# INNOVATIVE ASPECTS OF THE BOEING 777 DEVELOPMENT PROGRAM

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Abstract

The 777-200 airplane is The Boeing Company's all new wide-body jetliner. The work presented here is an overview of three innovative aspects of the 777 development program: the airplane flight characteristics development, the product definition process, and the integrated test program. The implementation of an advanced, fly-by-wire flight control system facilitated significant design decisions regarding the airplane aerodynamic configuration and flight control functionality. A new product definition process based on the concepts of concurrent engineering and 100% three-dimensional digital definition significantly reduced manufacturing costs through improved product definition quality. An integrated, time-phased test program to test individual parts, part assemblies, individual systems, integrated systems, and ultimately the complete airplane validated that the airplane met all customer certification requirements. Clear philosophies and a "working together" attitude among affected organizations were a cornerstone of the development program and ensured that the right decisions were made. The results of these efforts are measured by the success of the 777 program: an airplane that is easier to maneuver and trim while retaining conventional flight characteristics; improved product quality, with a dramatic reduction of change, error, and rework (more than 60%); and an airplane that is service ready and approved for extended overwater operation (ETOPS) at initial delivery.

## I. Flight Characteristics Development

Make the airplane easier to maneuver and trim while retaining conventional flight characteristics: that was our goal when we developed the flight characteristics of the Boeing 777-200 (Figure 1). The concept isn't complicated and yet the result is an airplane that is both familiar to the pilot and a pleasure to fly. Some of the key elements associated with the achievement of this excellent result are discussed below.

Before proceeding, several definitions are in order. Considerable ambiguity exists within the industry regarding the meaning of terms such as flight characteristics, flying qualities, handling characteristics, and handling qualities. The term "flight characteristics" refers to the manner in which the airplane moves (or does not move), when being flown manually, in response to pilot inputs and external disturbances. The term "handling qualities" refers to the ease with which the pilot may perform prescribed tasks relative to controlling the aircraft's motion. In other words, handling qualities constitute a yardstick by which the desirability of given flight characteristics may be measured. The other two terms appear to be variants of the two that have been defined and are not used in this paper.

The 777's full fly-by-wire digital flight control system played a central role in providing the means to readily achieve the desired flight characteristics and the excellent handling qualities that the airplane exhibits. Flight control functions (e.g., simple surface command, stability augmentation, open loop compensation) are the predominant drivers of flight characteristics and handling qualities on today's modern jet transports. A general description of these functions, as defined by the 777 control laws, is discussed below, although our intent is not to give specifics of the flight control system. A system description and discussion may be found in Reference 1.


FIGURE 1 - The First 777, WA001, Taking Off on Its Maiden Flight

As we began the flight characteristics development process, we were faced with the challenge of what to do, how to do it, and how to get it done on time so that the airplane flight test program could proceed on schedule. In addition, the final result had to be right; we would be defining the means by which pilots would manually control the airplane over millions of hours of flight operations. Such exposure is unkind to deficiencies in concepts. In 1989, activity began on what would ultimately lead to the definition, implementation, validation, and certification of the flight characteristics and handling qualities of the 777-200.

Overview

Looking back, now that the work has been completed and the 777 is in revenue service, a number of items associated with the flight characteristics development process generated significant benefits to the overall program.

1. The airplane was configured for relaxed longitudinal and directional stability, facilitated by implementation of the fly-by-wire flight control system. Reducing the size of the horizontal and vertical stabilizers resulted in improved airplane performance because drag and weight are reduced.
2. Development of the flight control functionality was guided by clear philosophies established early in the program. These philosophies provided a common vision for all involved and led to the development of manual flight control laws that provide conventional flight characteristics while making the airplane easier to maneuver and trim. Envelope protection functions were designed to assist the pilot to avoid inadvertent exceedance of operational boundaries. The net result is an airplane with flight characteristics compatible with the pilots' training and past experience, combined with superior handling qualities and new protection functions.
3. An effective design team was forged across the principal organizations that held a stake in the outcome of the flight characteristics development process. Participation by members of Flight Controls, Stability and Control, Flight Deck, and Structures during development of the flight control laws, with constant guidance and interaction from the project pilots, ensured effective communication and knowledge sharing. The development of trust and a clear understanding of the roles and responsibilities of the various members led to a true team environment where individuals sought input and help from each other.
4. Emphasis was placed on validation of the flight control functionality throughout the entire course of the program. This started with discussions of desired characteristics (functional requirements) and continued with development of proposed designs using the 757 flight simulator, flight evaluation of the baseline control laws with a 757 "demonstrator" program, refinement of mature control laws using the 777 flight simulator, and conduct of "dry runs" of the 777 flight test program on the simulator before first flight. By the time we flew the 777, all control laws were mature and, with a few exceptions, did not change (other than minor gain changes). This maturity of the manual flight control functionality was critical in supporting the aggressive monthly flight test rates of the 777.

777 Flight Control Functions—A Summary

The 777 has three flight control system operating modes for manual flight: Normal, which provides full flight control functionality; Secondary, which is a reversionary mode associated primarily with the loss of air data signals; and Direct, which is an analog equivalent of Secondary (i.e., if all digital flight computers fail). Conventional interconnected controllers (column, wheel, pedals) are used for pilot command input. The operating modes and associated functionality are summarized in Figure 2. An expanded description of Normal mode functions follows. Secondary and Direct modes have simple surface command control laws; that is, control surfaces move in proportion to the pilot's command inputs. A simple pitch rate damper is provided to ensure that desired maneuvering characteristics are maintained when operating at aft center of gravity (CG). The resultant reversionary mode flight characteristics are conventional and benign.

Normal Mode: Pitch Control Functions. Normal mode pitch control provides conventional flight characteristics in the presence of airplane relaxed static stability (RSS). Airplane stability is augmented using the C* (C "star") maneuver command concept. The pilot maneuvers the airplane by commanding the C* parameter, a combination of pitch rate and normal load factor, which in turn commands the elevator. Pilot awareness of airspeed and path control is emphasized by retaining speed stability appropriate to the flight condition (i.e., the pilot must retrim column forces when changing airspeed). The combination of C* stability augmentation and speed stability is referred to as C*U. Variability of airplane response characteristics to pilot inputs and external disturbances (including the effect of thrust changes on pitch control) is reduced as a result of the C* stability augmentation. Compensation for the effect of flap changes and speed brake extension/retraction is provided to minimize the effect of these configuration changes on the airplane's short-term

| Mode | Pitch | Roll | Yaw |
|---|---|---|---|
| Normal | Control<br>• C* maneuver command with speed feedback<br>• Manual trim for speed<br>• Variable feel | Control<br>• Surface commands<br>• Manual trim<br>• Fixed feel | Control<br>• Surface command/ratio changer<br>• Wheel/rudder crosstie<br>• Manual trim<br>• Yaw damping/turn coordination<br>• Fixed feel<br>• Gust suppression |
| | Envelope protection<br>• Stall protection<br>• Overspeed protection | Envelope protection<br>• Back angle protection | Envelope protection<br>• Thrust asymmetry compensation |
| | Controllers and throttles<br>• Backdrive autopilot and autothrottle commands so pilot has an awareness of what these systems are doing | Controllers and throttles<br>• Backdrive autopilot and autothrottle commands so pilot has an awareness of what these systems are doing | Controllers and throttles<br>• Backdrive autopilot and autothrottle commands so pilot has an awareness of what these systems are doing |
| Secondary | Control<br>• Surface command (augmented)<br>• Flaps up/down gain<br>• Direct stabilizer trim<br>• Flaps up/down feel | Control<br>• Surface commands<br>• Manual trim<br>• Fixed feel | Control<br>• Surface commands, flaps up/down gain<br>• Manual trim<br>• Yaw rate damper (if available) |
| Direct | Control<br>• Surface command (augmented)<br>• Flaps up/down gain<br>• Direct stabilizer trim<br>• Flaps up/down feel | Control<br>• Surface commands<br>• Manual trim<br>• Fixed feel | Control<br>• Surface commands, flaps up/down gain<br>• Manual trim |

FIGURE 2 - 777 Flight Control Functions

path response. Pitch turn compensation allows the pilot to make heading changes without having to hold back pressure on the control column (for bank angles up to 30 degrees).

Stall protection assists the pilot in avoiding inadvertent stall of the airplane. This function works in combination with conventional stall warning (stick shaker), speed tape indications (amber band and barber pole), and pitch limit indicator (PLI) to ensure pilot awareness of proximity to stall. Column pull forces of approximately 25 pounds are required for flight at stick shaker angle of attack. A significant increase in applied column force is required to increase angle of attack beyond the stick shaker level. The pilot can override the maximum stall protection system authority with effort.

Overspeed protection assists the pilot in avoiding high-speed dive upsets (in combination with bank angle protection, described later). This function works in combination with conventional overspeed warning and speed tape barber pole indications. Column push force is required to increase and maintain airspeeds above $V_{mo}/M_{mo}$. A column force of approximately 40 pounds is required to maintain flight at airspeeds of $V_d/M_d$. The pilot can override the maximum overspeed protection system authority with additional effort.

Normal Mode: Lateral and Directional Control Functions. Normal mode lateral and directional control provide conventional flight characteristics in the presence of airplane reduced directional stability. Pilot wheel inputs command inboard and outboard ailerons as well as flight spoilers proportional to wheel displacement. For high-speed flight, the outboard ailerons are locked out. Excellent roll response and turn entry/exit characteristics are provided by a combination of well-balanced aileron/spoiler mixing, yaw damper and turn coordination functions, and a wheel/rudder crosstie function (described below). Pilot pedal inputs command the rudder proportional to pedal displacement. Pedal-to-rudder gearing and rudder authority are adjusted as a function of flight condition via a rudder ratio changer. Yaw damping and turn coordination are provided by a beta-dot (sideslip rate) yaw damping function similar to that of the 757/767. A new gust suppression function improves ride quality.

The wheel/rudder crosstie function commands rudder deflection as a function of wheel displacement when the airplane is airborne at speeds below approximately 210 knots. This function was added to the 777 to support the reduced size of the vertical stabilizer and the resulting reduced directional stability. Wheel input commands rudder deflection that reduces sideslip caused, for example, by pilot rudder pedal input or thrust asymmetry. The crosstie also contributes to the airplane's excellent roll response and turn entry/exit characteristics as mentioned above.

Bank angle protection (BAP) assists the pilot in avoiding inadvertent roll maneuvers that could lead to large bank angle upsets. BAP commands control wheel inputs to resist bank angle excursions beyond the bank angle protection boundary (nominally 35 degrees). The pilot must apply continuous control wheel force to maintain bank angles greater than the BAP boundary. BAP will return the airplane to within the boundary if the pilot releases the control wheel. The pilot can override the maximum BAP system authority with additional effort.

The thrust asymmetry compensation (TAC) function assists the pilot in controlling the effects of thrust asymmetry, including sudden engine failure at high power. TAC operates both on ground and in air, commanding rudder to reduce thrust-related airplane yawing moment. The rudder pedals move in response to TAC inputs to ensure pilot awareness of control margins and TAC system operation. For engine failures on the runway, TAC compensation levels are adjusted to require additional pilot input, ensuring timely pilot recognition of the failed engine. In the air, TAC provides nearly full compensation; little if any additional pilot pedal or wheel input is required to maintain heading during and after an engine failure. The pilot can always override the maximum TAC system authority by displacing the rudder pedals.

Airplane Configuration—Relaxed Stability

Payload, range, and fuel burn are key indicators of an aircraft's performance in the highly competitive market for commercial jet transports. Avoiding unnecessary weight and minimizing drag must constantly be considered during development of a new airplane to optimize these indicators. Sizing of the empennage and associated balancing of the aircraft's CG relative to the mean aerodynamic chord (MAC) of the wing directlyinfluence both weight and drag and thus performance.

We decided early in the 777 development to aggressively pursue reducing the weight and drag associated with the horizontal and vertical stabilizers, going beyond that accomplished in previous Boeing designs. By the time the firm configuration of the airplane was defined, we had achieved significant results: block fuel requirements for a 2,000-nautical-mile (nmi) mission had been reduced approximately 2%. This translates into an additional payload of approximately 4,000 pounds or an increase in range of approximately 140 nmi for a fixed takeoff weight.

These benefits were made possible by application of proven technologies in two major areas. First, the use of both the C*U stability augmentation function and the wheel/rudder crosstie allowed the size of both the horizontal and vertical stabilizers to be reduced relative to conventional sizing practices. The smaller sizes reduce drag due to wetted area and reduce weight. In addition, pitch stability augmentation results in a more aft CG location (explained in more detail below), and a farther aft location reduces trim drag. Second, incorporation of structure/material technology (composites) resulted in structure lighter than that achieved by using aluminum as had been done on previous Boeing models. Horizontal and vertical stabilizer areas were reduced approximately 17% and 20%, respectively (Figure 3). Weight was reduced approximately 32% and 15%, respectively (Figure 4).

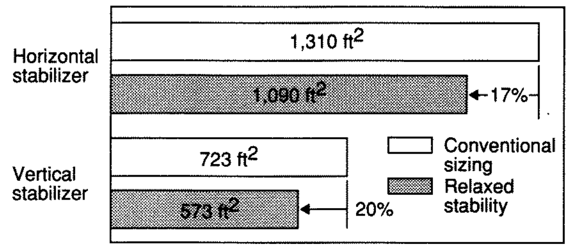


FIGURE 3 - Horizontal and Vertical Stabilizer Area Reduction

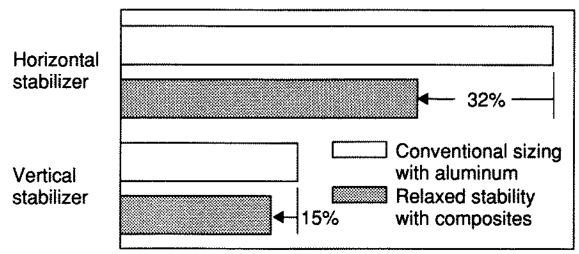


FIGURE 4 - Horizontal and Vertical Stabilizer Weight Reduction

Horizontal Stabilizer. To size the empennage, requirements for both control and stability must be met. Control cannot be augmented; augmentation functions cannot increase the maximum aerodynamic control available from the flight control surfaces. Stability, on the other hand, may be increased above the levels of the basic airplane configuration through the use of augmentation systems. The horizontal stabilizer is sized in the following manner. Requirements for aircraft controllability are specified (e.g., approach trim, takeoff rotation) and are typically (although not always) critical at the forward CG limit. Requirements for aircraft stability are also specified and are critical at the aft CG limit. The level of inherent aircraft stability required depends on whether credit is taken for a stability augmentation system. If credit is taken, the requirements may be "relaxed" and a lower level of inherent stability accepted (hence, relaxed static stability (RSS)).

The size of the horizontal stabilizer also depends on the airplane loadability requirements and the resulting range of CG travel that must be provided. This range is important to customers to ensure flexibility in loading the aircraft with interior options and payload. The 777 provides a generous loading range of 83.5 inches, or 30% MAC (see Figure 5 for a comparison of loading ranges for airplanes of comparable missions). Figure 6 summarizes the resulting trade between required tail size (area) to meet control and stability requirements as a function of the airplane's CG. By relaxing the stability requirement, not only does a smaller horizontal stabilizer result (yet the required loading range is maintained), but the entire CG range of the aircraft also moves aft. This allows the benefit of reduced trim drag, mentioned above, to be realized.

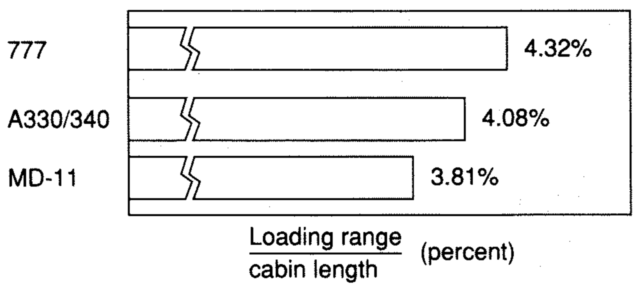


FIGURE 5 - Loading Range Comparison

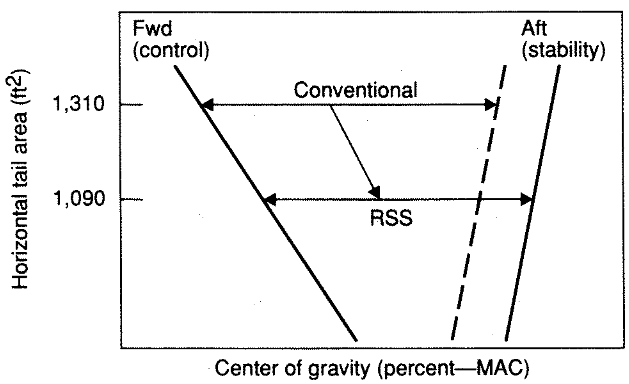


FIGURE 6 - Effects of RSS on Loading Range and Tail Area

Vertical Stabilizer. Conventional sizing of the vertical stabilizer is based primarily on meeting requirements associated with static directional stability. Sideslip characteristics and the pilot's ability to control the effects of in-air engine failure using wheel only have sized the vertical stabilizers on previous Boeing airplanes. With the wheel/rudder crosstie, the same desired sideslip and engine-out control characteristics can be achieved with the smaller vertical stabilizer. The rudder input due to the crosstie compensates for the reduced area.

Design Philosophy

Having discussed the major aerodynamic configuration-related innovations relative to flight characteristics development of the 777, we now turn our attention to the definition and development of the manual flight control functions of the airplane. In early 1989, the evolving 777 design, then referred to as the 767-X, was configured with a flight control system design similar to that of the 767 (mechanical system with electrically commanded spoilers). Nonetheless, the feasibility of a fly-by-wire flight control system was under consideration. By July of 1989, we had made the decision to implement such a system based on the following advantages:

- The airplane would be easier to build because of the reduced number of cables, pulleys, brackets, linkages, and actuators.
- Reliability and maintainability of the control system would be improved.
- Airplane weight could be reduced and performance improved as a result of stability augmentation.

The 767-X was originally envisioned as being common type rated (CTR) with the 757/767. Flight characteristics, handling qualities, and system failure modes and associated procedures would all need to be compatible with these earlier models. The flight control functions that were intended to be implemented in the new fly-by-wire system would be essentially the same as those provided by the 767 (but including the provision for stability augmentation). By early 1990, however, it had become apparent that providing 757/767 CTR was not of high value to our customers. CTR with the 757/767 was actually perceived by them as standing in the way of other technological advancements such as the 747-400 cockpit layout. CTR ceased to be a requirement.

The above decisions evolved over the course of approximately 1 year. During this time decisions were also being made regarding the flight characteristics of the airplane should the requirement for CTR be dropped. Obviously, with the constraint of CTR, required flight characteristics would be defined by those of the 757/767. With the constraint gone, however, the issue was open. Choice of flight characteristics as defined by control laws and controller type needed to be settled.

Our most recent experience with advanced flight control functions for commercial jet transport application had been with the canceled 7J7 activity during 1985-87. The proposed 7J7 approach, referred to as Gamma/Track, represented a significant departure from conventional flight characteristics and posed a considerable implementation challenge. At the close of the 7J7 activity, consensus had not been reached within the Boeing piloting and engineering communities that this was the preferred approach.

The 777 dilemma was obvious and certainly not new; the incorporation of a fly-by-wire flight control system opened up many new opportunities to affect the manner in which the pilot flies the airplane. The question was, which opportunities should be exploited? The solution to the dilemma came in a simple yet effective form—a set of top-level philosophy statements for manual flight control functions, which are summarized in Figure 7.

- **The pilot shall have ultimate responsibility and authority for the use of control.**
- **Pilot intuition, based on training and past experience, shall be preserved.**
- **Pilot awareness shall emphasize interaction with the primary flight controller devices.**
- **Control functions shall assist the pilot in avoiding or recovering from inadvertent exceedances of operational boundaries.**

FIGURE 7 - Philosophy for Manual Flight Control

These statements derive from the crew-centered principles for flight operations in Reference 2. They are oriented toward reinforcing the pilot's ability to make sound judgments and are based on the considerations discussed in the following paragraphs.

<u>The pilot shall have ultimate responsibility and authority for the use of control.</u> The pilot is the single most important factor in the safe and efficient operation of the aircraft. The pilot's ability to make judgments and take appropriate action when confronted with conflicting or incomplete information is unique. Ultimately it is the pilot who is best suited to decide what level of control/maneuvering is appropriate for any given situation. This is especially true for those unexpected situations that violate previously held assumptions (usually on the part of engineers).

<u>Pilot intuition, based on training and past experience, shall be preserved.</u> Intuition may be described as knowing what to do without having to consciously think about the required actions. The pilot's ability to make judgments based on intuition and then act may be crucial for those flight situations where time is insufficient to analyze deductively the required course of action. Pilot intuition is most heavily influenced by previous flight experience as well as training.

<u>Pilot awareness shall emphasize interaction with the primary flight controller devices.</u> Flight situation awareness is necessary for the pilot to make appropriate judgments relative to maneuvering and controlling the aircraft. The most effective human-machine interface designs help the pilot understand the current situation. Transfer of knowledge (feedback) is most effective when the pilot is an active participant in the airplane control loop, with tactile and visual cues supporting situation awareness.

<u>Control functions shall assist the pilot in avoiding or recovering from inadvertent exceedances of operational boundaries.</u> Airplanes have inadvertently exceeded their normal operational boundaries for various reasons, including externally driven upsets (e.g., windshear), system failure (e.g., autopilot failure), and pilot disorientation and/or pilot errors in judgment and actions. Regardless of the cause, the flight control functions are intended to help the pilot in dealing with such situations. In addition, these functions must provide effective situation awareness to assist the pilot in avoiding unintended excursions past the boundaries in the first place.

With the philosophy established, we were able to make the following significant design decisions:

- Retain conventional flight characteristics consistent with pilot expectations and reinforcement of pilot situation awareness. Improve handling qualities to reduce pilot workload (make the airplane easier to maneuver and trim).
- Enhance pilot awareness of operational boundaries. Implement flight envelope protection functions, providing tactile cues of impending operational boundary exceedances. Allow protection functions to be fully overridden by the pilot.
- Maintain awareness of automatic system behavior and associated airplane response by providing visual and tactile cues of autopilot and autothrottle commands to the primary flight controls and the engines by backdriving the pilot controls.

The net result is an airplane with flight characteristics compatible with the pilot's training and past experience, with superior handling qualities as well as new envelope protection functions.

<u>Working Relationships</u>

Common vision and goals, commitment to honest communication between organizations, mutual trust and respect for each other's ability to contribute to the program's success—these were all attributes of the "working together" attitude embraced by members of the 777 program. Much can be accomplished under such working relationships, especially when the task at hand is large and complex and requires a high degree of design integration. The fact that these working relationships existed during the development of the flight control laws contributed immeasurably to the outstanding results achieved for the 777 flight characteristics and handling qualities.

Five organizations played major roles in the design of the 777 flight control laws. Each furnished specific knowledge and experience and had unique roles and responsibilities regarding the outcome of the design activity. These organizations and their contributions are discussed below.

Project Pilots. The project pilots' ultimate responsibility was to ensure that the flight characteristics and handling qualities selected would result in an airplane not only safe and certifiable but preferred by the airline customers and their pilots. In this sense the project pilots served as a proxy for the customers as well as other pilot-focused groups involved in the 777 development process (e.g., flight operations, flight/crew training, and regulatory agency pilots). The project pilots provided daily guidance, insight, design evaluation, and feedback to the engineers involved in the flight control law design activities. The fact that the pilots gave unselfishly of their time, which was in high demand throughout the entire program, contributed greatly to the successful outcome of the overall design.

Aerodynamics Engineering—Stability and Control. The Stability and Control group was responsible for ensuring that the flight characteristics and handling qualities of the airplane were acceptable to the project pilots and would meet all flight characteristics certification requirements, including the effects of failures. This group, in addition to being responsible for the control and stability characteristics of the airframe, specified the basic requirements defining the behavior and performance of the flight control functions. These requirements included controller characteristics (column, wheel, and pedal), controller-to-surface gearings, actuator performance, and airplane steady and dynamic response characteristics to pilot inputs. Design guidance and requirements interpretation were provided to the Flight Controls group responsible for the design of the control laws. In addition, the Stability and Control group performed analyses and conducted piloted simulator evaluations to validate the resulting flight characteristics and handling qualities. Finally, this group was responsible for defining the flight test plans to test and certify the flight characteristics of the airplane.

Flight Controls Engineering—Performance. Within the Flight Controls organization, the Performance group was responsible for the design, specification, and verification of the flight control laws. This group worked closely with the project pilots and the Stability and Control engineers to transform top-level requirements into the detailed, complex control laws that govern the manner in which the 777 responds to pilot commands and external disturbances. Performance group members prepared the design specifications and assisted the flight computer supplier in implementing the control laws as well as conducting performance analyses and verification tests. Detailed requirements for sensor characteristics and actuator bandwidth were also specified by this group. The Performance group worked closely with members of the Structures organization to ensure that proposed control laws were compatible with static and dynamic loads requirements. Aeroservoelastic effects on control law performance were also evaluated by the Performance group with assistance from Structures.

Flight Deck Engineering. Relative to the development of the control laws, the Flight Deck group was responsible for the integration of specific flight control function characteristics with flight deck systems such as the primary flight display (PFD). For example, when the BAP function becomes active at 35 degrees of bank, the sky pointer on the PFD changes from white to amber to provide a visual supplement to the BAP tactile cues that the pilot feels on the control wheel. In addition, the Flight Deck group supported the Crew Training organization to ensure that pilot procedures and alerting functions associated with failures affecting flight control functionality were appropriate and correct. Flight Deck engineers worked closely with the project pilots and the Flight Control and Stability and Control engineers to ensure that a totally integrated design was achieved.

Structures Engineering. Structural flight loads, both static and dynamic, are influenced by the behavior of the flight control functions. The Structures organization was responsible for analyzing the effect of the proposed control laws on these loads and, working with the control law design team, for addressing any identified problems. Structural dynamic interactions with the stability augmentation functions were also investigated to ensure flutter stability and to achieve desired performance.

Other Organizations. Although the above five organizations had major responsibilities, many others contributed significantly to the control law development activity. For example, the Propulsion group engaged in a major effort to provide acceptable thrust signals to the TAC control laws. Obviously, no one group could successfully develop the 777 control laws alone. The magnitude of the job and the broad range of experience required made "working together" the only way to get the job done right.

Flight Control Functionality—Validation

Design validation confirms that a design is sound and well grounded on accepted requirements. In this light, validation is often thought of as coming after a design has been completed. Certification compliance demonstrations are an example of this kind of validation activity. We could not wait that long to validate the 777 flight control functionality. The desire to deliver "preferred" flight characteristics and the need to avoid change and rework during the aggressive 777 flight test program necessitated a different approach. The flight control functions, as defined by the control laws, needed to be virtually complete and correct before the 777 even flew. Thus, the start of validation preceded the initiation of detailed design, and validation activities ran continually over the course of the program.

Getting Started. Before specifying control law designs, we spent considerable effort discussing what we were trying to accomplish. The intent of each candidate flight control function was discussed, scrutinized, and summarized. Why the function was being considered, what value the function was expected to provide, and how it adhered to the philosophy for manual flight control were questions that we addressed at the beginning of the design process. In addition, we identified required and desired characteristics of each function and open issues that needed to be resolved. As a result of these activities, we established top-level design requirements. Next, we identified design approaches that met the design requirements and provided the desired characteristics. Identifying the design approaches led in turn to specifying the control law concepts. As the concepts matured, we updated the design requirements and developed detailed system requirements.

Representatives of the Project Pilots, Stability and Control, Flight Controls, and Flight Deck organizations participated in this early development process and greatly benefited from it. A real sense of group "ownership" was developed: the participating organizations worked together as a team and were willing to jointly accept responsibility for the outcome of the design. This approach to design fostered the common vision and goals, honest communication, and mutual trust and respect so important to success. The working relationships developed during this early activity formed the foundation upon which the 777 control laws successfully evolved.

The design activity described above took place during 1990-91. The initial control laws were developed using the 757 flight simulator; a 777 simulation was not yet available. Detailed engineering analyses of the proposed flight control functions and control law implementations, as well as many hours of subjective pilot evaluations using the simulator, initially confirmed the validity of the design concepts. The end result was a well-defined baseline for the 777 flight control functionality and the initial specification of the control laws.

757 Demonstrator Program: Inflight Evaluation. The planned pace of the 777 flight test program did not allow time for developmental flight testing of control law concepts. We would incur considerable schedule risk, however, if we assumed that final control laws could be designed without any flight evaluation. Although the development work accomplished by using the ground-based simulator was meaningful and appropriate, it could not ensure that the realities of flight would not reveal subtle (and sometimes not-so-subtle) deficiencies in concepts or implementations. Thus, we decided to conduct flight evaluations of the proposed flight control functions and control laws by using a specially modified 757 (Figure 8). The purpose of this testing was to reduce the risk of disrupting the 777 flight test schedule because of problems with flight characteristics and handling qualities.

FIGURE 8 - 757 Flight Test "Demonstrator"

Not all 777 flight control functions were evaluated during the demonstrator program. We deemed it necessary to assess flight characteristics and handling qualities through inflight evaluation when we judged pilot perception was misled or inadequately addressed during ground-based simulations. The effects of motion, vision, sound, and the level of pilot anxiety were all considered in making this judgment. Evaluation categories particularly sensitive to these effects included ride quality, landing flare and touchdown, takeoff, engine-out dynamics, fine trim, stall, turn entry and exit, and wind and turbulence effects. The control functions chosen for inflight evaluation were the C*U-based longitudinal control laws, stall protection, thrust asymmetry compensation (TAC), wheel/rudder crosstie, and the gust suppression function. The basic lateral and directional control functions of the 757 were used because of their similarity to the equivalent 777 functions.

The validity of the design approach was confirmed by flight testing conducted in 1992 over a period of approximately 6 months, with 167 hours of flight evaluations on 67 flights. The airplane was indeed easier to maneuver and trim while exhibiting conventional flight characteristics. A broad spectrum of pilots, including representatives of Boeing Flight Test and Crew Training, customer airlines, U.S. and European regulatory agencies, and pilot unions, participated in the evaluations and praised the results.

The knowledge gained from this testing was used to update the control law specifications. We made significant decisions, including the final selection of a landing flare law (necessary to retain conventional landing characteristics when using C* stability augmentation) from three candidates developed on the simulator. We identified new functions to further improve the flight characteristics, including speed brake and flap compensation functions to minimize the effect of these configuration changes on the short-term path response of the airplane. We also identified and solved numerous detail implementation problems.

Preparing the 777: Finalizing the Design. The control laws, incorporating the lessons learned from the 757 flight test program, were transferred to the 777. By the end of 1992, a complete 777 simulation was available, including a six-degree-of-freedom aerodynamic model and modeling of all pertinent systems that supported primary flight control functions. We adjusted control law gains for the 777 and conducted extensive analyses of predicted flight characteristics and control law performance (e.g., gain and phase margins, effective time delay). We conducted many piloted simulator cab sessions to evaluate the resulting flight characteristics and handling qualities (Figure 9). Particular emphasis was given to the evaluation of the effects of system failures.

The simulation cab was designed so that components of the actual flight control system hardware could be utilized. In particular, the primary flight computers (PFC), the digital computers in which the control laws were coded, could be used in the cab during pilot evaluations. This capability allowed hundreds of hours to be accumulated on these computers before the first flight of the airplane.

FIGURE 9 - 777 CAB2 Used for Pilot Evaluation

Note that this testing did not replace verification test activities; the PFCs underwent extensive verification testing during standalone bench testing and systems integration testing conducted in both the Systems Integration Laboratory (SIL) and the Flight Controls Test Rig (FCTR, also known as the "iron bird"). Controller characteristics also received close attention. The column, wheel, and rudder pedal hardware were objectively and subjectively tested in the FCTR to ensure acceptable characteristics.

Before first flight, we conducted "dry runs" in the simulator of the flight test plans associated with flight characteristics and handling qualities. Representative conditions from the detailed test plans were evaluated and adjustments were made to the test procedures or the conditions themselves as necessary. These dry run activities let the pilots and engineers be certain that the purpose and expected outcome of each test item were thoroughly understood and agreed upon in advance. The thoroughness of these preparations and the maturity of the flight control functions and their implementations meant we were ready for first flight.

Conclusion: Flying the 777. More than 5 years of careful preparation culminated in the successful first flight of the number 1 777-200, WA001, on June 12, 1994. The thousands of men and women at Boeing and at companies around the world who had contributed to the design, build, and test of the airplane were rewarded for their efforts by a nearly flawless flight that lasted 3 hours and 48 minutes. Although the weather was less than ideal, with low clouds, rain, and gusting winds, all test objectives were accomplished and the flight was completed with a perfect landing. As far as the flight characteristics and handling qualities were concerned, the pilots reported that all went very well from start to finish, with "no surprises."

With the successful completion of first flight, subsequent tests focused on an orderly expansion of the flight envelope, including flutter and flight loads clearance as well as basic handling quality evaluations. Each step of the test expansion was made after the project pilots were satisified that it was safe to continue. This initial testing was followed by comprehensive evaluation of flight characteristics throughout the flight envelope in all three modes of flight control system operation (Normal, Secondary, Direct). As evidence of how well the airplane was performing, WA001 completed 78 hours of flight testing in its first 30 days, a rate well above that of previous test programs for new models. A general discussion of the 777 flight test program is presented in the final section of this paper and in References 3 and 4.

By the end of July, we had completed all testing associated with the evaluation of Secondary and Direct mode flight characteristics and the identification of any necessary changes. These characteristics were considered very satisfactory, and only two minor changes to the flight control computers were required. By mid-September, we had also completed most of the testing to evaluate Normal mode characteristics. Although more changes (approximately 25) to the flight control computers were required to achieve desired Normal mode characteristics, the number was small considering the high standards we had set for ourselves and the complexity of the flight control functionality. Many of the changes were simple gain or gearing modifications to "tune up" the handling qualities. The fly-by-wire flight control system itself was of great benefit. The ability to quickly modify the flight computers allowed us to quickly and efficiently solve problems and assess proposed solutions. Certification of the resulting flight characteristics went smoothly.

The 777-200 received its certification approval on April 19, 1995, and entered into revenue service on June 7. As of this writing, seven airlines are operating 24 777s and have accumulated over 38,000 hours of operation. The flight characteristics and handling qualities of the 777 have been broadly praised by the pilots who fly the airplane. The years of preparation and working together have paid off very well indeed.

## II. Product Definition Process

Manufacturing cost reduction was a key driver in the program plan for the 777 to ensure that the airplane would be competitive with the offerings of other manufacturers and refurbished existing airplanes. Study of previous Boeing programs revealed that a major component of recurring cost was change in product definition (part and tool designs and the associated manufacturing plans) to correct part-to-part interferences and gaps and designs with poor producibility (Figure 10). The cost of this change was especially high because it came very late in the development program, resulting in scrapped or reworked parts and tools.

A revised product definition process was developed to address this major cost driver. The new process was based on a strategy of concurrent product definition in a working-together, design-build team environment. Digital product definition, digital preassembly, hardware variability control, and design for reusability were key initiatives that supported the new process. The overall objective of the new process was to reduce product-definition-driven change, error, and rework by 50% compared to previous best efforts.

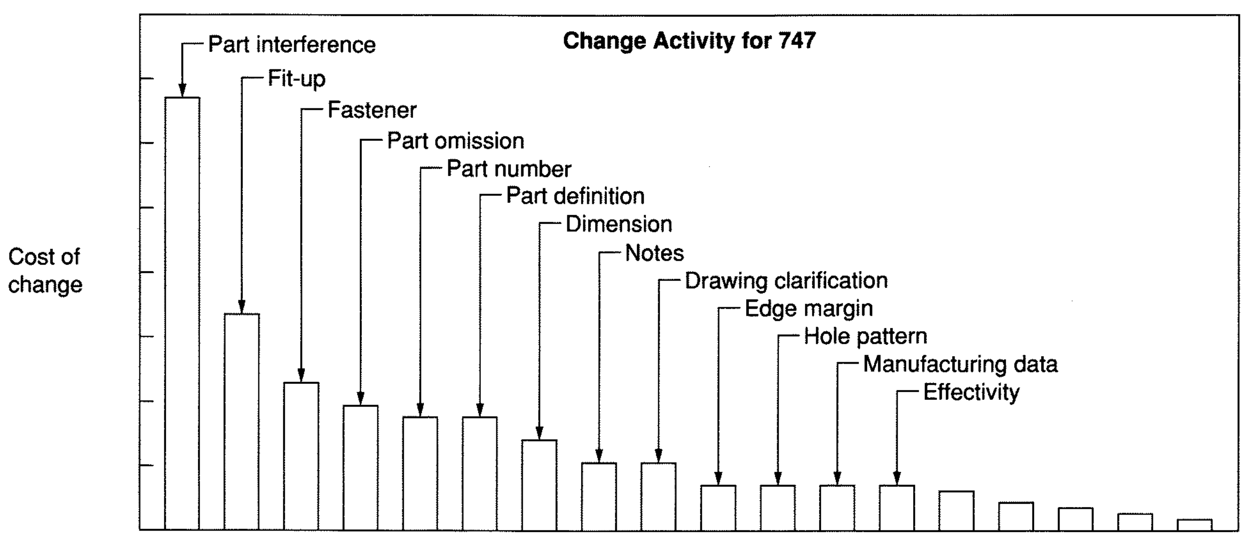


FIGURE 10 - Traditional Cost Drivers

## Concurrent Product Definition and Design-Build Teams

The product definition process at Boeing had evolved from the beginnings at the Red Barn, where a small design team worked adjacent to the fabrication and assembly areas in one building, to a very large design team that was organized by design discipline and physically separated from the factory. The increased size and complexity of the product drove this evolution. Organization by design discipline ensured that the expertise required for the complex system and structural design requirements could be developed, retained, and passed on to new engineers. In addition, a new discipline, Manufacturing Engineering, was developed to create the manufacturing plan and to be the liaison between the factory and the part and tool design engineers. This organization by function met the requirement of designing and building very large, complex products such as the 747, but it resulted in organizational silos that hampered communication and a serial design-plan-build process that was lengthy (Figure 11) and prone to errors that required correction before product delivery.

An additional problem with the traditional product definition process was the use of build-paced design schedules. Part and tool designs were scheduled "just in time" to support build requirements. A major problem with this approach was that structures with very long lead times were often designed and released before short-lead-time interior or systems components like wires and tubes were designed. It was common to plan for revisions to structural designs to add system penetrations and brackets late in the design phase (Figure 12). Although most of these system interfaces were accommodated without major effort, the process drove at least two major waves of product definition to the shop, required large planning efforts to maintain configuration control of the product, and occasionally required significant design change after parts and tools had been fabricated.

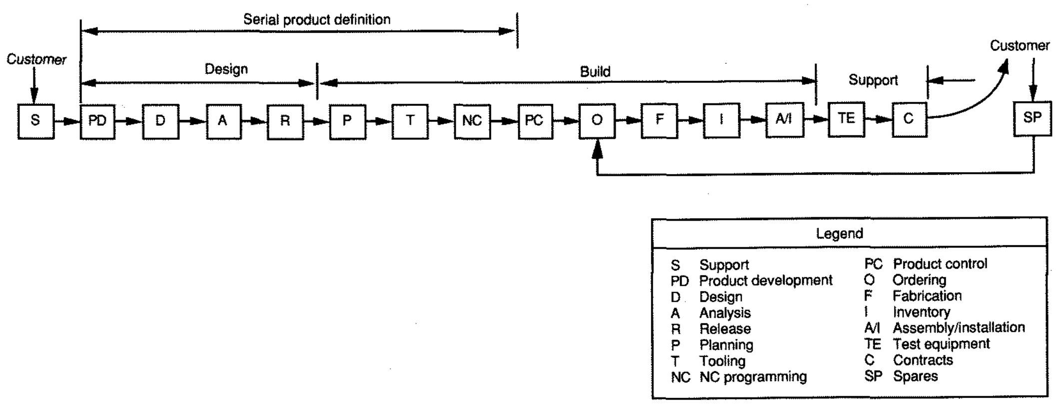


FIGURE 11 - Traditional Serial Product Definition Process

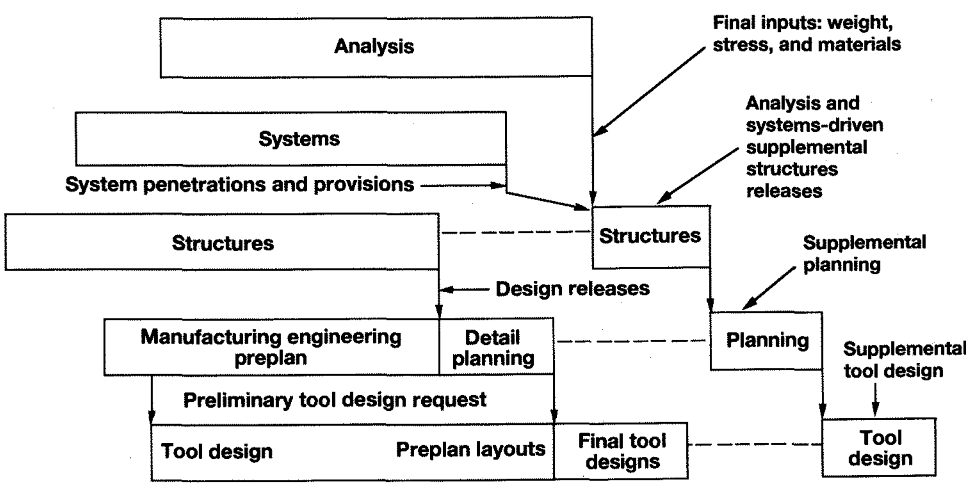


FIGURE 12 - Traditional Product Definition Schedule

Concurrent product definition using design-build teams (DBT) was adopted to address the schedule and organizational issues that drove change, error, and rework (Figures 13 and 14). DBTs were made up of design, tool, and manufacturing engineers along with support from the factory, Quality Assurance, Customer Support, Materiel, suppliers, and representatives of the customer airlines. Teams were formed around the various airplane components and systems such as floor structures, potable water, and electrical equipment. These component DBTs ranged in size from about 15 to 60 collocated members and were co-led by Design and Manufacturing Engineering.

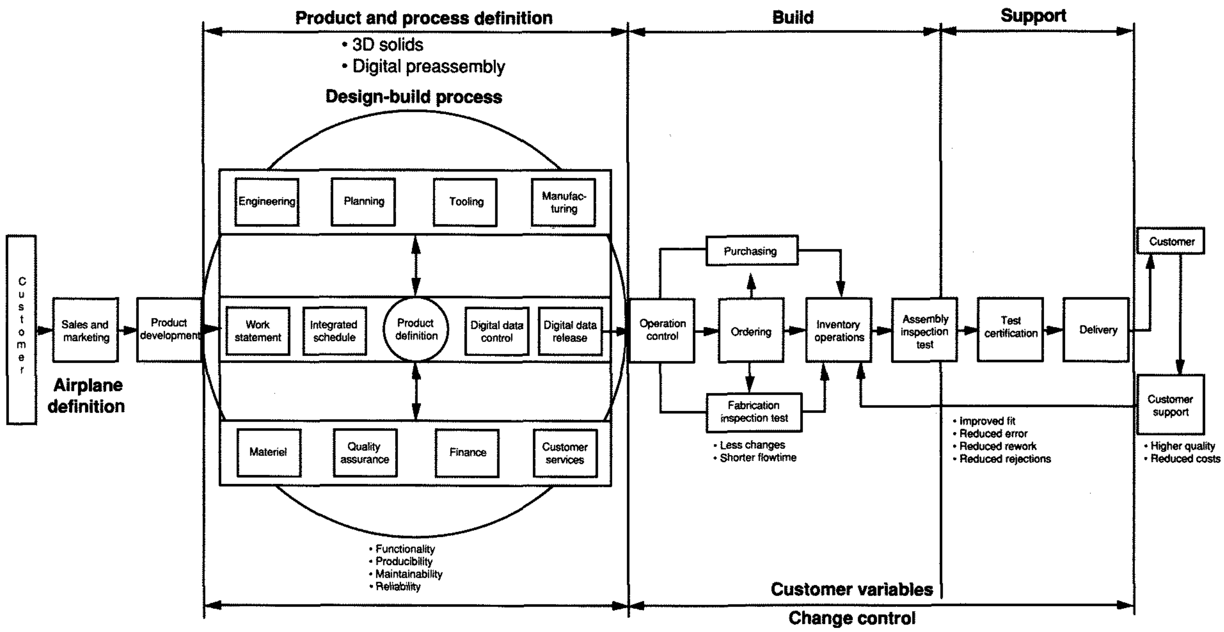


FIGURE 13 - Concurrent Product Definition Process

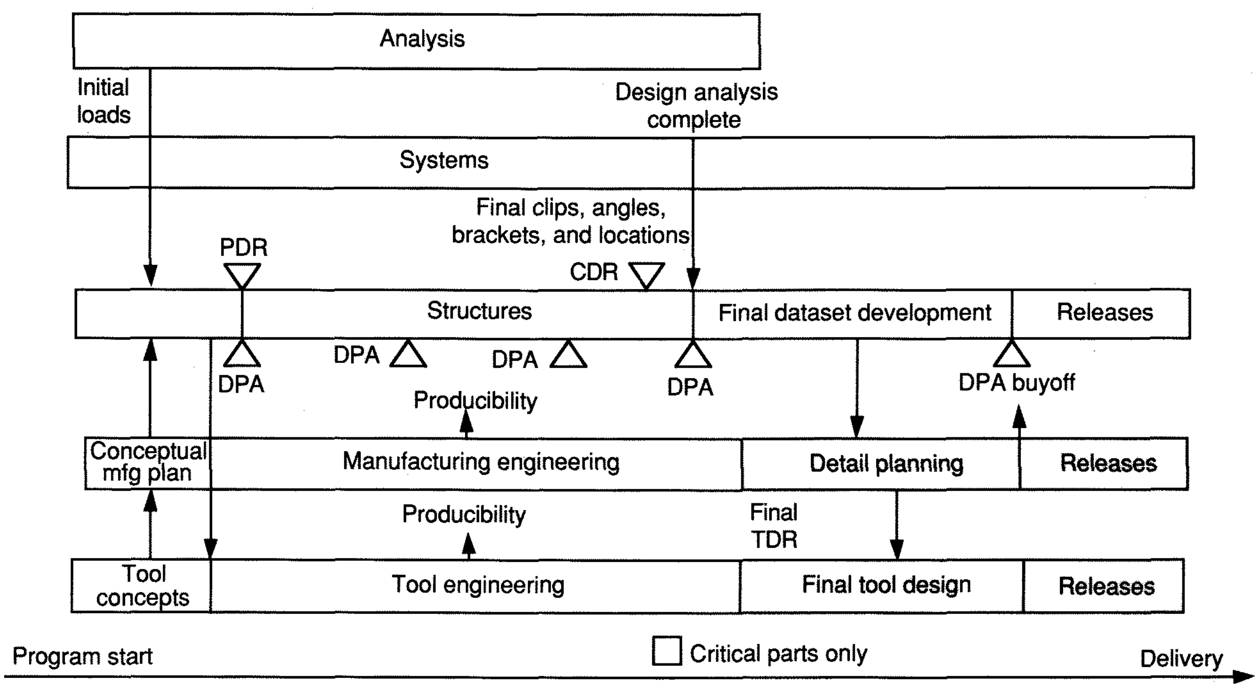


FIGURE 14 - Concurrent Product Definition Schedule

Integration DBTs were organized around sections of the airplane to work design and build integration issues across the component DBTs (Figure 15).

The strategy of concurrent product definition was to recognize design integration in addition to build requirements when developing the design schedule. Design integration was ensured through the use of "stages" (Figure 16). Stages 1 through 4 were design development stages that focused on creating an integrated overall design before releasing product definition for fabrication and assembly. A major review of the entire airplane was completed at the end of Stage 4 before detail design was completed in Stage 5 to support product definition release, Stage 6. All product definition (parts, plans, and tools) was reviewed by the DBTs to ensure that producibility as well as design requirements were met.

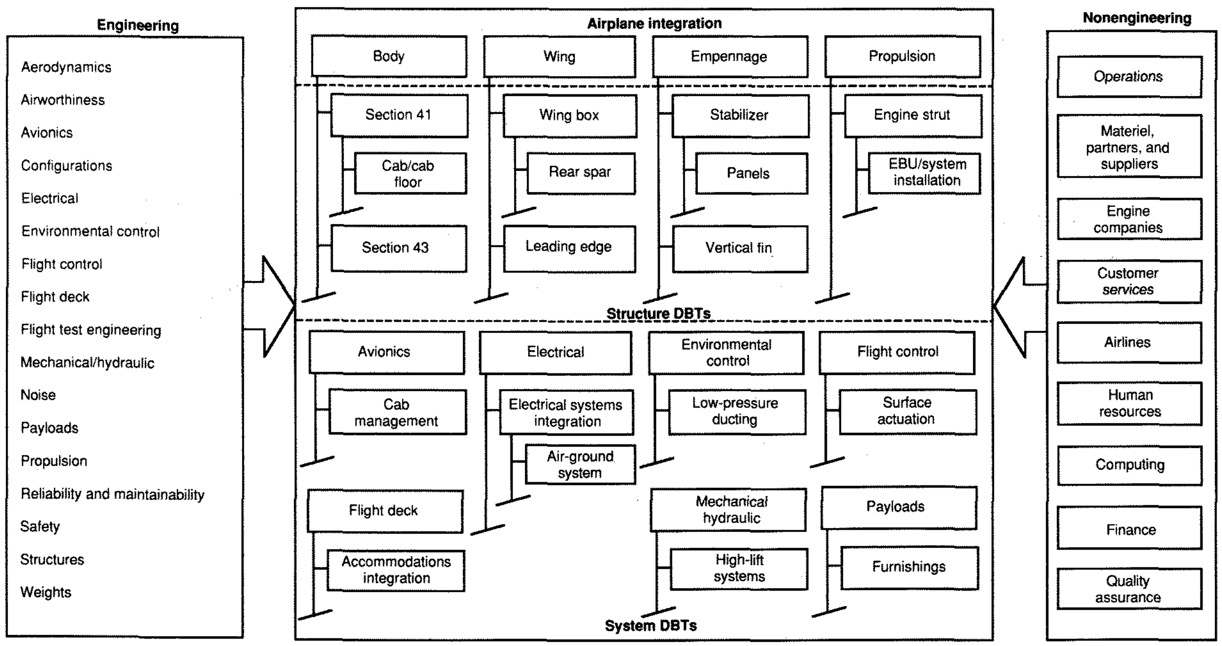


FIGURE 15 - Design-Build Team Structure

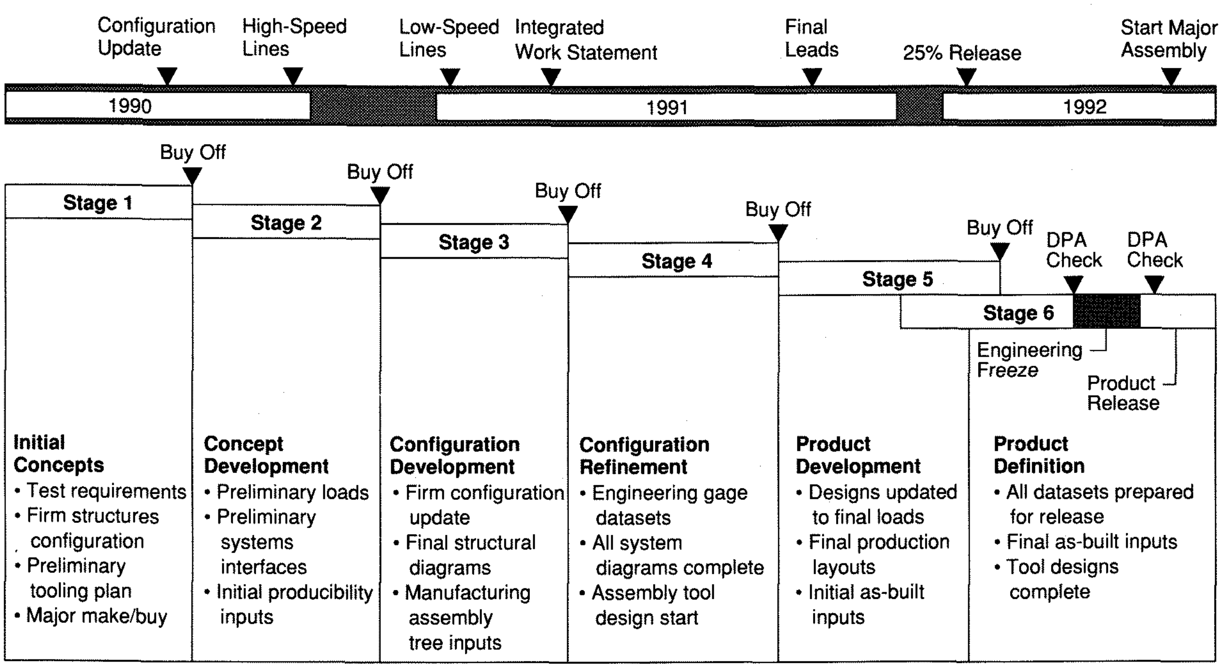


FIGURE 16 - 777 Design Stages

### Digital Product Definition

The 777 was the first product in its class to use 100% digital product definition (DPD). DPD means that all of the geometric definitions of parts and tools are incorporated in a digital dataset and secured in a database as the sole authority definition. The DPD dataset contained a three-dimensional (3D) solid definition of the part, a plottable two-dimensional (2D) drawing representation, and 3D wireframe data as required to facilitate manufacturing automation (Figure 17). The datasets were used to define traditional detail, assembly, and installation drawing tree levels. DPD was the foundation for the following three initiatives.

### Digital Preassembly

The use of 100% DPD allowed the 777 program to also use 100% digital preassembly and eliminate the need for physical mockups. The traditional product development approach at Boeing relied on physical mockups to validate design integration and to define parts that were difficult to accurately define on 2D drawings. Part types that were designed using the mockup included wire bundles, tubing, and insulation blankets. The mockups were constructed in three increasingly precise levels of definition (called Class I, II, and III) during the design phase. These mockups were expensive and time consuming to construct, and the parts that were defined using them required high rates of rework due to accuracy problems.

The 3D solids that were created for DPD were used in a computer simulation of the assembly of the airplane referred to as digital preassembly (DPA). DPA was used to make sure that the parts and tools fit together and could be assembled before the datasets were released for production. The 3D solids were created in progressively more accurate levels of definition corresponding to the requirements of the design stages (Figure 18). DPD datasets for the traditional mockup products like wire bundles were created using DPA to verify fit and routing requirements.

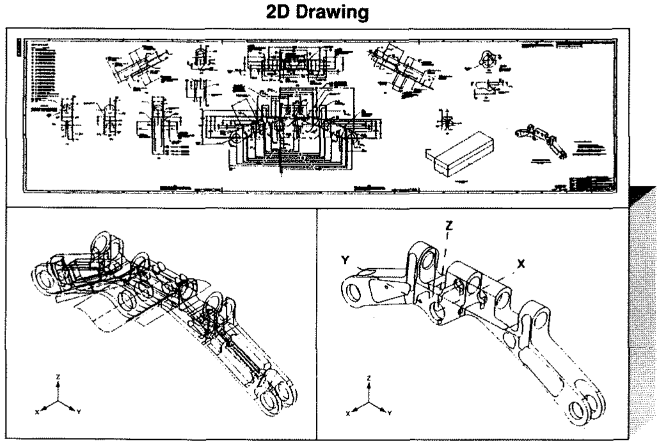


FIGURE 17 - 777 Digital Dataset

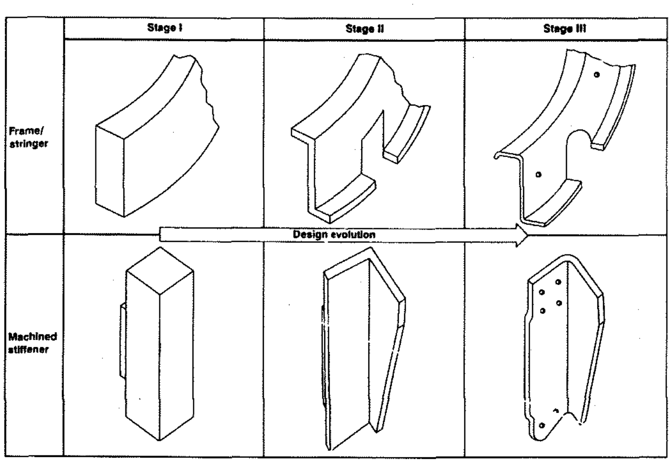


FIGURE 18 - Staged Solid Model Evolution

The CATIA CAD/CAM system along with Boeing-developed software was used to support the requirements of DPD and DPA. The largest networked CAD/CAM installation in the world was created to support the program, consisting of approximately 5,000 CATIA terminals hosted by 15 mainframe computers at the peak of activity.

Hardware Variability Control

Hardware variability control (HVC) is a process that emphasizes variation reduction of key areas of parts and assemblies to improve airplane-level performance targets for shape, fit, appearance, service life, and safety (Figure 19). HVC begins with the identification of top-level key characteristics, like wing sweep, related to airplane-level performance. The top-level key characteristics are flowed down through the assembly breakdown of the airplane to the detail part level. Statistical analysis is conducted to optimize key characteristic tolerance specification considering manufacturing process control capability in support of the airplane-level performance targets. A statistical process control plan is then developed for each of these key detail part and assembly characteristics to continuously improve the quality of the critical airplane performance items.

Design for Reusability

The external view of commercial transports belies the fact that they are highly variable products. Approximately 25% of the parts, primarily systems and interior components, are variable from one customer to the next. This variability was traditionally dealt with using point design solutions and considerable design and tooling effort on a recurring basis. A key objective of the 777 program was to reduce this with an initiative termed design for reusability. This effort started with analysis of previously ordered airplanes to determine which features should be made standard since the majority of customers wanted them and they were not mutually exclusive to other desired features. Further analysis was then used to create a set of about 200 standard options that covered the vast majority of customer requirements. Provisions for these 200 standard options—physical supports, systems connects, or space—were included in the basic design. The level of provision was selected to optimize cost and weight. In addition, the interior of the 777 was designed for flexibility with standard closet, lavatory, and galley interfaces and provisions for relocation within predefined zones (so-called "flex zones"). DPD and DPA were used to ensure that these predesigned and provisioned options fit and worked together correctly and were ready for reuse in future customer configurations.

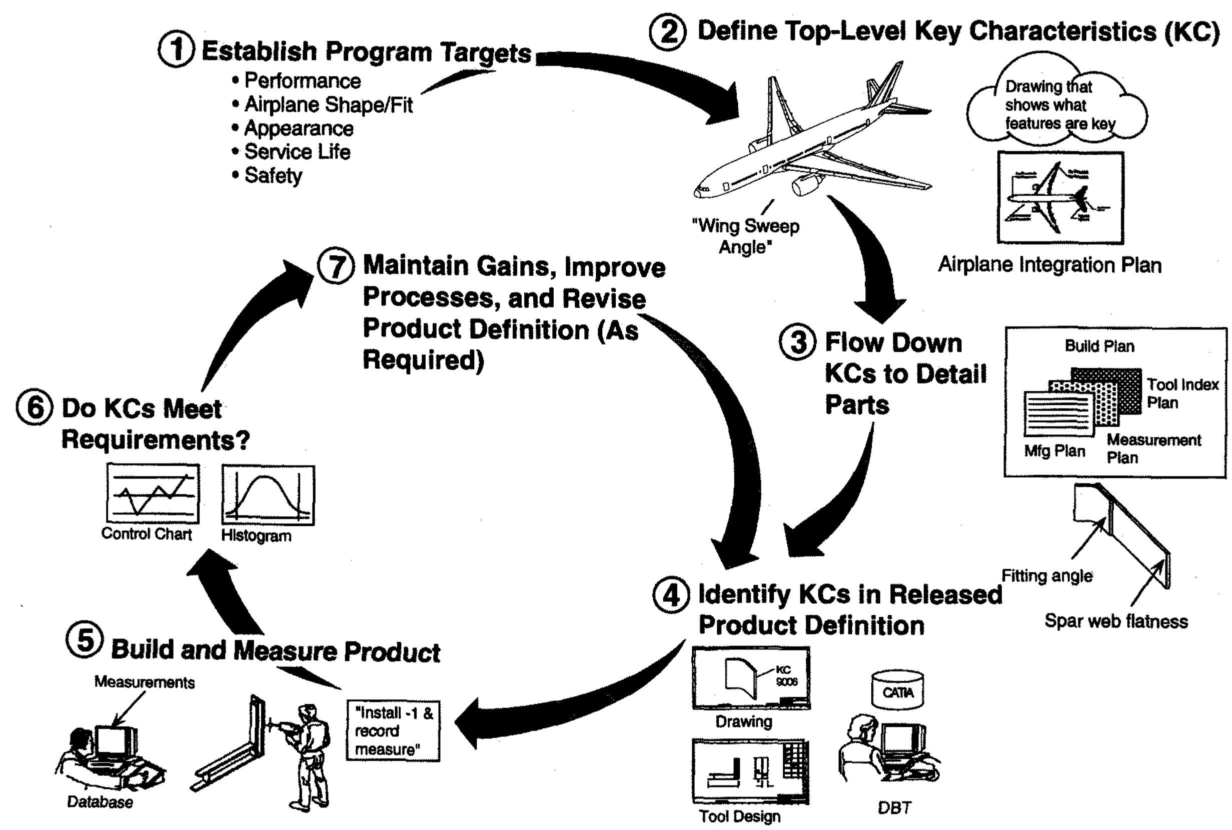


FIGURE 19 - Hardware Variability Control

## Results

The combined result of these product definition process initiatives was remarkable. Change, error, and rework were reduced by more than 60% compared with previous best efforts. Assembly quality was dramatically improved over that of previous models. The body was in alignment within 0.040 inch over a length of 150 feet (Figure 20). Fewer than 1% of the hydraulic tubes required redesign by the second airplane (Figure 21). In addition, the working-together spirit developed in the design-build teams lives on with a new level of cooperation and pride within the organization.

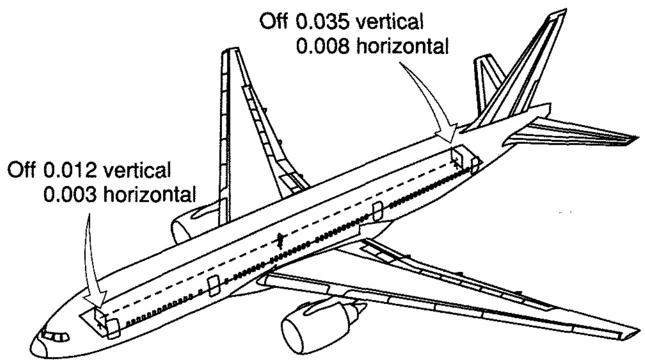


FIGURE 20 - 777 Final Body Join Accuracy

- **Business as usual**
  - **1st airplane: Approximately 90% of tubes redesigned to fit airplane**
  - **2nd airplane: Redesign down to approximately 20%**
- **777 with DPD/DPA**
  - **1st airplane: 47 of 1,950 tubes redesigned (2.4%)**
  - **2nd airplane: 4 of 1,950 tubes redesigned (0.2%)**

FIGURE 21 - 777 Hydraulic Tube Accuracy

## III. Integrated Test Program

Flight test—"the real world," "the last step of design," "the place mistakes are found and corrected." These are all statements heard since the beginning of airplane history. Wilbur and Orville Wright needed flight test to finish their design. All major airplane programs since have relied on testing to finish design. The competitive situation of the 777, however, was requiring changes in many traditional methods, as noted in the previous sections of this paper. The fly-by-wire system is an example of technology change and the changes in product definition an example of design process change. Process change for "test" would also be necessary.

Rather than looking at the test phase to solve problems, we needed to view test as validation of the design and build processes to customer requirements. Test could no longer be viewed as research and development; it needed to be viewed as a validation of design requirements, certification regulations, and customer operations.

The company initiative for a service-ready airplane, particularly as portrayed by the requirement for overwater operational approval (ETOPS) at initial delivery, further focused this viewpoint. We needed to go beyond answering the question, "Is it designed the way Boeing wants it?" We needed to answer the question, "Can the customer use it to accomplish his mission?" Will it add value to the airline's operations?

An integrated, time-phased test program was developed to test individual parts, assembled parts, individual systems, assembled systems, and integrated systems. The testing started, in some cases, even before design was complete. Testing was done by suppliers, Boeing, several governmental regulatory agencies, and our customers. Figure 22 graphically displays the components of this test program. Overviews of some elements of the 777 test plan are discussed on the following pages.

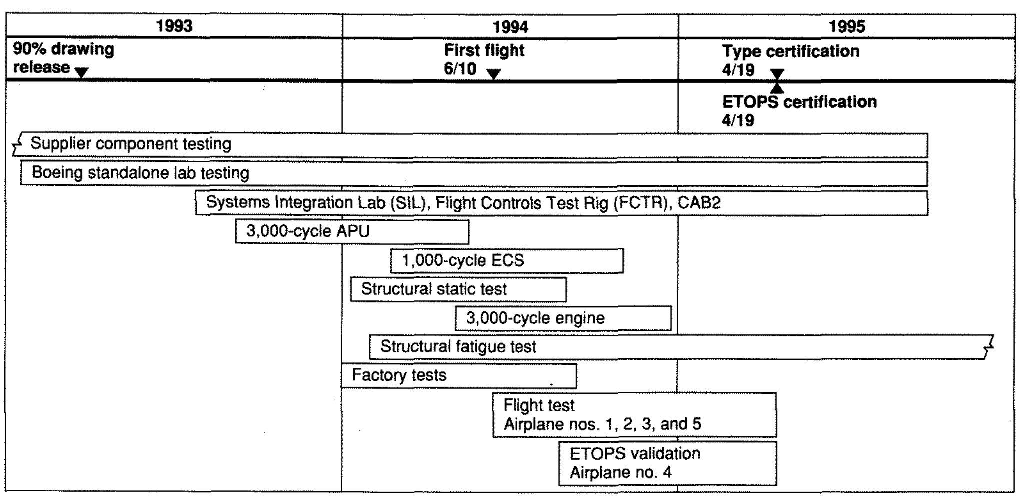


FIGURE 22 - Service-Ready Test Plan

Integrated Airplane Systems Laboratory

Validation testing of the major airplane systems used a number of laboratory facilities. Many of these laboratories were collocated in the Integrated Airplane Systems Laboratory (IASL), strategically located near the flight test facility. Four labs were used extensively by the 777: the standalone labs, Systems Integration Laboratory (SIL), Flight Controls Test Rig (FCTR), and Engineering Simulator Cab (CAB2). Many of the airplane system line replaceable units (LRU) were systematically tested by routing them through each of these labs. LRUs are the black boxes that house the electronic components of each system; they are changeable by the airlines at the airport gate. As each system arrived at the IASL, it was first tested for proper operation and validation of LRU-level requirements in the standalone labs. These labs permitted simulations with other components and/or airplane dynamics. Some of the standalones interfaced with other system standalone labs on a limited basis. Most of the integrated system-level integration testing, however, was conducted at the FCTR, the SIL, and CAB2.

Systems Integration Laboratory. The SIL was built to provide a tool for airplane-level validation. The SIL facility integrated many of the 777 systems, such as airplane avionics LRUs, the complete electrical system, the complete cockpit, and many subsystem LRUs. The lab was configured to spatially represent a real airplane, with "production" wire bundles and airplane structure that might affect the electronic signals passing through the miles of wire. All components involved in the flight control and cockpit management systems were kept to the latest design and build levels. Simulation provided airplane/environment inputs. Data from the wind tunnel, system standalone testing, and some previous testbed flying tests were used in the simulation generation.

Testing was conducted using flight test pilots, who performed the test as an actual flight. Each test involved starting the "airplane" from "cold start" and proceeding to final landing. Each flight recorded measurements from all systems, giving the engineers volumes of data to investigate system operation and interaction. Test problems were recorded for each flight, entered into a tracking system, and processed as a "real" airplane flight discrepancy report. The test results were rigorously documented in test session summaries and formal documents. Test session summaries were available immediately on line over the Boeing network.

Because the SIL closely approximates a real airplane, it was also used to validate the airplane/system functional tests that were subsequently used on the production line during the build process of the 777. These tests provide a formal feedback on the design-build process as the airplane proceeds down final assembly. The first several airplanes down the line are extensively evaluated, but as the build learning curve improves and small design problems are discovered and corrected, these tests gradually diminish in size.

A total of 3,782 hours of testing were conducted and test results analyzed before first flight of the first airplane. As the flight test program progressed, all changes and many of the discovered problems were tested and solutions validated in the SIL before their application on the test airplanes. This added approximately 2,000 more test hours. The effectiveness of this lab was verified during the flight test program. Monthly flight rates of the 777 test airplanes exceeded those of all previous programs, yet the number of new problems found on the airplane was low.

Flight Controls Test Rig. This lab tests all flight control components, including LRUs, actuators, control surfaces, the complete hydraulic system, the flight control DC power system, and other airplane system LRUs critical to the flight control functions. The testing investigated control operations, feedback inputs, and some aspects of system fatigue testing. Simulation was used to input loads and some of the system inputs to generate responses from the flight control computers. Approximately 6,500 hours of testing was performed to ensure that all possible normal and emergency conditions were explored. This testing allowed a very complicated system to operate as designed during flight test, with adjustments necessary only for the constants and not for major control laws or operating code.

CAB2. CAB2 is a full cockpit engineering simulator. It was used for pilot evaluation of 777 handling qualities and system operation. It included a visual system and all LRUs critical to pilot operations. Full simulation of the airplane characteristics were developed from data from the wind tunnel, engineering analysis, and testbed flight test results. Handling qualities, crew procedure, and pilot-system interactions were evaluated, including performance of the airplane and systems in severe windshears and flight control failures deemed not practical or too hazardous to be accomplished on the flight test airplanes. Examples of failures included flight deck control jams and disconnects. CAB2 provided many hours of practice and training for the maneuvers required for the test airplanes. As flight testing proceeded, actual airplane data were used to update the simulators.

Auxiliary Power Unit 3,000-Cycle Test

The auxiliary power unit (APU), which is used as an air and electrical source in flight, was tested on the ground to ensure its readiness and reliability. This testing was in addition to that normally conducted by the vendor, AlliedSignal. The APU was subjected to many of the environmental and operational conditions encountered in airline service. Approximately 10,000 test hours were conducted by AlliedSignal, of which 2,100 hours were used specifically to evaluate service readiness as part of the Boeing ETOPS plan.

Engine 3,000-Cycle Test

Because engines are a key part of ETOPS certification, the engines underwent an intense ground test validation program beyond that required for basic design validation and certification. Individual engine operations that reflect inservice ETOPS situations are defined as "cycles." Through mutual agreement with U.S. Federal Aviation Administration (FAA) and the European Joint Aviation Authorities (JAA), 3,000 such cycles were chosen to quantify the ETOPS requirement. Pratt & Whitney (P&W) conducted the cycles on a "production configuration" engine before Boeing started its ETOPS testing. Once the cycles started, the FAA required no changes to the engines.

Static Loads and Structural Fatigue Test

The 777 full-scale static and fatigue airplane test programs were the culmination of hours of structures testing, ranging from small structural elements material characterization tests, to subcomponent tests (e.g., wing upper surface cover panel), to full-scale components (e.g., a 20-foot section of the fuselage). These tests were all run to validate analysis methods and design allowables and to provide the final proof of the capabilities of the airplane structure.

The airplane static load test was conducted to satisfy the FAA/JAA certification requirement that the manufacturer must demonstrate the airplane structure is capable of carrying design limit load (the highest possible loading under extreme flight or ground conditions that the airframe experiences in its lifetime) without causing detrimental permanent deformation of structure. Beyond the certification requirement, Boeing tested to wing destruction to determine the amount of growth available in the 777 wing. This test structure was the second airplane down the 777 assembly line—a structurally complete airplane. The test vehicle had 4,300 strain gages installed, which were connected to a data acquisition system where approximately 1,500 channels of data were recorded and monitored. The entire structure was placed in a system of towers and reaction fixtures. The airplance was subjected to more than 20 major sets of load applications.

Another structurally complete airframe—the structural fatigue test vehicle—is currently being exposed to typical operating loads experienced by the 777. The loads applied to this structure describe the spectrum the airplane will experience daily in a cyclic manner throughout its lifetime. Boeing is testing this structure to the number of flights equal to two lifetimes of the airframe (more than 20 years of service). A typical flight profile is applied approximately every 4 minutes, 24 hours per day. The fuselage is pressurized to operating cabin altitude and back to sea level for every cycle, to stress the fuselage pressure vessel to various airline scenarios. Approximately 1,000 strain gages monitor this testing. The testing started in January 1995 and is expected to be at two lifetimes by September 1996.

Flight Test

The flight test program really began in the factory. As the 777 came together, components and systems were tested incrementally on the first airplane. These tests were engineering tests beyond the scope of the factory functional tests. After rollout from the factory, another set of intensive tests was conducted on the preflight line. These tests were designed as the final integration tests to validate the standalone, systems, and integration tests that had been performed in the laboratory environment. When all systems were ready, the airplane was approved for its first flight. On June 12, 1994, the 777 took to the air for the first time; it flew the most successful first flight in Boeing history. The flight lasted 3 hours and 48 minutes. All systems were exercised. Major highlights included (1) each engine was shut down and then restarted, (2) the normal flight control system was shut down and the airplane was flown on its backup system, and (3) gear and flap systems cycled through normal and backup modes. The only anomaly on this flight was a vibration of the nose gear door. The cavity was not properly vented; a small change was made and the vibration was corrected by the third test flight.

With this auspicious beginning, the 777 began the most extensive test program ever conducted on a Boeing commercial airplane. Figure 23 presents key features of the 777/P&W flight test program. Five airplanes were full-time members of the flight test program. The figure shows the major tests performed by each airplane in the fleet. Figure 24 presents the test hours, flowtimes, and instrumentation channels used by the airplanes.

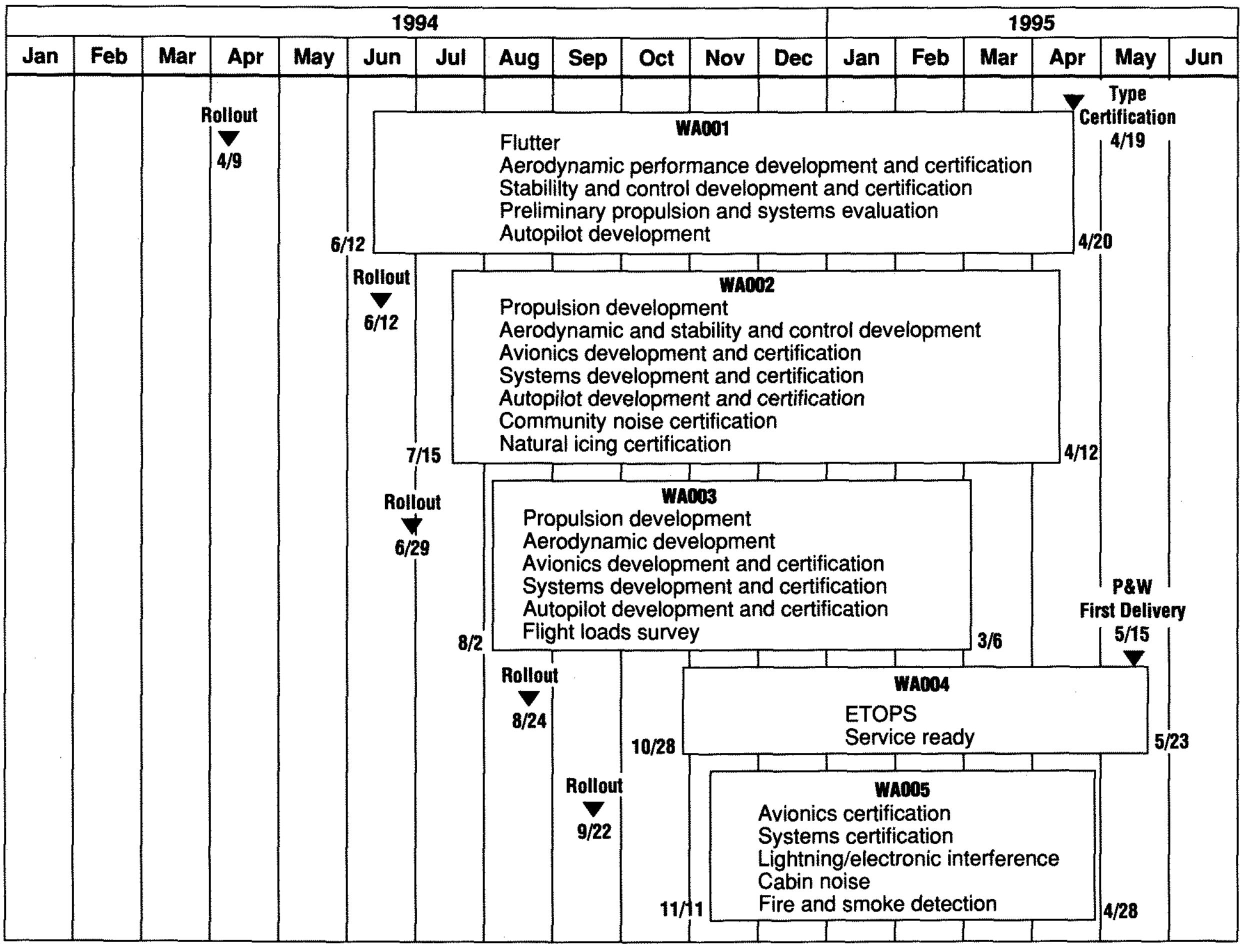


FIGURE 23 - Key Features of P&W 777-200 Flight Test Program

| | 777 Basic | 777 ETOPS | 777 P&W Total |
|---|---|---|---|
| Test airplane | 4 | 1 | 5 |
| Program duration (months) | 10.5 | 5.4 | 11.1 |
| Number of flights | 852 | 1,001 | 1,853 |
| Dedicated flight test hours | 2,283 | 1,116 | 3,399 |
| - Concurrent flight test hours | 11,271 | 49 | 11,320 |
| Dedicated ground test hours | 4,046 | 330 | 4,376 |
| Instrumentation channels | | | |
| - Analog | 6,959 | 39 | 6,998 |
| - Digital | 172,133 | 1,032 | 173,165 |

FIGURE 24 - 777-200 P&W Test Program

Early test flights were used to determine the airworthiness of the airplane and its new flight control system and then to expand the flight envelope by testing structural dynamic damping over the altitude/speed range of the airplane. We tested all systems on the airplane concurrently on the early flight tests. These concurrent tests were either "flight following" tests of the primary test or tests run between primary tests as data were evaluated or condition changes were made. Every effort was made to use every minute of flight time. To meet the early start date for ETOPS, each system had to be evaluated to ensure that testing would not have to start over if a system change was required.

The next challenge was to evaluate low-speed performance and handling characteristics of the 777. This testing explored stall speeds (minimum flight speeds), takeoff speeds (normal and abuse), landing speeds, and all the stability and control and handling characteristics in these speed ranges. These tests provided the basic data for all low-speed-flight manual information. The testing was followed by a detailed look at the high-speed envelope. At this time the number 2 airplane entered the test program and was subjected to engine/airplane performance, operation, and interface testing. Development also began on the autoflight systems (autopilot, flight management, GPS, etc.). Again, concurrent testing on every flight examined systems and service-ready issues.

With testing in progress on airplanes 1 and 2, airplane 3 joined the fleet. The primary task of this airplane was an inflight load survey. Strain gages on the structure and pressure ports on the wings gathered both structural response data and aerodynamic pressure data during maneuvers performed to the flight limits of the 777. This information, along with that from the fatigue and static load airframes, fully validated the 777 structural design. A month-long ground calibration and pressure port installation prepared the airplane for these rigorous flight profiles. To improve the chance of sunny weather with no moisture, the airplane and its test crew went to Hawaii. The subsequent inflight loads and pressure survey was completed in 2 weeks. The testing required 29 flight hours to evaluate 275 inflight conditions.

Meanwhile, airplanes 1 and 2 were evaluating the remaining items necessary to ensure the start of the ETOPS evaluation flights. On October 28, 1994, airplane 4 entered the test fleet for ETOPS cycle testing.

Airplanes 1 and 2 transitioned into certification flying to satisfy the FAA and JAA airworthiness regulations. This testing was accomplished primarily with FAA participation; the JAA participated to cover the few regulation differences between the two agencies. Before this certification flying was conducted, the details of what had to be done to satisfy the regulations were submitted and approved by the FAA. This process was important because it defined the specific test requirements to meet the written regulations of U.S. Federal Aviation Administration and European Joint Aviation Authorities so a complete test plan could be developed.

An improved method of identifying and tracking problems found during the validation process was updated for the 777. In the past this process lacked a central, singular collection of problems. The new process allowed everyone involved to identify a problem, track its resolution, and then test the resulting solution. This was a complete closed-loop system; it mandated that something be done to resolve the problem. It proved to be a valuable tool for quantifying the completeness of the configuration tested and for validating with the FAA/JAA that problems were fixed and rechecked. It allowed testing to take place once, when the airplane was ready. It prevented last-minute surprises resulting from some forgotten problem being unanswered. Its success was a tribute to the openness of the "working together" culture of the program.

The fifth airplane in the test program brought a full-up cabin system to complete our service-ready evaluation of the airplane. Because the software was late and inadequate, most of the test time for this airplane was spent developing the system. A degraded system with all certification items was available at certification. Full passenger entertainment capabilities were not completed.

The test airplanes were instrumented to measure 171,789 parameters, of which 6,915 were special transducer-based flight test measurements. The other 164,874 were digital measurements recorded from the airplane data buses. As the airplane performed under various test conditions, engineers were able to monitor how each system was reacting, including the information it was sharing with other systems. This insight into the interaction of airplane systems let us identify most of those small problems that in the past would have become evident only after the airplane was in service. To record, monitor, and reduce all the data, the flight test data system was updated from its 747-400 configuration. The update addressed primarily ARINC 629 data bus acquisition and monitoring, instrumentation/airplane system isolation, and the ability to handle increased measurement quantity. Figure 25 shows a top-level view of the system.

The flawless operation of the data system throughout the test program was a major contributor to the test flowtimes and flight rates achieved by the program. The data system produced more than 5 billion bytes of data. Turnaround time was less than 8 hours. An important feature of the system is its ability to monitor all test measurements on board the aircraft. Many "engineering" programs were available on board to process data into final engineering data format and quality. This capability allowed flexibility in test conduct and sequencing. The entire system could be conditioned, preflighted, and used to record, monitor, and report in a very short cycle time. Engineers maintained a ground-based interactive database of all test requirements that could easily be called upon to condition the onboard system to meet the scheduled day requirements and then provide the interface to extract the recorded data.

The ETOPS Program

ETOPS at first delivery was a new experience at Boeing. It required development of a plan to ensure that the systems and integrated airplane were ready to perform the overwater mission reliably. Working with the FAA, we developed a program of 1,000 specific cycles (startup, takeoff, fly, land, shutdown, maintain).

ETOPS validation testing required us to act like an airline, to operate with a daily routine. Flight and maintenance processes historically used during flight test were designed to keep an airplane on its test mission, not to be an airline. The concept of working together gave us the opportunity to learn from one of our customers. United Airlines allowed us to observe and learn how they operate and maintain airplanes. On this framework we built a process of operations similar to those of an airline. The airplane was used around the clock, every day, and testing was structured to provide one or

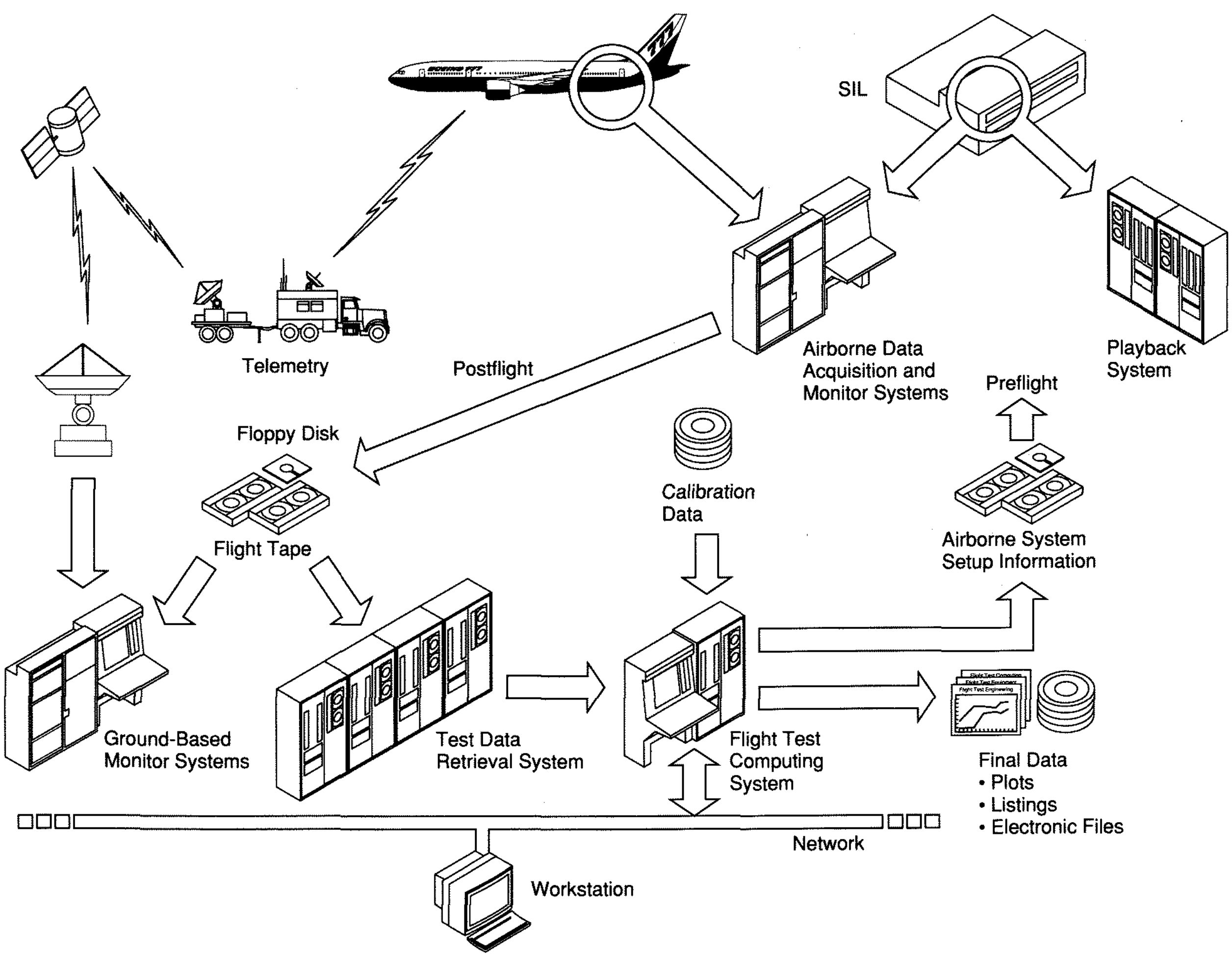


FIGURE 25 - Flight Test Data System

more blocks of flight time as well as time to complete the maintenance cycles determined critical to ETOPS operations (Figure 26). The airplane, its crew, and its systems were exposed to a variety of weather conditions, temperatures, and operational scenarios. The test airplane flew 1,116 hours, completing 1,000 cycles and performing approximately 52 ETOPS-specific missions.

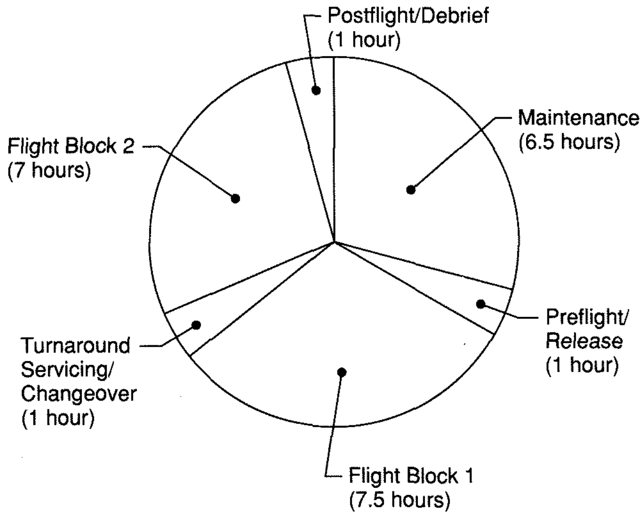


FIGURE 26 - Typical ETOPS Day

## Follow-On Engine Certifications

Certification of the 777 with P&W engines was followed by test programs for the General Electric and Rolls-Royce engines. Because the majority of the airplane and systems validation was done on the five P&W-powered airplanes, only a subset of testing was needed for the follow-on engine programs. This testing involved evaluation of the differences between the certified P&W engine and the General Electric and Rolls-Royce engines as well as the effects of the new engine installations on the airplane/systems handling and performance. Requirements from two new airline customers were also added to the follow-on test program. Two airplanes were used for these tests (Figure 27), one for the FAA/JAA 777 model testing and the other to complete the ETOPS requirements.

## Summary

The testing of the 777 was the most extensive conducted on any Boeing commercial airplane. The program strategy of working together, getting it right the first time, service readiness, incorporation of new design processes, and improved build processes led to systems and an airplane that were ready for

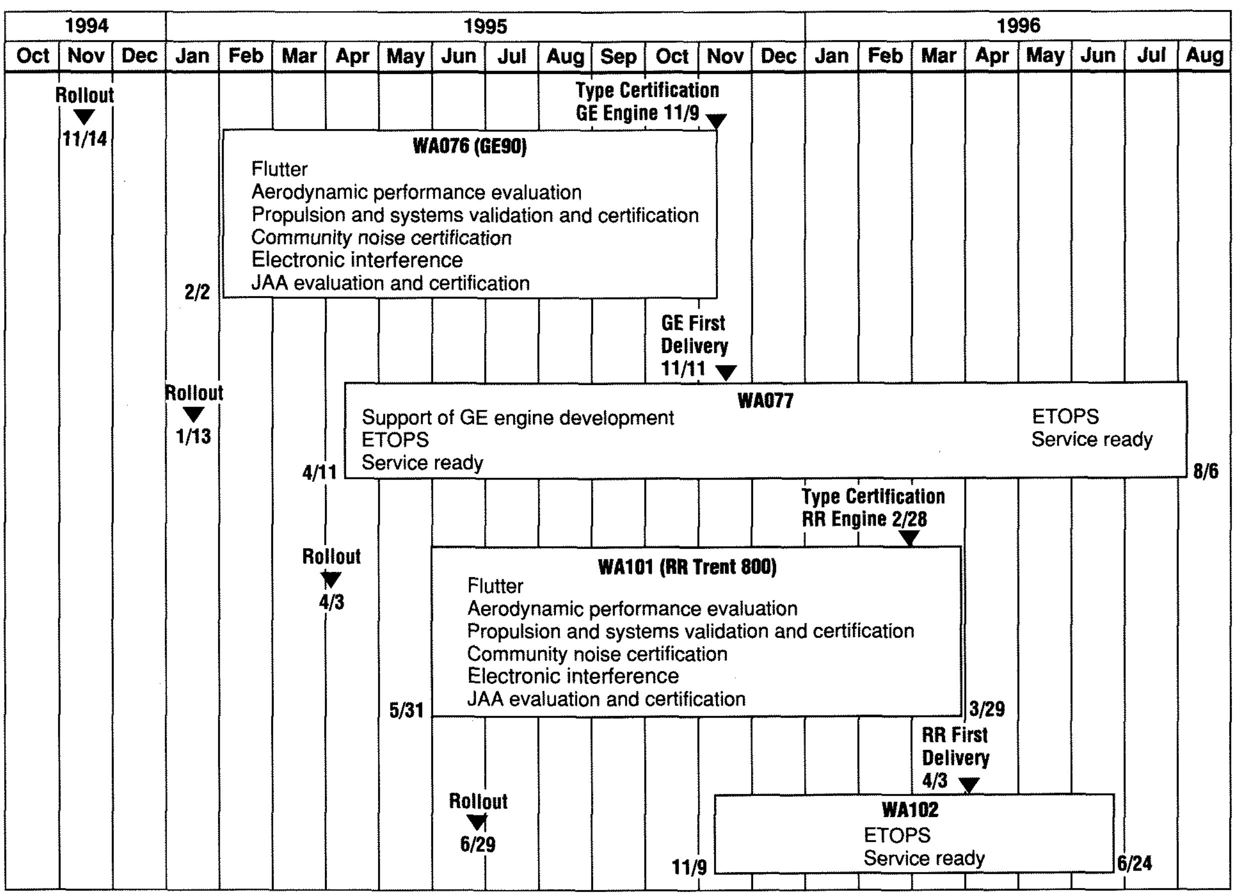


FIGURE 27 - Key Features of General Electric and Rolls-Royce 777-200 Flight Test Programs

test—an airplane that was ready to be evaluated from the customer's perspective from the start. This is not to say that there were no problems, but the ones that did arise were quickly identified, and the disciplined process of design-build allowed easy access to the root causes. Testers, designers, regulators, builders, and customers working together made the journey participative rather than confrontational. This program has set in place a culture that can be applied to future airplane development. The 777's successful introduction and use in service is a tribute to all the new processes and innovations used to make this airplane.


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