

The first Boeing 777 jetliner takes to the air on June 12, 1994, for its initial flight test. The 2-hour, 48-minute program included flying the plane at low altitude to evaluate how it would handle when the ground was close enough to affect the airflow around the aircraft. Also tested was the "configuration deviation test" to ensure that the plane would perform as expected should key electronic units fail less than a year later; on June 7, 1995, the first production unit started revenue service by flying from London to Washington, D.C.



BOEING'S SEVENTH WONDER

"I guess you could call this the end of the beginning," said an emotional Boeing Co. worker last May 17 while watching United Airlines' first 777 jetliner take off from Boeing Field in Seattle, Wash. As the plane flew into the clouds above the airfield, it carried with it the hopes of Boeing's entire technical staff, who considered the delivery flight to be the "beginning" of the 777's expected half-century of service—encompassing several generations, as aircraft lives are measured.

With an intensive five-year US \$4 billion-plus development effort behind it, the 777 has a lot to live up to. The success of its six predecessors, more than 7700 aircraft in models from the 707 to the 767, led to Boeing's commercial domination of the skies in the last two decades.

Airline travelers, eager to get their first glimpse of this new superjet, will be forgiven if they think it looks "like any other airliner." It has no distinctive hump like the 747, no notable tail engine like the DC-10, and no droop snoot like the Concorde. So what makes the 777 truly one of the most remarkable industrial achievements of the 1990s, and maybe even the century?

Fresh start

The answers are in the new technology used in the 777 itself, and in the design-engineering revolution that stormed through Boeing, based in Everett, Wash., during the creation of its first all-new jetliner since the early 1980s. Advances in electronics and in computer-aided design, manufacture and simulation provided the foundation for the new technology. Using these tools and systems to an unprecedented

The 777 incorporates the most advanced avionics of any commercial U.S. aircraft and is the first plane of any kind to be almost entirely computer-designed

extent, Boeing was able to start afresh with the 777, changing the way in which the company builds aircraft. The results have been so dramatic that practically every new Boeing flight product—from the new generation of the venerable 737 family and F-22 air superiority fighter to International Space Station and the proposed X-33 reusable launch vehicle—is adopting some part of the program pioneered by the 777.

The 230 000-kg plane is the biggest twin-engine aircraft ever to fly, uses the largest and most powerful jet engines ever developed, and is the first U.S.-built commercial transport to rely completely on fly-by-wire controls (control surfaces that are activated by electric signals rather than cables). It is also the first Boeing jetliner to be 100 percent designed on computer and will almost certainly be the last new widebody jet to be designed and built in the United States or Europe in this century. The initial 777-200 model can carry 375 passengers for 7400 km.

For all that, Boeing started late with the 777. By 1989, with competing products like the Airbus A340 and the McDonnell Douglas MD-11 already launched and orders taken, Boeing needed direction. To everyone's surprise, the

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company took the radical step of asking the airlines to help it design a jetliner of their choice. This "market-driven" concept may seem familiar today, but in the late 1980s it bordered on revolutionary. Boeing admits that until the advent of the 777, it openly subscribed to the *Field of Dreams* philosophy—build it and they will come.

Gang of eight

In January 1990, Boeing asked eight world-class airlines to help define the new aircraft's configuration and mission. Almost immediately, the new design, which started as the 767-X, took a different direction from every previous Boeing design, with the basic shape driven from the inside out. In addition, a "working together" philosophy became the watchword for the 777, and eventually for the entire company.

This radical change in Boeing's *modus operandi* took contractual form on Oct. 15, 1990, when a simple, hand-written note was scripted at the conclusion of negotiations with United Airlines, Chicago, the carrier that placed the launch order for the 777. It reads:

"In order to launch on-time a truly great airplane, we have a responsibility to work together to design, produce and introduce an airplane that exceeds the expectations of flight crews, cabin crews, and maintenance and support teams and ultimately our passengers and shippers. From day one:

- Best dispatch reliability in the industry
- Greatest customer appeal in the industry
- User friendly and everything works."

The note was signed by James Guyette, United's vice president of operations; Richard Albrecht, Boeing Commercial Airplane Group's vice president; and Phil Condt, then Boeing's New Airplane Program general manager. Copies of the note now hang like religious artifacts on walls all around Boeing.

From the moment of that signing, the 767-X evolution quickly turned into the 777 revolution. Teams of engineers from each of the four launch customers—All-Nippon Airlines, British Airways, Japan Air Lines, and United—set up offices in Seattle and were given full access to the 777 design team. Working together, teams were also formed with all the suppliers as part of a concerted effort to break down artificial barriers between design areas. This was no small task since 20 percent of the aircraft was supplied by almost 60 international companies, some as far away as Australia and Japan.

Robojetliner

Jetliners traditionally had been developed in a linear fashion, with one team designing the structure of a section before passing the design along to the systems people, and so on. This often led to late rework as systems designers tried to cope with the shell they inherited. By developing cross-functional "design-build teams," Boeing hoped to streamline coordination and improve quality across the entire aircraft at once. At the project's peak, some 238 design-build teams were simultaneously working on the 777.

Critical to the team's success were coordination of tasks and quality control, two weapons in the battle against the "non-value-added costs" that can easily turn ruinous in late design changes and revisions. Forming the vanguard in that fight was a computer-aided three-dimensional interactive application called Catia. Boeing had experimented before with the Dassault/IBM Catia design system by using it to build small parts of other aircraft, but this time Catia was used to develop its first 100-percent "paperless" airliner. Employing three-dimensional digital software, designers could see parts as solid images on their computer screens. They were able to then simulate the assembly of those parts on-screen and easily find and correct interference problems.

Although Catia was expensive to introduce and initially cumbersome to use, the system helped Boeing eliminate 65 percent of



BOEING CO.

▲ Technicians prepare a Pratt & Whitney Co. turbofan engine for a ground test. The 777 is propelled by two such engines, which are the largest ever made. Alternative versions are supplied by General Electric Co. and Rolls-Royce PLC.

change errors and rework, 15 percent better than the target set. At the peak of the design work, over 2200 Catia workstations were networked to a cluster of eight IBM 3090-600J mainframe computers working on almost 3 terabytes of data.

Catia also saved Boeing from having to make expensive engineering mock-ups of the 777 before it built the real thing. Mock-ups provide engineers with the physical reassurance of a design—allowing them to check that parts fit together properly and do not interfere with cable and wire runs—before they commit the design to production.

Boeing actually did make one mock-up: the nose of the 777, to verify that digital pre-assembly would work. This job even included checking the performance of "Catia-man," a computer-generated human model. Quickly nicknamed "Robocop" (after the movie of that name), the model moved around the cyberspace version of the 777 to ensure that a real human could roam freely in the plane and inspect or change any of its parts. The mock-up was built to confirm that airline crews could be as agile in the 777 nose as Robocop.

Ready to serve

Inside the enormous Everett assembly plant, which was doubled in size for the 777 at a cost of almost \$1.5 billion, computer-based design advances were matched with new automated manufacturing systems. Once final assembly began, the 777 slotted together like a child's Duplo blocks. Unprecedented levels of first-time fit and alignment were achieved. For example, after the 37 680-kg wing and center fuselage section (which are joined in one piece before mating with the rest of the aircraft) were lowered into position on the first 777, the 63.8-meter-long section was found to be out of alignment by only 0.69 mm and the port wing tip out by a mere 0.03 mm.

Boeing's promise to deliver a "service ready" aircraft from Day One was a tall order in itself, but to recover its position as market

pace-setter, Boeing had to go even further.

With United, Boeing hatched a plan to test the aircraft so thoroughly before entry into service that the U.S. Federal Aviation Administration and European Joint Aviation authorities would clear the 777 for extended-range twin operations, or Etops, allowing it up to 3 hours' flying time from an airport. This became known as "Etops out of the box."

To achieve these targets, Boeing devised a giant laboratory that contained every system used on the aircraft. The \$370 million Integrated Aircraft Systems Laboratory linked engineering versions of every 777 system in real time, allowing full "flights" to be enacted on the ground. Testing everything up-front would also avoid a myriad of potential integration problems, such as the flight management system problem that delayed the 747-400.

The lab opened for business in October 1992 and began expediting the "build-test-fix" philosophy in almost 70 smaller functional labs. Up to 57 major aircraft systems, 3500 line replaceable units (changeable equipment like a power supply assembly), and 20 000 parts were tested and integrated with other parts.

Once the main aircraft systems were successfully "talking" to each other in the lab, testing moved to the three big integration labs. These relied on a bank of 43 Harris Night Hawk computers with multiple parallel processors that ran simulations faster than a real-time event would occur, while less-demanding simulations were handled by Concurrent computers. This kind of brainpower permitted the systems integration lab, for example, to test avionics with real-time simulations of the aircraft in flight.

Another of the big testing labs consisted basically of the flight control test rig. Called the "Iron Bird," this lab handled the validation of the fly-by-wire flight control system by moving a partial set of the 777's "flight feathers"—an aileron (a roll control surface on the wings), a rudder (on the vertical stabilizer), an elevator (pitch control on the tail surface), and a set of spoilers (plates to spoil air flow over the wings during landing). The third test lab was a 777 cockpit simulator.

With completion of virtually every test in the project, the prototype 777 was cleared for flight test in record time. Accelerated testing also allowed the seemingly impossible goal of "ETOPS out of the box" to be achieved, with just days left before United began its first service of the aircraft on June 7.

Digital avionics systems

The 777 is Boeing's first truly digital airliner. Although the 757, 767, and the latest version of the 747 all use some discrete digital avionics, none has either the inte-

grated systems of the 777 or its fly-by-wire flight control system. In all, the aircraft has more than 2.6 million lines of code incorporated in the avionics and cabin-entertainment system, compared to 400 000 in the 747-400. Of the total, some 600 000 lines of code are dedicated to the Airplane Information Management System (AIMS) built by Honeywell Air Transport Systems Inc., Phoenix, Ariz.

AIMS uses an innovative, highly integrated avionics architecture that forms the brains of the 777. It consists of dual cabinets that contain all of the central processing and input/output hardware needed to handle flight management, flat-panel cockpit displays, and central maintenance of the plane. The two cabinets' hardware also takes care of condition monitoring, digital communication management, engine data interface, and a data conversion gateway. Even if one of the two AIMS cabinets is not functioning, the aircraft can still be flown.

Unlike traditional distributed architectures that require each line-replaceable unit to be self-contained, the functions gathered together in AIMS share processors, memory system, and operating system, as well as utility software, hardware built-in-test equipment, and I/O ports. Honeywell believes this sharing of power will improve reliability and maintainability. It also cuts electronics weight by 20 percent and power requirements by 30 percent.

Honeywell was able to build AIMS because of advances in high-speed processing and in robust software partitioning, which allows several software packages to be used in the same computer. The AIMS cabinets also build on advances in application-specific integrated circuits (ASICs), so that more channel functions could be integrated in a single processor channel.

AIMS high

AIMS "talks" to the rest of the 777 through 12 data bus networks, of which 11 are Arinc 629 and one is optical fiber. The majority of data transmission passes through two isolated Arinc 629 data bus networks, one for aircraft systems and another for the digital flight control system. The Arinc 629 is made up of a pair of twisted wires, which form a bidirectional data highway.

Because of the sheer amount of functionality and digital signaling required on the 777, only a high-speed Arinc 629 multibus, with the ability to ship 2 Mb/s, can do the job. Some of the plane's systems, however, function well with lower bit-rates and so can be linked with an analog, unidirectional Arinc 429 bus. One function card in each of the AIMS cabinets is used as a data conversion gateway, enabling AIMS to interface with bus networks and discrete signals.

The Boeing 777 is in addition the first

commercial aircraft to use optical-fiber cables. Connected to AIMS, these cables transmit high-speed digital computer data to the two cabinets from a maintenance access terminal and side displays in the cockpit.

With its success in the 777, AIMS is being adapted for other uses. Honeywell has proposed a version, for example, for upgrades to the U.S. Air Force's E-3 Airborne Warning and Control System (Awacs) aircraft. Several avionics manufacturers are considering AIMS for use in the Defense Department's Joint Advanced Strike Technology fighter project. And using AIMS as a base, Honeywell has developed the VIA 2000 modular avionics architecture, which it is offering for cockpits ranging from DC-10 upgrades to the new generation of 100-seat regional jetliners.

Besides its use of AIMS and optical-fiber cables, another new step for Boeing in designing the 777 was the introduction of the fly-by-wire flight control system. This system makes it possible to use lighter wing and tail structures by obviating the need for complex and heavy mechanical cables, pulleys, and brackets. The pilot's commands (through the control yoke) go to three GEC-Marconi primary flight control computers (PFCs) that form the heart of the system.

Each PFC, containing around 132 000 lines of Ada code, calculates control commands for primary surface actuators, the more delicate trim system, and the control column feel system that gives the pilot the important seat-of-the-pants feedback he would get from direct-link mechanical controls. In manual mode, the PFCs receive the pilot's inputs via the Arinc 629 through the control column and rudder pedals. In automatic mode, the commands come in from the Rockwell-Collins triplex autopilot and flight director.

Failure not an option

Many levels of control and power have been built into the plane to guard against catastrophe. In the unlikely event of a total PFC system failure, for instance, a backup analog command path is available through the actuator control electronics. These are simply analog-to-digital devices that transfer the pilot's stick inputs into an order to move the relevant flight control surface. If all else fails, the crew can still fly the 777, even with reduced authority, by using an old-fashioned, independent mechanical link controlling the stabilizer trim system and two flight spoilers.

The use of fly-by-wire drove Boeing to adopt a multi-redundant power system. Standard electronics bays in other Boeing jetliners consume up to 14 kVA, but the in-flight entertainment system alone in a fully equipped 777 will consume 22 kVA. Thus,

the 777 has three 120-kVA Sundstrand constant-speed integrated drive generators, one on each engine and a third on the auxiliary power unit in the tail.

Additional backup support comes from a second power shaft on each engine that produces up to 20 kVA through a variable-speed, constant-frequency unit. Three permanent magnets on the same shaft generate power for the fly-by-wire system. The

plane also has a fourth emergency system, producing 7.5 kVA. A ram-air turbine, it is housed in the wing root, and drops into the airstream and spins into action if all electrical and hydraulic power fail.

The multiple levels of control and power almost seem designed to have each aircraft meet Boeing's prediction that the last 777 built would still be flying in 50 years.

To keep the 777 order book full for the

next few decades, Boeing is busy developing two new versions of the big twin. The short-body 777-100 will be the longest-range airliner ever (15 800 km with 265 passengers). And the stretched 550-passenger 777-300, introduced at the 1995 Paris Air Show in June, will be the longest airliner, 3 meters longer than the Boeing 747, whose older versions the 777 will replace. Even with the huge job of developing not just one but three versions of the 777 complete, Boeing's twinjet will no doubt remain one of the world's top industrial megaprojects for decades to come. ♦



BOEING CO.

▲ The most extensive use ever of computer-aided design allowed the 777 team to skip making a mockup (other than for part of the nose) and go directly to assembling the first aircraft. Its wingtips were out of alignment by only 0.03 mm when the major parts were brought together. Here, in October 1994, the first aircraft to be assembled is positioned to cure the seal between wing and fuselage.



BOEING CO.

▲ Boeing test pilot John Cashman spent many hours "flying" the 777 in the Integrated Aircraft Systems Laboratory in Seattle before taking the real 777 up for its maiden flight in June 1994. Up to 400 "flights" per month for six months were made in the lab before the first aircraft was actually put together. Integration issues discovered and resolved in the ground facility shaved months, and probably years, from the 777 test and development program.

To probe further

The origins of the 777 are explored in "The Customer Influence in 777 Design," American Institute of Aeronautics and Astronautics (AIAA paper 93-1139) as well as in two 1994 articles in *Flight International*, "Genesis of a Giant" (Aug. 31-Sept. 6, Vol. 146, no. 4436, pp. 61-62) and "Inside the 777" (April 6-12, Vol. 145, no. 4415, pp. 23-27). Boeing Co. is described in Robert Serling's *Legend and Legacy—The Story of Boeing and its People* (St. Martin's Press, New York, 1994).

Last September's *Airliner Magazine* carries articles on the Arinc 629 digital communications system, the AIMS instructor training system, and 777 flat-panel displays. For a copy, contact Boeing Commercial Airplane Group, Box 3707, M/S 2M-89, Seattle, WA 98124-2207.

Two issues of the *IEEE Aerospace and Electronic Systems* magazine cover different aspects of the 777: "Integrated Modular Avionics for Next-Generation Commercial Airplanes," by Michael J. Morgan (August 1991, Vol. 6, no. 8, pp. 9-12), and "Design of the Boeing 777 Electric System," by Luiz Andrade and Carl Tenning (July 1992, Vol. 7, no. 7, pp. 4-11). London's Royal Aeronautical Society has covered aspects of the Boeing 777 at its conferences. At the Conference on Advanced Avionics on the Airbus A330/340 and Boeing 777 Aircraft, (Nov. 17, 1993), Brian G. S. Tucker of Boeing Co. discussed "Boeing 777 Primary Flight Control Computer System—Philosophy and Implementation," and Mark Johnson of Honeywell discussed "Boeing 777 Airplane Information Management Systems—Philosophy and Displays." At the Conference on Design and Maintenance of Complex Systems on Modern Aircraft, held last April 6, Mark Anderson, also of Honeywell, discussed "Advanced Maintenance Techniques in the Boeing 777 Airplane Information Management Systems." Write to the Library, Royal Aeronautical Society, 4 Hamilton Place, London, W1V 0V2, United Kingdom; fax, (44+71) 499 6230.

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