for the 787, a new workforce of manufacturing technicians informally dubbed “super mechanics” were specially trained for standard assembly work as well as working with composites, and were taught to verify their own work. However, the 2007–2008 production catastrophe, much of it caused by the overwhelming wave of “traveled work,” prompted Boeing to revert to existing practices in areas such as quality control. Mark Wagner
By April 2007 Boeing had begun powering up avionics, hydraulic, flight control, and other systems for the first time using real “aircraft” power. The move marked a key step toward completing integration of all the systems before actual assembly began. “For the first time these labs are seeing actual ship’s power,” said Sinnett. “We powered the hydraulic systems with variable ship’s power, in other words varying the power provided as a function of engine speed as determined, in turn, by throttle position in the ITV.”

Although by this stage only about 25 percent of integration tests had been completed, several issues had been uncovered. But to Sinnett this was good news. “The goal is to find as many problems as early as we can. We are essentially on the number of problems we thought we’d be at. That’s a couple of thousand integration problems we’ve fixed so far.” Sinnet added that “the good news is that the bulk are integration issues, rather than problems that should have been picked up by suppliers during bench testing.”

The combined test team in the AIL reached the “full functionality” point at the end of May 2007, although integration issues continued to dog progress. This was largely down to the sheer size of the work package confronting the team. Excluding software for the in-flight entertainment systems, as well that used in the COTS processors, the 787’s systems required 6.5 million lines of code, or more than three times that used in the 777.

**BRINGING IT TOGETHER**

By mid-2005 steady progress was being made toward finalizing the detailed design, though the rate of release of digital-design datasets for the production of hardware varied enormously, depending on the part. Nacelle and pylon parts for the engine, for example, were well on the way to detailed release, with the first Rolls-Royce Trent 1000 due to start tests in mid-February 2006. “On the other hand, the wing-to-body fairing will be one of the last items to be
closed out. We have agreed where it will contact the fuselage, and we’re finalizing the shape of the fairing in the next month or two,” Gillette said in May that year.

By now the design team had racked up more than eight-hundred-thousand hours of computing time on Cray supercomputers, which are used in conjunction with traditional wind-tunnel work and the digital design tools. “We still do a great deal of wind-tunnel tests, and we’re about eighty percent done with those,” said Gillette. About fifteen-thousand hours of wind-tunnel tests were planned, with the remaining fifth focused on laying out the final lines.

Data from this latter work, mostly focused on the 787-8 variant, was used to develop initial flight-control system software for the first flight simulators. The final round of wind-tunnel work was wrapped up by early 2006, though more follow-on work was planned for subsequent stretch and midrange variants. “We will go back and do specific tune-up testing for the 787-3 and 787-9. It’s a pretty action-packed schedule, and it’s more like a continuous development,” said Gillette.

Firm configuration was completed in September 2005, kicking off the production of structures, systems, and parts all over the world. By mid-2006 factories and even some parts were sufficiently far enough along for first viewing. Eager to demonstrate the incredible rate of progress, Boeing took a group of globe-trotting journalists on a whirlwind tour to visit gleaming new production sites on three continents.

While stops in the United States and Europe revealed impressive but otherwise empty facilities, it was at Fuji in Japan that the very first structural parts of the first 787 were on show. Nestled in a holding fixture on the floor at the back of the Fuji 787 assembly site, and completed just three days before the arrival of the visitors, was the first production composite lower wing center-box skin section.

The group gathered closely around while some, including 787 Airplane Development and Production Vice President Scott Strode, appeared visibly moved by their first encounter with a tangible artifact of the Dreamliner. “Seeing the first real piece of the structure is terrific,” said Strode. “Watching the team see the results of their design work materialize is more of a symbolic milestone, but it’s also a big part of this job. It’s not just the tip of an iceberg, it’s more than that. In terms of industrialization, we’ve got a massive team building up with things going on in countries as far afield as Japan, Korea, Mexico, Russia, Turkey, and all across the USA. Sometimes it is staggering to think how many people are contributing at this time. We’re talking well in excess of ten thousand people.”

By July the skins for the first wing center box, or Section 11, were joined together, and the completed unit was shipped down the road to the nearby Kawasaki site, for integration with the main landing gear wheelwell, or Section 45. To many in the program this officially marked the starting point for the manufacture of the first 787.

In early December 2006 Boeing held a “virtual” roll-out celebration at its Everett site to mark the key role being played behind the scenes by Dassault Systèmes and other production system suppliers. Up to a year had probably been saved in the development program, Boeing said, compared to previous jetliners by having all the partners connected in real time to the same digital toolset. The event itself used engineering-based simulations and video of production getting under way to unveil plans for the 787’s final assembly production flow.

“This is not a cartoon made up for display, but real digital data,” said Bair, who stood in front of giant projected screens as what appeared to be an almost full-scale image of a 787 “rolled” into a virtual Everett building. Bair revealed that the assembly line would require about five hundred workers initially, rising to as many as eight hundred when production peaked at about one aircraft every three days. Compared to the many thousands required for earlier Boeing “7-series” jetliners, this was an astonishingly low number of workers for such rates. The projected final-assembly cycle time was just six days by the one-hundredth aircraft.

Painful though the adjustment seemed to local unions, the production plan reflected Boeing’s new role as a large-scale integrator rather than as the traditional original-equipment manufacturer. Also, though no one could know at that time, the troubles to come would trigger union strife and require far more resources to solve than Boeing or anyone else had ever predicted.

Even the assembly-line crew would be different, and Boeing faced the challenge of developing a workforce combining experienced employees from other lines with a new group of specially trained employees. Under Boeing’s “Lean Plus” initiative, the employees, called manufacturing technicians, were cross-trained and certified in a variety of disciplines instead of just one. The technicians were trained to verify their own work and follow a “clean-as-you-go” policy to reduce the dangers of foreign-object damage.

“We partnered with Edmunds Community College to provide preemployment training [PET] at our new employment resource center [ERC] in Everett, which was set up in the fall of 2006,” said 787 Manufacturing and Quality Vice President Steve Westby. To get a place on the 787 line, applicants underwent assessments before completing eighty-seven hours of PET training in their own time. Training for the first class started in January 2007, with trainees completing ten weeks of course work covering forty-four different job functions. The training involved
working on actual 787 fuselage sections for added realism. “We expect over eleven hundred people will have gone through the ERC by the end of 2007,” said Westby, who added that the mixed intake helped avoid added stress on the skilled workforce. “When we started work on the 787 the other programs were already running at a fairly high rate of production and we didn’t want to interrupt those.”

The first Section 11/45 was completed on schedule in Japan in December 2006 and arrived by 747LCF Dreamlifter at Global Aeronautica’s fuselage integration site in Charleston, South Carolina, on January 15, 2007, along with the first Section 43 forward fuselage from Kawasaki. The Alenia-made horizontal stabilizer became the first major assembly to be delivered to the Everett site, arriving on April 24 on board Dreamlifter N708BA, which provided a treat to plane spotters in Prestwick, Scotland, where it stopped to refuel en route from Grottaglie, Italy.

The first complete vertical fin made a much shorter journey, from Boeing’s Frederickson site up to Everett on May 7. Meanwhile, Mitsubishi’s first shipset of one-hundred-foot-long composite wings, completing the Japanese 35 percent share of structural work, was delivered directly to Everett in mid-May, a few weeks behind the original target date.

In late March, from the other side of the globe, the first Alenia-built fuselage Sections 44 and 46 arrived in Charleston.

The first half of 2007 was perhaps the most critical period in the history of the 787, as the trickle of parts arriving at Everett turned into a torrent. On May 11 the first Section 41 nose unit and aft fuselage section arrived from Spirit in Wichita and Vought in Charleston, respectively. With the arrival of the first wing set from Japan on May 15, and the first center fuselage sections from Global Aeronautica the following day, the major elements for ZA001 were finally in place and assembly could start.

Even though the first center fuselage and nose Section 41 were loaded into the assembly jigs on May 16, the process was officially marked by a ceremony five days later, on May 21. “Today we begin assembling the first airplane of a new generation,” said Strode, who added, “the 787 not only will revolutionize air travel, it represents a new way of building airplanes.” The mood at the event—outwardly, at least—was upbeat, and Boeing felt optimistic about meeting the target date for roll-out, which was set for July 8, 2007. In the U.S. dating convention, this was 7-8-07, a day carefully selected to symbolize the Dreamliner as well as to avoid a clash with the Paris Air Show. The “power on” milestone, in which all the systems would be electrically activated for the first time, was penciled in for late July, with first flight targeted for August 28, 2007.

LEAN LINE

Amid the growing anticipation, Boeing officially inaugurated its 787 final assembly line and invited the media to view the closely guarded facility in late May. Although only allowed to look down from a balcony high up in the west wall of Building 40-26, the dramatic new changes were immediately obvious in the “lean” way Boeing planned to put the new Dreamliner together.

The new vision for 787 assembly was a simple nose-to-tail flow. Gone was the line of partly assembled aircraft in their traditional “slant” positions, and with it the complex choreography of moving them down the line slot by slot. Compared with the visually busy lines elsewhere throughout Everett, the 787 line in Building 40-26 would seem almost empty even when it was pumping out one aircraft every three days—a record for any widebody.

The line looked uncluttered mostly because the massive “monument” assembly tools had vanished as part of the move to “lean.” Thanks to this, and the decision to bring in the 787 parts as large sub-assemblies, the line and its new processes were unlike anything seen before in the Everett building since the first bays were erected for the 747 program more than forty years ago. “This is a very different production model,” said Westby. “There are changes in technology covering everything from the way we exchange information to the logistics involved in how we get the parts here.”
Looking like a real aircraft for the first time, the 787 moves to position two for landing gear and engine installation, as well as interior installation. In this scene, however, the second flyable 787—ZA002—remains far from being as complete as it should be at this stage. Although components were 50 percent more complete than ZA001 on arrival at Everett starting from June 2007, final assembly did not start until February 2008—about six months later than expected. Note the rudder already prepainted for balance reasons in ANA livery, and the distant 777 tail in Emirates colors in the adjacent assembly bay.

Mark Wagner

Although Boeing’s principles incorporated a “real focus on ease of manufacturing as well as ease of design,” Westby added, “we’ve take a lot from the people who are helping us build this around the world. But by far, we’ve taken the most from what we’ve learned on our other lines, particularly the 737 and 777.”

By the time the 787 assembly was being established, the 737 and 777 lines were flowing through the factory with aircraft assembled in a nose-to-tail position, the 737 line at Renton moving continuously and the 777, at the rate of seven per month, “pulsing” along the line. Both lines had been reconfigured along lean principles for greater efficiency. “This is the first time we’ve designed a line from the start for nose-to-tail positions,” said Westby.

Following delivery of the parts to Everett by road, rail, or Dreamlifter, all the sub-assemblies were gathered in Building 40-36 on the northern side of the complex. The largest subassemblies were delivered on a specially designed cargo loader vehicle (see chapter 7), which trundled slowly around from the ramp area, while smaller parts arrived by truck and forklift. On arrival, the largest parts were picked up by a massive mobile gantry crane, nicknamed “the Boat Loader” because of its resemblance to the large mobile cranes seen at docksides.

Normally the biggest crane on the dock side, this specially modified 45-foot-tall ISL70 crane is easily absorbed into Boeing’s 472-million-cubic-foot Everett site. Dubbed “the Boat Loader” and supplied by Wisconsin-based Shuttlelift, the mobile gantry crane lifts sections from the cargo loader and delivers them from the preintegration area for induction onto the final assembly line. To work indoors, the crane’s General Motors 8.1L gas engine was converted to propane, thus eliminating harmful exhaust emissions. The crane’s four hoist drums, on the lower side beams, also were modified to move independently to handle irregular components such as the wing sections. The crane also is radio-controlled, providing steering for the four-wheel-drive/four-wheel-steering modes. Mark Wagner

When it was full, Building 40-36 resembled a model aircraft kit box, with big pieces of aircraft ready to be “glued” together. The parts were prepped for induction into the final assembly line in a process called preintegration. The same building also housed the horizontal stabilizer assembly area, as well as outboard wing integration, fin and
rudder assembly, and installation of floors and the tail cone. Once parts were prepared for the line they were picked up by the boat loader and carried through to the adjacent Building 40-26 for loading into the final assembly line.

Building 40-26 housed four positions and was designed with the flexibility to operate at a fast “pulse” rate, or gradually ramp up into a continuous moving line if necessary. “We have the ability to move it like the 737 and 777 if we want to,” said Westby, who added that the plan was initially to use the first three positions, with the fourth reserved for future expansion. Assembly time for the early “flow” aircraft was expected to be about seven weeks, while the “six-day flow” was envisaged by line number 100. The much-anticipated three-day flow was targeted for the ten-per-month rate in about 2010.

The assembly of the aircraft began in position 1, where final body join and systems installation and connection got under way. Symbolically dubbed “the Big Bang,” the work at position 1 included wing body and fin join, along with the assembly of the finished Section 48 empennage unit. Wings also were brought to the position on large mobile cradles, which doubled as tools for fitting the raked wingtips and the engine pylons. Other cradles also brought Section 41 and other fuselage parts into place for body joining.

Dwarfing all other tooling in Building 40-26 was a huge mobile structure called the MOATT, or “mother of all tooling towers.” Consisting of twin towers supporting cantilevered booms, the MOATT “acts like a clamshell and surrounds the aft part of the aircraft,” said Westby. Supporting the join between the aft sections 47 and 48, the MOATT picked up the horizontal stabilizer, fin, and “basically acts as a stand to build the whole aft end of the aircraft,” he added.

Forward of the tower were a pair of circumferential join tools, located fore and aft of the wing. The front tool joined the forward Section 41 to the midfuselage assembly, while the rear tool joined the aft 47/48 sections to the rest of the fuselage. “There are very few manually drilled holes,” says Westby. Using a process called “determinate assembly,” the parts were designed to virtually snap together.

This meant that all the pieces had to be precisely lined up to avoid any mismatch. Based on earlier experience on the 737 and the 747, Boeing implemented a sophisticated, rail-guided jacking and alignment system made up of about nine major units. Positioning data were derived from the digital design database and precisely aligned and rechecked using a series of laser transmitters mounted in a specially constructed truss high in the rafters.

To Boeing workers this impressive blue-and-yellow structure is the “mother of all tooling towers,” or MOATT. However, it officially lives by the more prosaic title horizontal stabilizer/vertical fin/APU installation (HVA) tool. As the major tool on the line, it pulls together all the largest components in one position. Comprising two subassembly platforms that join around the aft fuselage, it also includes jib-crane-style handling devices, as well as an alignment and positioning system for the horizontal stabilizer/tail cone assembly, and an elevator system for APU installation. Mark Wagner

From position 1 the airframe moved on the rail-guided jacking pads to position 2, where the inboard trailing and
leading edges, fairings, engines, nacelles, and main landing gear doors were fitted. The main landing gear also was fitted, allowing the aircraft to roll forward to position 3 without the need for external support. The final position was dedicated to interior completion and production test work.

The assembly process, or “one-piece flow,” as it was described, was to be sped along its way by a third-party logistics company called New Breed. The company interfaced between the suppliers and the final assembly line, providing receiving, sequencing, kitting, inventory, and order management. The prekitted parts were provided for line-side delivery at point-of-use positions. Larger parts, such as engines and nacelles, were supplied separately by the manufacturers. At least that was the plan, a lot of which was to change beyond all recognition in the coming months.

While assembly of ZA001 still appeared to be progressing well, Boeing revealed its plans for the rest of the test fleet. Next would come the static test airframe, followed by ZA002, the second Rolls-Royce–powered test aircraft. Fourth would be the fatigue test airframe, while the following six would include the remaining two Rolls-Royce test aircraft, the initial production 787s for launch customer All Nippon Airways, and the two General Electric GEnx-powered test aircraft, ZA005 and ZA006.

Plans also included refurbishment of the test aircraft in 2008 for delivery to ANA and Northwest Airlines, while the seventh aircraft, and the first to be handed over to ANA in May 2008, was to be the first at the production-standard weight. “It looks like we’re coming in just under the wire on weight,” said Scott Stode. “We’re not over, and just under—which is good,” he added. But sadly, disaster lay ahead.
Chapter 9
DEVIL IN THE DETAILS

ON JULY 8, 2007, the sleek and beautiful new 787 was officially unveiled to the world. The massive doors of Building 40-26 rolled back to reveal the blue, white, and silver aircraft glinting like a new toy in the summer sunshine.

Fifteen thousand people at the ceremony erupted in wild cheers and applause, while elsewhere it is estimated that more than a million people around the United States and at suppliers all over the planet watched and celebrated via satellite and the Web.

It was a wildly successful public relations and marketing event, but as the crowds milled around the new baby, touching its shapely fuselage and admiring its fine lines, there were a few who quietly knew that something was wrong. Closer inspection revealed multiple holes, many missing fasteners, dummy structures, and the empty shell of a flight deck and cabin. With first flight supposedly a mere seven weeks away, there seemed an ominously huge mountain of work facing the Everett assembly team.

The premature rush to roll out was revealed when ZA001 was viewed close up. Due to its temporary coverings, fasteners, false surfaces, and unfinished flight deck, the empty shell was derided by some as the “Potemkin Dreamliner.” This was a reference to artificial villages purportedly built along the banks of the Dnieper River in the 1700s by Russian minister Grigori Aleksandrovich Potemkin to fool and impress the visiting monarch Empress Catherine II.

Fears that the celebrations may have been premature were soon confirmed when the company began hinting at a possible slip in first flight to late September 2007, or even beyond. The first official clues emerged in late July, when Boeing President and Chief Executive Officer James McNerney admitted that the company was “slightly behind” on the project and that research and development spending for the year had been cranked up dramatically to $3.7 billion, largely “to preserve the 787 schedule.”

But hints of trouble to come could be traced as far back as mid-2006, when Boeing confirmed that it was slowing down studies of how to ramp up its planned 787 production rate from ten per month to twelve in 2011. At the time, 787 Business Management Vice President Craig Saddler said the study was slowing to ease pressure on suppliers and to give them more time to get their production processes right. “To be honest, they’re a bit tentative,” he said. “We’ve been asking them to do something they’ve never done before. We’re probably better off letting people build parts—their confidence will come way up and I think we’re going to find out we’re in a lot better shape than we thought we were.”

The potential for committing too hastily to new production practices had been exposed by Boeing’s own experiences with the assembly of a flawed composite fuselage barrel section earlier in 2006. Described by Bair as the “infamous barrel that didn’t work,” it led to the development of a new mandrel that was later used to make two new demonstration barrel sections in Boeing’s developmental center. The original problem was caused because the composite mandrel “expanded too much, and rather than redo it, we sent it back to the machine shop, and leak paths developed. We should have thrown it away,” recalled Bair. “This one was flawed going in and we thought we could
make it work, but we couldn’t.” The result was bubbles and voids that developed in the composite as it was being wound on the mandrel.

The incident was viewed as a something of a godsend by Strode, who said, “Because of the examination of what went wrong, we could have avoided future problems cropping up in particular factories. I’m not saying we’ve had problems, but this has certainly reduced the chances of it happening in the future.”

There were other worries, too. By mid-2006 a concerted charge was under way to drive out more weight, which in July that year was “around 2 to 3 percent” over target, according to Bair.

Recognizing the growing urgency, engineering resources were brought in from across Boeing “as well as from the supplier partners,” Saddler confirmed. “There are a whole lot of ideas on how we can reduce weight—some of which could cause more testing to be done.” A “war room” was put together, and weight czars appointed for each part of the aircraft. The one comforting factor in all this was that the initial wing assemblies—the center wingbox—from Fuji “came in lighter than predicted, so that makes me feel good.” Only time would tell how misplaced this good feeling was.

The astonishing achievements of the 787 sales team added to the pressure to deliver on time. Firm sales pushed through the 420 mark by mid-September 2006, making it easily the first commercial airliner program to have racked up so many orders before the first flight. But as fall 2006 began in Seattle, Airplane Development and Production Vice President Scott Strode eyed the calendar nervously. “The next three months is the most critical phase for the program because that’s when we begin really building the first article, and activating all the labs and getting the systems going.

“We are really into that ‘crunch’ time of moving from the engineering and testing part of the program and into assembly. Just about every major work package is into fabrication, and we’re ramping up globally. We’re also beginning the delivery phase for the electronics into various labs,” he said. Yet Strode was aware of the growing rumors of development delays, systems and structural problems, and schedule slips. He acknowledged, “There is a similar pattern to all these programs. We are a little late on getting some of the engineering out, and we are compressing the schedule to accommodate that. There are a few critical areas we are behind on and we’re working hard on those.”

One such area was materials. “We’ve had a lot of tough struggles in obtaining big titanium forgings,” said Strode, echoing earlier warnings from Mike Bair, who described the raw material as a “watch item, because this aircraft consumes an enormous amount of titanium. Right now there is a pinch point in the market for titanium.” Strode’s chief worry at this point appeared to be putting it all together. “Hardware deliveries in terms of systems are not an area we are concerned about. What we are concerned about most is the integration of the systems and software and validating all the functionality. We have got all that going on through the rest of the year.”

Strode also openly acknowledged the massive gamble the new 787 production system represented. “We have a great deal of concurrency with the design, build, and test activity all going on, which carries inherent risk. However, all in all, the testing has gone better than expected, though we still have a lot of big ones coming up. But so far, knock on wood, we’ve had good results!”

As the rush to final assembly began, Strode identified four main targets. “Number one is getting the first complete composite airframe on its way through its layup and curing—that’s really critical. Second is the manufacturing of all the parts in the supply chain and the orchestration of that. Number three—we certainly want to keep on track with the development of systems, and the testing of their functionality in the labs. Fourth, we need the engine programs to get the data they need, and for them to keep building hours. Those are the big watch items.”

**WEIGHT WATCHER**

But despite the confident public face, further signs that all was not entirely well continued to emerge. In late October 2006, Boeing revealed a larger than expected ramp-up in R&D spending, to $450 million for the year. Some 60 percent higher than first predicted, the increase was partly due to the start of work on the newly launched 747-8. But at least half was attributed to the 787.

McNerney said that the nonstop fight against weight, which he described as a “dogged issue,” was partly to blame, but he was otherwise bullish on the spending, which he characterized as “pretty aggressive contingency planning.” Boeing revealed that it was pouring resources into combating “traveled work,” a phrase guaranteed to send shivers up the spine of any Boeing employee who could recall the chaos this caused during the production crisis in the late 1990s.

Traveled, or out-of-sequence work, meant that tasks scheduled to be undertaken at a certain point in the production process had to be performed at another time, and sometimes another place. This generally resulted from parts or systems not being delivered at the right time or, in the case of a new program, simply not being ready in
time. The resulting knock-on disruption to other parts of the assembly process could easily get out of hand, as all who experienced the earlier production meltdown knew only too well.

To counter the traveled work, Boeing prepared to temporarily undertake some final assembly work on wiring and other systems that, under the production plan, was supposed to be performed by suppliers before delivery at the Everett assembly site. Boeing reassured investors that the measures would probably only be required for the first one or two aircraft. Financial analysts Bernstein Research said “the additional R&D is negligible in what we estimate will be a roughly $8 billion development program for Boeing.” It added that Boeing, while historically on time and performance, “has typically been over budget. All evidence we have seen suggests that the 787 will be no different.”

Temporary and missing fasteners plagued the program from the start. The overstressed fastener manufacturers could not keep pace with the massive volume demands of the aerospace boom of the mid-2000s while simultaneously developing a new set of composite-friendly fasteners for the 787. No amount of paintwork could disguise these telltale signs of the shortage appearing in the skin of ZA001 at rollout.

Early development issues discovered during experiments with a composite mandrel convinced some suppliers, such as Alenia, that it was best to stick to tried and tested units made from dependable, but extremely heavy, invar. Here a rarely seen exposed mandrel awaits its next set of stringers and skin wrapping at Alenia. Mark Wagner

By year-end it was becoming apparent the 787 program was having to race to reach the finish line. Bair, unwilling to disguise the situation, said “scrambling is a core competency of the Boeing Company,” and confirmed not only that some suppliers were struggling, but also that weight remained a problem to the tune of roughly 2.5 tons. Without pointing fingers, Bair added worryingly, “There are some partners who are going to be late. We know how late they’re going to be.”

Late changes by Boeing also were impacting the systems. In mid-January 2007, the company unexpectedly ditched plans to fit wireless in-flight entertainment (IFE) technology to the 787, but insisted the move to a conventional hard-wired replacement system would not impact either schedule or cost. Systems Director Mike Sinnett said the “hard decision” to reject WiFi IFE was made because Boeing could not get 100 percent agreement from countries around the world to allocate frequencies in the IFE system’s 5-gigahertz operating bandwidth. In addition, concerns were raised about the ability of the wireless technology to reuse the same frequencies for multiple
uses, and for it to keep pace with the expected volume of seat-back content. The only good news was that the change saved more than one-hundred pounds in weight.

News of the change coincided with an analyst’s report saying that some 787 customers had been told their aircraft deliveries could slide. Boeing immediately denied the Wachovia Capital Markets report and said, “There are no delivery delays in 2008 and we are still scheduled to meet entry-into-service in May 2008.” The first flight, it insisted, remained on track for the end of August 2007.

Meanwhile, unknown to most of the outside world, the traveled work problem crept over the Everett production system like an unstoppable tide. Having been designed to integrate large-scale sub-assemblies, it was simply not geared up to absorb the extra work that began to show up at its door with every Dreamlifter flight.

Many of the first structural subassemblies arrived as virtually empty shells and needed to have systems installed, while the shells themselves were frequently covered with marks, or pieces of sticky tape, to indicate defects that required fixing. The first nose Section 41, for example, was delivered from Wichita without many of the avionics and flight deck systems installed. To make matters worse, parts were arriving held together with red-painted temporary fasteners, reflecting an industrywide shortage that was to have a particularly debilitating effect on the embryonic 787 production system.

On arrival, each temporary fastener had to be drilled out and replaced with a permanent one. This was time-consuming and complicated because the paperwork trail for each part was often written in the original non-English languages of the cosmopolitan supply base. Translations were supplied, but Boeing workers worried that errors could easily be introduced. Furthermore, replacing fasteners sometimes caused local damage to the composite structure, requiring repairs and further slowing the pace of final assembly.

Boeing had predicted inevitable problems with the formidable logistics of the global assembly plan, and to help overcome these, appointed outside specialists to effectively manage the process. The company, called New Breed, was used on other Boeing programs and interfaced between the suppliers and the final assembly line, providing receiving, sequencing, kitting, inventory, and order management. They helped provide prekitted parts for line-side delivery where they were required for final assembly.

Although New Breed’s system was designed to accommodate slips in the schedule and some out-of-sequence work, it was stretched to the breaking point under the strain of the supply-chain train wreck. “The challenge for New Breed at the moment is there are a lot of ‘traveled parts’—which is not a part of their plan,” said Scott Strode who, at the time, remained outwardly optimistic of a quick recovery. “We have a lot of work going on to mutually understand that,” he added.
There was another problem: when they did arrive, the parts did not fit together as perfectly as planned. On June 12, just before the start of the 2007 Paris Air Show, the Seattle Times published a worrying revelation. When Everett workers mated the Section 41 nose unit with the Section 43 center fuselage, a 0.3-inch gap appeared between the butt lines. In a trade where mismatches of a few thousandths of an inch are considered canyonlike, the news was astonishing.

At the air show in France, Bair provided an explanation that, in retrospect, was almost as concerning as it was meant to be reassuring. The sections, it appeared, had been delivered so incomplete that they did not include adequate secondary support structure. As a result the barrels had slightly deformed, or “sagged,” said Bair. “The issue was because we didn’t have all the fasteners to put in the secondary structure. Spirit had to put the structure into the cradle while they finished it, and it turned out that it sagged a bit and got a minor bulge in the lower part of the barrel.”

Overlooked amid the mismatches were precision fits between the wings and the fuselage that would have made headlines on any previous program. Scott Carson told Bair that the fit had been “absolutely astonishing”—with the left wing only one forty-thousandths of an inch out of alignment, while the right wing was “dead on.” The result, said Bair, was a “testament to the accuracy of the design tools, and the stability of composite technology, which will serve us well as we increase production.”

Titanium supplies became a “watch item” in the early days of the program, just as large billets of the material were needed for large, long-lead forgings such as the main undercarriage leg, an example of which is seen here. Mark Wagner
the load at Everett. As the production crisis worsened, the number of aircraft planned to pass through Kelly grew, and by early 2008 covered more than twenty.

On September 5 Boeing finally acknowledged that the flight control software, fastener shortage, and documentation issues had conspired to delay the first flight until at least mid-November, and possibly as late as mid-December. ANA had meanwhile been reassured that delivery was still set for May 2008. Besieged by reporters’ questions, Mike Bair was on the defensive. “We didn’t digitally simulate missing thousands of fasteners. In hindsight maybe we should have been more diligent in looking at that, but it certainly wasn’t something that was on our radar screen.”

Six days later, at a Morgan Stanley investor conference, the chief financial officer for Honeywell admitted that integration of his company’s flight control software into the overall avionics suite had been complicated and had taken longer than hoped. But he also hinted that the blame was not just Honeywell’s. Echoing comments made at the same conference a day earlier by Rockwell Collins CEO Clay Jones, the Honeywell CFO also hinted that problems were linked to Boeing’s delay in finalizing the design. Jones, whose company made the pilots’ controls, said similar definition delays had impacted the delivery schedule.

McNerney also was at the conference and warned that the fastener shortage could pose a longer-term risk for the 787 than previously estimated. Until now, Boeing had said that the fastener issue would be resolved by the time the twentieth aircraft was assembled. “We’re making progress, but it’s still a scramble, if I’m honest,” he said.

Boeing attributed the fastener shortage to industrial capacity issues, blaming a wave of consolidation in the fastener industry several years earlier as well as the surging demand from the booming aerospace sector. The new consolidated firms such as Alcoa, McNerney said, “misjudged” the air transport industry’s rebound after 2004 and failed to invest in new capacity. Bair had earlier said that the fastener industry was “very stretched with the 737 and 777 at record rates, not to mention Airbus. We came in with a new aircraft and new fastener requirements, and quite frankly it’s been a struggle.”

By late September it became increasingly obvious that the struggle was too much, and in the first week of October, Boeing quietly warned Chinese carriers, with a cumulative sixty orders, that delays were likely. At a painful program review the next Monday, October 8, the 787 management team formally acknowledged that they were facing a six-month delay. Since this was large enough to impact the company’s performance, Boeing had no choice under Securities and Exchange Commission regulations but to arrange a press conference to publicly disclose the problems.
An early setback was the decision to drop, at least for the moment, plans to install a wireless in-flight entertainment system. Here a ship set of seat-back screens, all hard-wired together, undergo tests at Boeing’s integrated aircraft systems lab. Mark Wagner

Pictured during rollout at Spirit AeroSystems in Wichita, Kansas, the first nose Section 41 was shipped as an empty shell to Everett. Spirit, like other first-tier partners, had been fighting a losing battle to complete its subassembly on time because of inadequate support from its many tier two and three suppliers. Many of these smaller companies lacked sufficient numbers of quality inspection and production personnel to support Boeing’s ambitious ramp-up. Note the peach-colored streaks marking the zones between the caul plates used during processing in the autoclave. Succeeding Section 41s became increasingly complete, with ZA004 100 percent complete. Guy Norris
By late 2007 the first sections for ZY998, the fatigue airframe—also known as line number 9998—were collecting together at Everett. Here the tail fin, festooned with mounts for strain gauges, awaits integration. Mark Wagner

MORE DELAYS

On October 10 McNerney and Carson confirmed that deliveries of the initial thirty to thirty-five aircraft to the first fifteen customers would be delayed. At the same time, both stressed that the basic program remained sound. “We wish we didn’t have to do this,” McNerney said. “But new kinds of innovation, as this airplane represents, represent challenges.” Carson added that unplanned rework on ZA001 had “simply proved to be more difficult to complete” than expected. “Acceleration on the work we needed to see has not occurred, but we do believe the more difficult structural work is now behind us.”

More resequencing of work was also under way to ease the strain, particularly at the Charleston and Vought factories, where the use of new workers and facilities had come under increased scrutiny. With hindsight, Carson said training needed to be tackled earlier at sites such as Global Aeronautica, though he added, “there is no fundamental flaw in Charleston.” McNerney insisted that the company’s basic global manufacturing strategy remained valid. “We’re convinced that as we work our way through these problems we’re going to be glad when we get to the other side of start-up.” Despite the delays, Boeing still predicted delivery of 109 aircraft by the end of 2009, just three short of the original plan. The good news, said Carson, was that software was “no longer a pacing item. We expect to have flight test–ready software fully loaded in the next few weeks. The final load for the simulator was delivered in September and is working very well.”

Six days after announcing the new delays, Carson had more news. On October 16 he named Pat Shanahan vice president and general manager of the 787 program, replacing Bair, who returned to his former role as vice president, business strategy and marketing, for Commercial Airplanes. Shanahan, who had overseen the last days of the 757 as well as headed the 767-400ER, moved from vice president, missile defense systems, at Boeing Integrated Defense Systems. Here he had helped turn around the troubled ground-based midcourse defense system, a complex antimissile program. Referring to this experience, Carson said Shanahan would “tackle the challenges we face in bringing our new production system fully on line.”

These challenges were increasingly focused on trying to strengthen the weakest links in the supply chain. Less than two weeks after moving out of the 787 program, Bair hinted that Boeing’s patience with some of its team members was just about exhausted. Speaking frankly to the Snohomish County Economic Development Council about unidentified suppliers, he said, “Some of these guys we won’t use again. We made a bunch of mistakes and we learned a lot.” He also proposed that future projects could be developed around “supersites” where suppliers and final assembly could be colocated to minimize logistics and improve responsiveness.

But who were these delinquent suppliers? A big clue came in early November, when Shanahan announced that Scott Strode, previously vice president of airplane definition and production, was to be sent to “oversee” all 787 activities with Vought Aircraft Industries. Within the week, Vought CEO Elmer Doty openly acknowledged to analysts, “I don’t think you need rumors to assume we are among the riskiest, if not the riskiest, of the structure producers.”

Dispatching Strode to Vought was the closest Boeing had come to openly exposing the need for much tighter control over its suppliers. In early December, just days before the first 787 update under Shanahan’s watch, Carson
commented, “In addition to oversight, you need insight into what’s actually going on in those factories. Had we had adequate insight, we could have helped our suppliers understand the challenges.”

Boeing now targeted January 2008 for the power-on milestone, the moment when the 787 systems would be powered up and the aircraft begin to come to life. Shanahan explained why this was important. “First, power-on is a significant knowledge point technically because we can then retire risk around the integration of the airplane. And second, our schedule becomes much more predictable once we get the power on because the airplane is finally in the state that our factory was designed for.”

Boeing internally penciled in March 31, 2008, for first flight and believed that with an aggressive flight test program, it still might be able to deliver the first aircraft by the end of the year.

Most of Boeing traditionally closed down between Christmas and New Year, but for the besieged 787 team there was no such luxury. Despite round-the-clock shifts in 40-26 and a massive ramp-up of Boeing staff throughout the supply chain, further delays became inevitable. On January 16 Boeing announced fresh holdups and, worse still, said it would be at least two months before it could even identify how long the delivery delays would be or when the bulk of the test fleet would join the program.

The first flight now slipped to about the end of June, with the blame again placed on traveled work and problems associated with verifying production records and processes. Shanahan said, “We thought in December over the holiday break we’d turn the corner on the completion of critical structural traveled work from our partners on the fuselage. We’ve not been able to finish that assembly work, and the process to reconcile the partner’s engineering with our production records and processes is very onerous and time-consuming. That’s proved to be the critical pacing item to putting power on the aircraft.” The new power-on target was early April.

Scott Carson added, “We have resisted the temptation this time to make a broad and sweeping generalization about where we are on the rest of the aircraft. Until we have completed an assessment of the condition of assembly on aircraft 2 through 6—that are critical to flight test—we don’t want to be in a position where we have to do all this again.” Carson did acknowledge, however, that the delay “will move first deliveries into early 2009.”

Although Shanahan sounded some positive notes over progress on systems tests and fasteners, he was honest about the production problems. “If we’ve learned anything over these past three months it’s that we’ve underestimated how long it would take to complete somebody else’s work. We designed our factory to be a lean operation. We thought we could modify the production system to accommodate the traveled work from our suppliers, and we were wrong.”
Using so many temporary fasteners meant that the first fuselage sections arrived without adequate secondary support structure built into the upper crown area. As a result, the first Section 41 partially “sagged” when removed from its temporary support frame and was about 0.3 inch out of alignment with the midbody Section 43 when the two were mated in early June 2007. The worst mismatch was around the lower left-hand side of the fuselage, around the data port area. Mark Wagner

The irony was that the 787 production crisis was coming just as Boeing was breaking records for new orders. Business had never been better, with 1,413 net orders for 2007 easily outstripping the 1,044 orders taken in 2006, and exceeding 1,000 for an unprecedented third consecutive year. The numbers included new orders for the 787, which only added to the building pressure on production. The delays also impacted the suppliers, who, under the original risk and revenue deals signed with Boeing, would not receive payments until after 787 certification. A report in the Chicago Tribune the previous December said that suppliers wanted to renegotiate the terms of their contracts to help offset the impact of delays on cash flow for 2008.

Real progress came in February, when a Dreamlifter arrived at Everett with the first fully stuffed Section 41 from Wichita. The nose section for the second 787, ZA002, was complete with everything from windshield wipers to its radome. There was better news, too, on the remaining fuselage sections, which also arrived 50 percent more complete than they did for ZA001. But there was still plenty of work that traveled with them, and Boeing was now completely focused on revamping its production process to fix the problems.

Some of the fixes were small, while others were dramatically huge. On the factory floor, for example, Boeing reverted to its original quality assurance system, which had been discarded under the lean processes adopted for the 787. Going back to the original system enabled the huge number of “nonconformances” thrown up by the traveled work to be dealt with in batches by senior assembly personnel rather than by an individual rejection tag-by-tag basis under the newer system.

Deep inside the already complete wing root of ZA001 lay more trouble. Tests of the wingbox, identical to the structure at the heart of this area, revealed the need for extra strengthening. While newer production units were redesigned with additional ply layers, the existing boxes were reinforced in situ with about two hundred clips and five hundred extra fasteners. Mark Wagner

A much larger fix was Boeing’s acquisition in March of Vought’s interest in Global Aeronautica. Under the revised structure, Global Aeronautica became a 50–50 joint venture between Boeing and Alenia North America. The
move marked a major step in Boeing’s recovery plan to regain oversight and management of key sections of the 787 supply chain. It enabled Boeing to better manage production schedules and control of the supply chain and allowed it to address directly issues such as staff training.

But yet more problems were coming. In March an analyst report by Goldman Sachs suggested that power-on would slip to June 2008, signifying a much more serious program delay. Analysts JSA Research dismissed the reports as “innuendo and rumor,” but, significantly, Boeing itself would not comment. Then within days, Steven Udvar-Hazy, the highly influential CEO of the leasing giant International Lease Finance Corp., dropped a bombshell. At a JPMorgan financial conference he reported that the 787’s composite center wingbox needed redesign and that the entire program would slip at least six months as a result.

On March 20 Boeing confirmed the worst, but played down the impact. “It is a normal part of the development of a new airplane to discover need for improvements, and that is what we are experiencing on the 787. The robust test process in place on the 787 program has confirmed the majority of our designs, but we have found the need for some improvements.” The problem turned out to be a potential weakness revealed when panels in the Fuji-made twelve-by-five-foot composite spar section buckled prematurely during structural testing. It emerged that to save weight, Fuji had reduced the gauge of the composite spars running transversely across the unit, but the tests showed that it had been cut back too much.

A temporary fix, involving stiffeners attached in situ, was developed for the first six aircraft. “All airplanes after airplane seven will have the solution incorporated from the beginning,” Boeing said. To reassure the wobbly investment community, already concerned over the 787 delays, Boeing added that “the fundamental technologies being used on the 787 are proving to be reliable and effective” and that “material choices and manufacturing techniques for the airplane are sound.”

ANOTHER SLIPPAGE

By now it was obvious that further schedule changes were coming. Sure enough, on April 9, the company revealed not only more delays, but also a major reshuffle of the overall development schedule for the 787-3 and 787-9 variants. The first flight was set back to an unspecified time in the fourth quarter of 2008, due to “slower than expected completion of work that traveled from supplier facilities into Boeing’s final assembly line, unanticipated rework, and the addition of margin into the testing schedule.”

The new delivery schedule was based on a more conservative production plan developed with the 787 suppliers. That revised schedule now targeted the first delivery in the third quarter of 2009, with “approximately 25 deliveries” by the end of that year, 69 in 2010, 103 in 2011, and 120 in 2012. The stretched 787-9 was now brought forward and was to be the next derivative, with delivery planned for early 2012. The shorter-range 787-3, previously set for delivery in 2010, now became the second derivative.

Rework and traveled work were the chief culprits, but Carson believed that the latest plan was far more realistic. “Our revised schedule is built upon an achievable, high-confidence plan for getting us to our power-on and first-flight milestones.” The decision to opt for a more gradual production ramp-up resulted from a comprehensive assessment of its supply chain and production system announced in January. The result eased pressure on the supply chain but came at a steep price for the airlines, and inevitably for Boeing, which now faced hefty compensation payments. “We deeply regret the disruption and disappointment these changes will cause for our customers, and we will work closely with each of them to minimize the impact,” said Carson.

News of the rescheduling was met with relief by most of the suppliers, some of which spoke openly for the first time about the problems. Hamilton Sundstrand President David Hess, speaking to Aviation Week, blamed the repeated delays on an overambitious schedule and a logistics collapse associated with Boeing’s rush to keep its July 2007 rollout on schedule. Once suppliers fell behind, Boeing “panicked a little bit, and rather than follow the logistics plan that they had planned on where everything gets delivered to the structure partners . . . they said, ‘Everybody just send your stuff here.’ So bang, tens of thousands of parts ended up on the factory floor without any documentation or traceability. They had to start putting a jigsaw puzzle together without any directions.”

Further home truths emerged later in April, when McNerney sent a message to Boeing employees. Though reaffirming his belief in the global-partnership model, McNerney said, “We may have gone a little too fast, too fast in a couple of areas. I expect we’ll modify our approach somewhat on future programs—possibly drawing the lines in different places with regard to what we ask our partners to do, but also sharpening our tools for overseeing overall supply chain activities.”
Shortly after rollout of ZA001, Boeing switched the assembly sequence to give the desperately overstretched production system a forty-five-day breathing space to try to catch up. The result was that fatigue test article ZY998, or line number 9998, moved up the line ahead of the second test aircraft ZA002. Unfortunately the move, though radical, was too little and too late to avoid worsening delays. Mark Wagner

Inadequate oversight of suppliers led to a cascade of problems that stacked up as “traveled work” at Everett, with a drastic impact on the program schedule through 2007 and early 2008. Despite this, progress was made, and the parts for ZA003, which entered final assembly in May 2008, were collectively 65 percent more complete than were those for ZA001 on arrival in Everett. Mark Wagner

May saw the start of final assembly of the third 787, ZA003, parts for which were far more complete than were those for the first two, with about 65 percent less traveled work on arrival at Everett. Surrounded by signs that the system was finally getting into gear, Boeing felt sufficiently comfortable to allow reporters onto the final assembly line for the first time.

The line looked healthy and full of airplanes, with three flying and one fatigue airframe under assembly. But telltale signs of the stress of the past year were all around. The line was cluttered with temporary jigs and support structures more reminiscent of the 1960s than Boeing’s cherished twenty-first-century lean dream. Shanahan said the worst of its final assembly problems were behind it, but cautioned that issues with power systems and electric brake monitoring controls remained as potential obstacles to power-on and the first flight.

Shanahan said, “Technically we’ve activated the factory. We’re getting to the point where the traveled work is low enough that we can activate the factory the way it was intended to be utilized.” The dedicated teams of workers assigned to deal with the traveled work on each airframe were gradually being disbanded. From ZA003 onward, workers would stay at each of four factory positions as airframes moved through to completion.

The 787’s heart pulsed into life for the first time on June 11, 2008, when flashing red lights alongside ZA001 marked the start of the power-on process. ZA001 now began a series of gauntlet tests that would evaluate the entire systems performance prior to airborne testing. At the same time, newly arrived subassemblies were showing significant signs of improved completion. June 5 saw the Mitsubishi-made wing set for ZA006 arrive from Nagoya
and, unlike previous wing sets, it was already equipped with fixed leading edges provided by Spirit and fixed trailing edges made by Fuji.

Speaking about the power-on and gauntlet tests a few weeks earlier, Shanahan had warned of potential problems. “That’s really when the fun starts, we can really see how stable the airplane is. So, are there any problems that need to be resolved? Guess what? There will be lots of those. I expect people will run in every half-hour and they’ll drop their grenade, then we’ll dispatch people to deal with those issues.”

But as power-on tests of the hydraulic systems began, the first significant grenade was tossed into Shanahan’s office not from Building 40-26, but instead from South Carolina, where Section 44 for the fourth test aircraft had sustained damage at Global Aeronautica’s facility. An Alenia employee had installed the wrong fasteners while joining the section to the center wingbox. The fasteners had splintered the composite structure around the holes, causing so much damage that the delivery of the entire center section had to be postponed for five weeks—finally arriving at Everett along with Section 41 on August 4.

At the Farnborough Air Show that summer, brake control software and mid-fuselage completion on the second 787 had taken center stage in the race for the first flight. For the brakes, GE Aviation Systems “had to go back and rewrite portions of the software, and it is the reverification that’s put it on the critical path. I’m confident we will get it done,” said Shanahan. “It’s not that the brakes don’t work, it’s to do with the traceability of the software, which goes back to the whole certification process.”

GE Aviation Systems’ Future Growth Vice President Peter Woolfrey acknowledged, “We’ve had issues to deal with, both thermal issues and brake control, as well as a lot of new technology. It takes a lot to bring together and to expect it to get it right 100 percent first time around. But there’s nothing fundamentally wrong, and there’s nothing that can’t be resolved.”

The completion of the mid-fuselage on the second aircraft was a pacing item, because it was the airframe destined for ground vibration tests that had to be passed prior to the first flight. “It doesn’t change flying in the fourth quarter, but I’m eating margin I don’t want to eat and the collateral will be on aircraft three,” said Shanahan.

Meanwhile, trouble of another type was creeping up on the 787. The three-year contract with the IAM, the powerful machinists’ union, was set to expire on September 3, just a few days after Boeing aimed to complete assembly of ZA001. However, by the time negotiations began in August, the continuing issues with systems and other catch-up items had pushed this date back into October.

The talks began meanwhile with hopes of averting a repeat of the 2005 strike that cost Boeing an estimated $1.5 billion in revenue. But with the 787 poised for the final push toward the first flight, the stakes were much higher this time around. This time the negotiations would include an extra factor not present in earlier contracts, that of job security and outsourcing—a direct fallout of the 787. To Boeing’s dismay, talks got nowhere, and on September 6 the IAM went on strike after 87 percent of the union’s twenty-seven thousand members rejected the proposal.

While the labor dispute boiled over, progress was still being achieved in the factory. In Building 40-23, three bays down from the final assembly line, the static test vehicle passed its crucial “high blow” pressurization test. During the two-hour test, the airframe reached an internal pressure of 14.9 pounds per square inch, or 150 percent of the maximum expected to be seen in service. The test was a clear demonstration of the strength of the composite structure, and paved the way for separate static tests of the leading and trailing edges, which would clear the way to the first flight.
In August 2008 the nose and main landing gear were “swung” for the first time, marking another big milestone for systems interaction, which required more than four million lines of software code. The “extend-and-retract-by-wire” gear swing required perfect integration of avionics, the common core system, the electrical power system, the hydraulic system, and the structure itself.

Despite the strike, engineers started preflight tests on the aircraft’s air data system in October, while ground tests of systems and avionics continued in the ITV and AIL labs. Speculation meanwhile grew that the first flight would inevitably slide into early 2009, and on October 10, a UBS analyst report stated that first 787 deliveries would likely not take place until 2010. On top of all this, Boeing’s stock price plummeted as an unprecedented global financial crisis rattled markets.

Against this gloomy outlook there was one significant bright spot. On October 15, American Airlines announced orders for forty-two 787-9s, plus purchase rights on up to fifty-eight additional aircraft. The firm aircraft were scheduled for delivery from September 2012 to 2018, and the options from 2015 to 2020. The deal pushed overall 787 orders right up to the nine-hundred barrier—a testament to the continuing appeal of the design despite the development delays and problems.

More good news followed on November 1 when, to the relief of Boeing, the suppliers, and the airlines, the IAM agreed new terms and ended the fifty-eight-day strike. The big question now was how soon the 787 would actually fly.
Chapter 10

TAKING FLIGHT

On May 12, 2009, came one of the most important moments yet on the road to the aircraft’s first flight: the first start of the Hamilton Sundstrand APS 5000 APU. Although this was only a brief run of around fifteen minutes, the aircraft was by now truly coming to life. In an ironic twist, the moment came almost exactly two years after Hamilton Sundstrand formally handed over the first flight-test unit to Boeing from its power-system facility in San Diego, California. By now all eyes were on ZA001 for the start of main engine tests, and this magic moment for the program finally came at 9:30 a.m. on May 21, heralded as usual with a puff of white cloud caused by the burning of lubrication oil within the engines.

Outwardly all seemed to be accelerating to a first flight in June 2009, possibly around the time of the Paris air show. Boeing maintained that its first-flight target date remained by June 30, as had been publicly stated, though the company cautioned that safety would not be jeopardized by rushing to meet an arbitrary deadline. Internally, however, a very different story was slowly emerging.

Finally, after years of planning, development, and delays, the moment of truth arrived at 10:27 a.m. on December 15, 2009, as ZA001 lifted off for its maiden flight. Within moments of takeoff, the Dreamliner vanished into the overcast. Mike Carriker, who commanded the first flight, later recalled, “Three minutes after departure we went IFR [instrument flight rules]!”

Side-of-body reinforcement work on ZA001 was completed inside one of Boeing’s paint hangars throughout October and early November 2009. The work was complicated by simply getting access to the wing root in the already completed aircraft. In spite of the cramped working area, the Boeing team developed techniques for retrofitting the new support by “match drilling,” or using the existing fastener holes.

Unknown to virtually anyone outside a small group within Boeing at the time, strain-gauge readings from the next phase of more aggressive tests on the static airframe had raised red flags about specific structural problems where
the wing joined the fuselage. Alerted by strain-gauge readings, engineers inspected the area and, to their utmost dismay, discovered that small sections of the stringers had “disbonded” from the upper wing skins to which they were originally cocured. The issues were focused on the side-of-body join between the Mitsubishi-made Section 12 wing box and the complex, Fuji-built center wing box Section 45/11. The problems centered on the eighteen stringer caps on the upper section of the side of the body, at the junction between the wings and fuselage, where the center wing box joins to the main wing sections, and these problems meant that strengthening would be needed. There was no question; more delays would be incurred. Yet right up to the end of the Paris air show, Boeing still hoped that a limited flight-test exercise might still be possible while the longer-term fixes were being perfected.

Flanked by Boeing’s T-33 chase planes, ZA001 weaved through solid cloud layers in search of clearer skies. “The first two minutes after takeoff, we retired more risk in that airplane than we had in the first two years,” said Carriker.

Painted in the colors of launch customer ANA, ZA002 joined the test program on December 22, 2009. Although it was destined never to be delivered to the airline whose colors it wore because of the sheer amount of structural changes in the early aircraft, ZA002 would play a vital role in gaining certification. Mark Wagner

However, on June 19, a final review concluded that the flight envelope would be so small there would be virtually no value to any of the testing done, and certainly nothing that could usefully contribute to final certification. Boeing’s top management conferred with program engineers and, having conceded they were left with no option, reluctantly announced on June 23 that the first flight was once more postponed. Now began the urgent task of developing, verifying, and testing the beefed-up side-of-body join sections on ZY997 before installing the fixes on the flight-test aircraft.

Clearance of the modification would require component-level as well as full-scale tests on the static airframe, and all that would take time. “While we will proceed with urgency, we will not compromise the process for the sake of schedule,” said Scott Fancher.

Although the required fixes were relatively small, the most worrying aspect of the static-test failure was the apparent disconnect between the test results from the hardware and the computer-based predictions. The issue appeared to be emblematic of the more systemic problems encountered by the program as a whole and was one more trouble spot for Boeing to deal with as it moved to perfect the design and production process in 2009. “We will correct the situation with both care and urgency,” added Carson.
With thrust reversers, flaps, and spoilers deployed, ZA001 comes to a smart stop despite the wet runway at Boeing Field. Landing gear, brakes, and hydraulics-systems testing were key tasks for line number one and would culminate in critical evaluations in the much drier, warmer airfields of the American Southwest later in 2010.

Mark Wagner

Despite the furor over yet more delays and speculation over the delays’ impact on the program’s spiralling development costs, optimism for the long-term future remained undaunted. The backlog showed remarkable robustness; only around 6 percent of orders were cancelled by mid-2009, and plans remained intact to push production to around 10 per month by 2012. On top of this, Boeing also revealed plans at the Paris show to develop a second assembly line, and the 787 facility in Charleston, South Carolina, was widely predicted as the most likely site. With one final hurdle remaining to the agonizingly delayed start of flight tests, the real adventure was about to begin.

Traffic hurries along the Interstate 5 on December 15, 2009, oblivious to history being made so close by, as ZA001 arrives for a flawless first touchdown on Boeing Field’s 10,000-foot-long runway 13R.

Putting the bitter disappointment of the latest delay behind it, Boeing marshaled resources from across the enterprise to tackle the urgent side-of-body reinforcement. A multidisciplined “design for manufacture and assembly” team of engineers and mechanics formed to work the retrofit.

The design of the beefed-up joint was partially developed using a structural model from the company’s helicopter specialists in Philadelphia. The model broke new ground for Boeing’s understanding of composite structural analysis and, just as vitally, helped reanchor the company’s shaken confidence in the models that were used for the rest of the design. “Models are the basis for certification. So if the models aren’t predicting what’s happening, you’ve got to understand it,” said Scott Fancher, Boeing vice president.

Throughout July and August 2009, several designs were considered, but the final reinforcements consisted of a selection of fittings that could be “held in your hand,” said Fancher. The most distinctive were four new, metallic “bathtub” fittings that attached to the sides of each of the stringers at the root, where the stringers met the vertical side-of-body join position at the fuselage. Hidden beneath the fittings at the end of the I-beam was a bite-shaped cutout, or “trim,” designed to help redistribute the loads passing through the stringer to the side-of-body. The original fitting supporting each stringer was also reinforced and enlarged.

By late August, encouraged by the progress on the reinforcement, Boeing finally had the confidence to officially announce that first flight would happen by the end of 2009 and that first delivery was expected to occur in the fourth quarter of 2010. The new schedule included the addition of several weeks of schedule margin to reduce flight-test and certification risk. This more realistic acknowledgement of the task ahead was surprisingly well received by the
nervous investment community.

Landing with its distinct, birdlike wing dihedral, ZA001 is pictured seconds from touchdown at Boeing Field, as Mount Ranier looms large in the distance. On May 12, 2010, just days before this image was taken, the 787 had been flown by ANA pilots Captains Masami Tsukamoto and Masayuki Ishii. The event, which was described as “amazing” by both, marked the first time non-Boeing pilots had flown the aircraft. Mark Wagner

At the same time, Boeing injected confidence back into the market by confirming that it aimed to hit a production rate of 10 787s per month by late 2013. However, it also had to admit that “the initial flight-test airplanes have no commercial market value beyond the development effort due to the inordinate amount of rework and unique and extensive modifications made to those aircraft.” The move, which applied to ZA001, 002, and 003, cost the company $2.5 billion, but avoided longer-term and expensive attempts at refurbishment.

While feverish triage on the 787 occupied the Everett workforce, Boeing was busy plotting the next move in its long-term production strategy. After almost four months of rumor and counterrumor, in late October 2009, it officially confirmed North Charleston, South Carolina, as the location for a second 787 final assembly site. In addition to serving as a location for final assembly of 787s, the facility would also have the capability to support testing and delivery. As well as expanding production capability to meet what Boeing saw as essentially undiminished market demand, the “decision allows us to continue building on the synergies we have established in South Carolina with Boeing Charleston and Global Aeronautica,” company president Jim Albaugh said.

Coming on the heels of the relatively recent, debilitating strike at Everett, the bold move was greeted with dismay by workers in Seattle and by delight amongst supporters in South Carolina, who had lobbied intensely to house heritage Boeing’s first-ever commercial-jetliner production line outside of Washington State. To reassure the concerned union members in Seattle that Charleston was not the thin end of the wedge, Albaugh added that “while we welcome the development of this expanded capability at Boeing Charleston, the Puget Sound region is the headquarters of Boeing Commercial Airplanes. Everett will continue to design and produce airplanes, including the 787, and there is tremendous opportunity for our current and future products here.” Albaugh also emphasized, “We remain committed to Puget Sound.”
In early February 2010, the fatigue airframe, ZY998, was trundled around to the purpose-made structural test rig in the northwest corner of the sprawling site. The test was “instrumental in confirming the longevity of the airplane,” said Scott Fancher. Unlike the static tests on ZY997, where loads were applied to the structure to simulate normal operation and extreme flight conditions, fatigue testing was a much longer process and simulated up to three times the number of flight cycles the 787 was likely to experience during a lifetime of service. *Mark Wagner*

Boeing moved quickly to develop the new site, which was initially aimed at 787-8s, but had the capability to eventually include other variants. In the meantime, until the second line was brought on line in Charleston, Boeing laid out plans to establish what it called “transitional surge capability” at Everett, to ensure the successful introduction of the 787-9. Boeing indicated that once the second line in Charleston is up and operating, the surge capability in Everett would be phased out.

While surveying teams set out to prepare for the new East Coast facility’s ground-breaking ceremony later that month, the side-of-body team in Everett completed installation of the reinforcement on ZA001 on November 11. Without a pause, it then moved quickly to complete the same fittings at 34 stringer locations on the static test aircraft and ZA002. Some 19 days later, Boeing reran the design limit-load test—the true acid test for the structural reinforcement. Speaking later to *Aviation Week & Space Technology*, Fancher recalled there “was a sigh of relief” when it passed the test, but added that by then “to be honest, we were pretty confident.”

Flight-test instrumentation is installed into the fuel system of ZA001’s right wing main tank prior to the first fueling in early May 2009. ZA001 instrumentation was mainly concerned with measuring volume and capacity, while ZA002 was fitted with an oxygen analyzer and fiber-optic temperature sensor to monitor tank conditions. These would be a focus for certification, since the 787 was the first all-new U.S. air transport to require FAA-mandated fuel tank inerting systems from day one. *Guy Norris*

On December 10, Boeing completed the review and analysis of the static test. To the flight-test team, itching to take ZA001 into the sky, the report was seen as a mere technicality. Confident that this time it would really happen,
the team had been busy rerunning a truncated version of the final gauntlet testing originally undertaken that summer. Over December 11 and 12, Mike Carriker and 787 engineering test pilot Randy Neville took ZA001 out onto Paine Field’s main runway for a series of taxi tests that gradually reached higher speeds. Finally, by that Saturday afternoon, ZA001’s nose wheel lifted briefly off the runway as the crew pushed the blue and white aircraft to rotation speed at around 130 knots. A final flight readiness review was passed successfully, and finally, after more than two years of waiting, first flight beckoned.

TAKE OFF

Boeing announced the first flight window would open at 10 a.m. on December 15, bringing a stampede of journalists toward Seattle from around the world. But as the day drew closer, it seemed the weather gods would play another cruel trick on Boeing. Weather front after weather front crashed in on the Puget Sound from the Pacific; storm-force winds blew, and rain poured.

Hoping for a miracle, or at least a break in the weather, Boeing nonetheless carried on preparations, and by the morning of the planned flight, an estimated crowd of 12,000 had gathered in and around Paine Field. Huddled together for warmth against a penetrating icy breeze, onlookers scanned the skies in hope of seeing the cloud base lift for first flight. As the time for the flight test window opened and skies lightened, anticipation grew.

Inside ZA001, Carriker and Neville waited for word that conditions were creeping toward Boeing’s minimal horizontal and vertical visibility requirements for first flight, as well as a tailwind of 9 knots or less. Just after 9:30 a.m., word came of a further improvement in the visibility, and around 10 a.m., a tiny patch of blue sky briefly opened up in a tear between the racing clouds. Despite these optimistic signs, weather radar showed more rain coming from the southwest, and the flight crew decided it was now or never.

Carriker talked on the radio to the pilot of a Cessna who was flying close to the San Juan Islands, where the 787 would head to begin its test flight. Seeking guidance on weather conditions, he requested visual flight-rules clearance from the tower. When he was satisfied the time had finally come, the strobe lights were switched on and engines started. At 10:11 a.m., ZA001 taxied out to the north end of runway 16R while a swarm of news helicopters, and even one carrying an IMAX camera and crew, hovered overhead.
By May 2010, the four Rolls-Royce Trent 1000–powered 787s had completed 1,450 flutter and ground-effects tests, completing that part of the FAA certification program with no significant changes required, said Boeing Commercial vice president Pat Shanahan, general manager of airplane programs.

Here, ZA001 soars overhead on short finals to Boeing Field. Mark Wagner

Boeing’s weight-reduction redesign work of 2008 and 2009 was focused on a series of “block change” phases to be introduced at Line 7, and the next block changes flowed in at line numbers 20, 34, and 54. The changes, mostly to floor beams and frames, led to supply-chain problems, and parts for aircraft 21 and 22 started arriving at Everett with ten times more rework than expected. In late April 2010, Boeing bit the bullet, halting deliveries of all new 787 fuselage sections and wings to Everett for over a month to allow time for major structural partners to catch up. In a view reminiscent of the scene 40 years before, when 747s without engines were stacking up at Everett, incomplete 787s are seen on the delivery ramp in May 2010. Note the lone 747LCF Dreamlifter, the Royal Air Maroc 787, and (inset) protective measures to keep the weather at bay. Mark Wagner

Taxiing to the south end of the field, with flaps set at 20 degrees, ZA001 took runway 34L and waited for the two Boeing T-33 and single T-38 chase aircraft to call in on final approach. A moment later, Carriker pushed forward the throttles of ZA001’s two Trent 1000s, and, like a hound leaving its slips, the 787 leapt along the rain-slicked runway, sending up sheets of spray in its wake. Matching the speed of the chase aircraft precisely, Carriker rotated at 140 knots, and, with the sound of its passage almost masked by the helicopters and cheers from the crowds, the
787 became airborne at 10:27 a.m.

Boeing banked on round-the-clock, 24/7 testing to win certification by late 2010. Here, ZA001 taxies in at night at Boeing Field after a busy day of flight testing. Back at the ramp, another flight-test team is preparing to take over for a night of ground tests. As the months passed, Boeing grew more confident of achieving its goal, despite falling behind its monthly test-hour target. “The efficiency of flights is higher, so we’re doing more test points. We’re shooting for two blocks every day, and we need to fly each aircraft ninety hours per month,” said Pat Shanahan in May. Already the omens were improving; not only were the rates already creeping up beyond 110 hours per aircraft, but the amount of daylight was also increasing. Mark Wagner

Flanked by the chase planes, ZA001 was swallowed up by the overcast within moments, its undercarriage still down and locked. Back on the ground, as many still gaped in awe at the swirling vortex that marked the passage of the 787 into the solid gray cloud deck, the rain swept back in.

On the flight deck, Carriker and Neville climbed ZA001 slowly, at 165 knots, toward a target height of 15,000 feet. However, the weather was not cooperating any more at that altitude than it had at sea level, and bad visibility prevented them from climbing any higher than 12,000 feet while maintaining visual flight rules (VFR; rules governing flight in day and night conditions). Accompanied by the chase aircraft, the crew ran through several test cards, including retracting and extending the landing gear. Eventually, hemmed in by bands of ugly rain clouds around the Puget Sound, Carriker reluctantly called it quits and opted to return to Boeing Field about two hours earlier than planned.

The rain was teeming down as ZA001 loomed out of the murk over downtown Seattle and headed in toward Boeing Field from the north. The crew executed a perfect touchdown despite the conditions and taxied in triumphantly to a specially prepared area of the Boeing delivery and flight-test ramp. Through the rain-spotted flight-deck windows, Carriker could be seen punching the air with delight and giving the crowds the thumbs-up sign.

The flight had lasted three hours and five minutes and was an unqualified success despite being cut short by the poor visibility. But having trained for more than four years for this moment, Carriker could not disguise the look of pure joy on his face as he descended the steps of ZA001. His first words were simply, “Holy smokes! I guess it felt like we flew into the future of the Boeing company.” In a testament to Boeing’s flight control and simulation predictions, Neville commented, “The aircraft flies beautifully. There were no surprises, and it did exactly what we were expecting.”

At last Boeing’s Dreamliner project was about to live up to its name.
## Appendix

### SPECIFICATIONS AND MILESTONES
(as of June 2010)

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<th>787-8</th>
<th>787-3</th>
<th>787-9</th>
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<tr>
<td><strong>Passenger capacity</strong></td>
<td>200 to 250 passengers</td>
<td>200 to 350 passengers</td>
<td>250 to 290 passengers</td>
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<tr>
<td><strong>Wingspan</strong></td>
<td>187 feet (56.52 meters)</td>
<td>170 feet (51.8 meters)</td>
<td>200 feet (60.96 meters)</td>
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<tr>
<td><strong>Length</strong></td>
<td>186 feet (56.7 meters)</td>
<td>186 feet (56.7 meters)</td>
<td>200 feet (60.96 meters)</td>
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<tr>
<td><strong>Height</strong></td>
<td>56 feet (17.1 meters)</td>
<td>56 feet (17.1 meters)</td>
<td>56 feet (17.1 meters)</td>
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<tr>
<td><strong>Cruise speed</strong></td>
<td>Mach 0.85</td>
<td>Mach 0.85</td>
<td>Mach 0.85</td>
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<tr>
<td><strong>Total cargo volume</strong></td>
<td>4,000 cubic feet</td>
<td>4,000 cubic feet</td>
<td>5,000 cubic feet</td>
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<tr>
<td><strong>Maximum takeoff weight</strong></td>
<td>484,000 pounds</td>
<td>564,000 pounds</td>
<td>545,000 pounds</td>
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<tr>
<td><strong>Range</strong></td>
<td>7,450 to 8,920 nautical miles (14,300 to 16,600 kilometers)</td>
<td>8,000 to 8,920 nautical miles (14,300 to 16,600 kilometers)</td>
<td>8,000 to 8,920 nautical miles (14,300 to 16,600 kilometers)</td>
</tr>
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<td><strong>Program milestones</strong></td>
<td>Authority to offer: late 2003</td>
<td>Authority to offer: late 2007</td>
<td>Authority to offer: late 2010</td>
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<td></td>
<td>Program launch: April 2004</td>
<td>Planned entry into service: 2011</td>
<td>Planned entry into service: 2013</td>
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<td></td>
<td>First configuration: June 2005</td>
<td>First quarter 2012</td>
<td>First quarter 2012</td>
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<td>Major assembly start: May 2006</td>
<td>Planned entry into service: end of 2010</td>
<td>Planned entry into service: end of 2010</td>
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<td></td>
<td>Roll out: July 2007</td>
<td>Planned entry into service: end of 2010</td>
<td>Planned entry into service: end of 2010</td>
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<tr>
<td></td>
<td>First flight: December 15, 2009</td>
<td>Planned entry into service: end of 2010</td>
<td>Planned entry into service: end of 2010</td>
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