

RE-INVENTING THE LEGEND: THE DEVELOPMENT OF THE 747-8

Chris Collisson
The Boeing Company

Keywords: Boeing 747, jet transports

Abstract

This paper will cover how the 747-8 family of airplanes was developed in the conceptual and preliminary design phases.

Topics will include the following: the commercial airplane market the 747-8 was designed to address, the enablers and technology applied to the airplane, how the schedule and timing for the program was decided, the major design decisions made and what lies ahead as the 747 legacy continues into the future.

Particular emphasis will be given to the technical decision making that took place as the airplane design was developed and how creating a major derivative airplane is influenced by the design of the parent airplane.

1 Market

Boeing had been working on the successor to the 747-400 since the early 1990s. Various airplane programs had been started but never completed (747-500/600, 747X, 747XQLR).

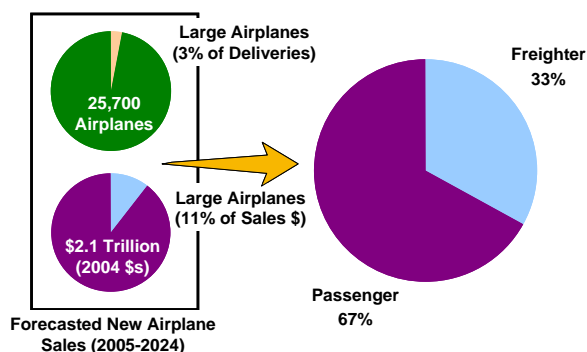


Fig. 1. The Large Airplane Market in 2005

One of the reasons these projects did not succeed was the large airplane market shown in

Figure 1. As the worldwide commercial airplane market fragments, the large airplane market has continued to shrink, currently sized at around 900 units.

This market size limits the amount of money that can be spent on developing an airplane if the program is to be profitable.

By early 2004, other market factors were at work to spur on the development of a new 747 derivative. The replacement market for the 747-400 was now around 5 years away, as the oldest of those airplanes reached 20 years of age. In addition, the market was no longer interested in purchasing 747-400s without some improvements, particularly in noise and economics. Not only was the future of the 747 line in jeopardy, but without a major 747 derivative the A380 appeared to be poised as the 747-400 replacement.

2 Enablers / Technology

With the market clearly dictating desire for an improved 747 but with certain non-recurring cost limits, the challenge became delivering a significantly improved product at a reasonable cost.

Thanks to the launch of the 787, one enabler necessary for the 747-8 was in place – a new and improved engine (see Figure 2).



Fig. 2. The GEnX Engine

This would improve both community noise and operating cost, but would not be enough to launch a new 747 derivative. Due to the size and weight of the new engine, its installation alone on the existing 747-400 airframe would not meet the market requirements for range, noise and operating economics. The search was on for other enablers.

Past wind tunnel work showed that the aerodynamics of the 747 could be significantly improved given the more than 30 years of improvements since the wing was originally designed (see Figure 3). The airframe materials could be improved as well as they had not been updated since the 747-400. The market, however, could not finance a complete overhaul of the airframe as had been shown by past 747 program cancellations. How much of a change it could support would need to be figured out quickly as the pressure of schedule was building.

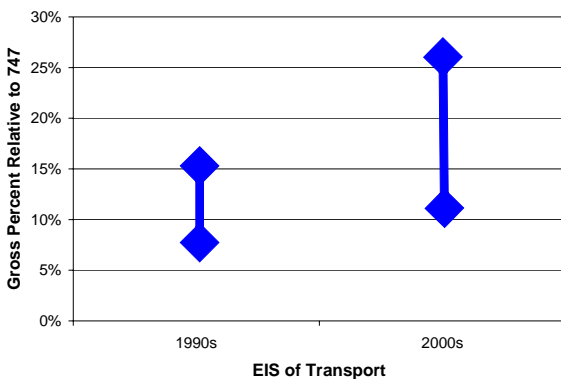


Fig. 3. Aerodynamic Improvement Potential

3 Schedule

In early 2005, with sales of the 747-400 slowing and the end of 747 production in sight, the pressure to make a decision about a future 747 derivative was mounting. In addition, the 787 program was well underway, making it difficult to find time in the wind tunnel to see if the right balance of performance and cost could be reached. The key was determining if a design cliff could be avoided (see Figure 4).

Computational Fluid Dynamics [CFD] and structural analysis of wing improvements

showed that the cliff could be avoided, and 747-8 design work continued.

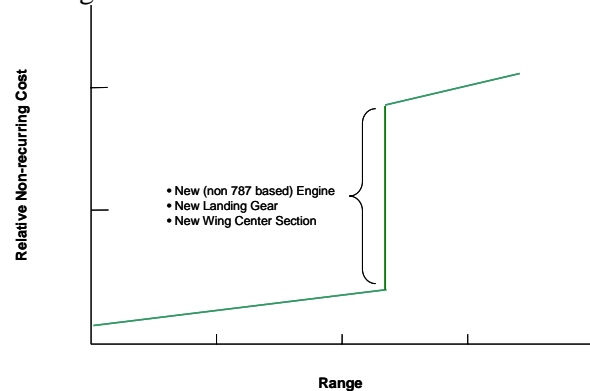


Fig. 4. Cost Growth 'Cliff' Chart

The market forecast for 747-400 sales and customer need for freighters were the drivers of the program schedule. Entry Into Service [EIS] for the first 747-8 was set at September 2009 in early 2005, with very little wind tunnel testing even complete (see Figure 5).

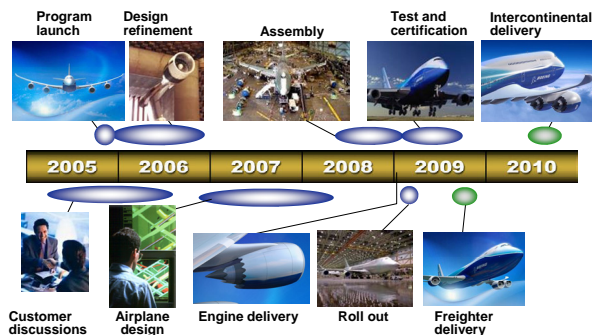


Fig. 5. 747-8 Program Schedule

By November of 2005, enough market support had been garnered to launch the airplane program. Cargolux and Nippon Cargo [NCA] were the launch customers, at the time ordering a total of 18 747-8F airplanes.

4 More With Less

With the 787 program in full swing and the limited market forecast for large airplanes, the team working on the 747-8 was very small. A year from launch just a handful of people were on the team; at program launch the size of the team had only grown to the low hundreds. See

Figure 6 for a comparison with other recent programs.

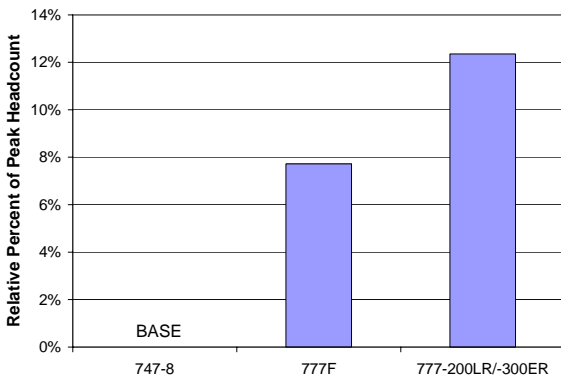


Fig. 6. Headcount at Launch Comparison

This created a much more nimble environment than is often seen during the development of a derivative airplane. The flow of information amongst the small team was much better than typical, allowing for design changes to evolve much faster than before. In turn, this allowed the team to reach conclusions on whether new features would work for the airplane much sooner.

In particular, this was seen in the design of the wing, where the design evolved from a minimal improvement in Lift to Drag Ratio [L/D] to a major improvement in L/D in less than 6 months.

Many of the weight improvements to the airplane also came about in short order. One particular afternoon in the spring of 2005, most of the airplane weight improvements were mapped out on the wall by a group of around 20 people. These ideas combined with the wing and engine are what ultimately made up the bulk of the 747-8 design which in turn met the market needs for improved payload, range and economics.

4 Airplane Overview

Major changes to the 747-400 to create the 747-8 are as follows:

- New GENX -2B engines
- Relofted wing including a raked wingtip
- Double slotted inboard and single slotted outboard flaps

- New Main Landing Gear [MLG] wheels, tires, brakes and trucks
- Maximum Takeoff Weight [MTOW], Maximum Landing Weight [MLW] and Maximum Zero Fuel Weight [MZFW] increases
- Body stretch of 220 inches (160 inches forward, 60 inches aft)
 - +51 passengers, +2 lower lobe pallets and +2 LD1s
 - +4 main deck pallets and +3 lower lobe pallets
- New Environmental Control System [ECS] packs
- Additional flight deck functionality
- Additional hydraulic power
- Fly by wire [FBW] spoilers and outboard aileron
- Double hinged lower rudder
- New door 2 entry, Sky Loft provisions and New (787 style) Interior

These changes are illustrated in Figures 7 and 8.

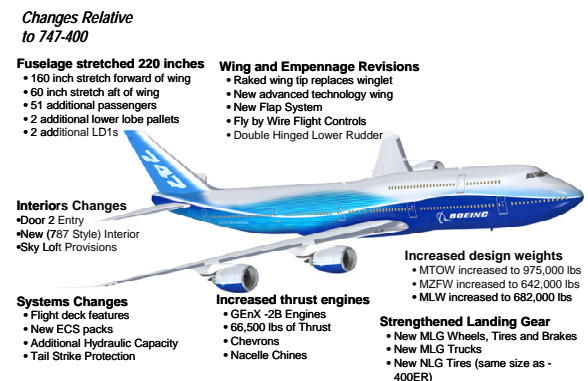


Fig. 7. Passenger Walkaround Chart

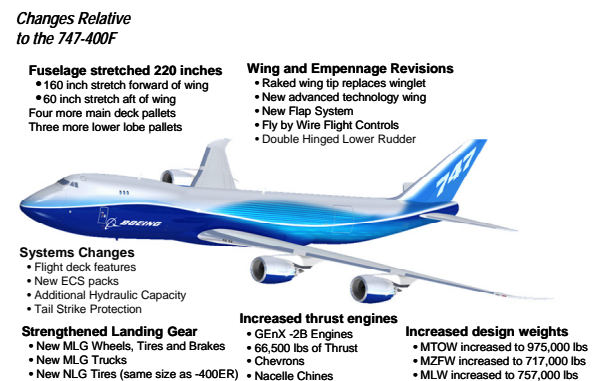


Fig. 8. Freighter Walkaround Chart

5 Major Design Decisions

The evolution of the design started out with two key decisions – on the engine size and payload / range capability of the airplane.

For the freighter version, the payload / range decision was fairly easy. The freight market is based around the 747-400F range, and since stops and connections are not market discriminators, the range was kept equivalent to the 747-400F and the improvements focused on increasing payload while improving operating cost (see Figure 9).

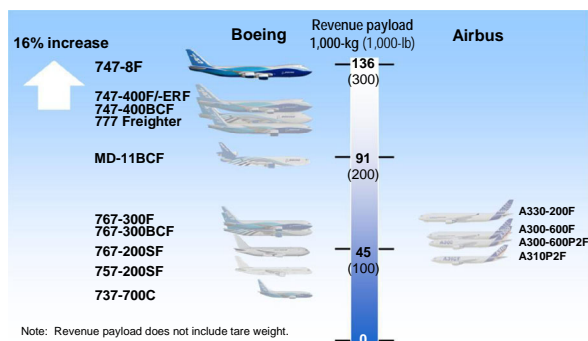


Fig. 9. 747-8F Payload Comparison

For the passenger version, the decision was more complex. Improvements in range, payload and operating cost were all needed. Airlines in Asia wanted to be able to fly from Asia to the US east coast non-stop. Airlines in Europe wanted more capacity because additional range above the capability of the 747-400 did not open up any new routes for them.

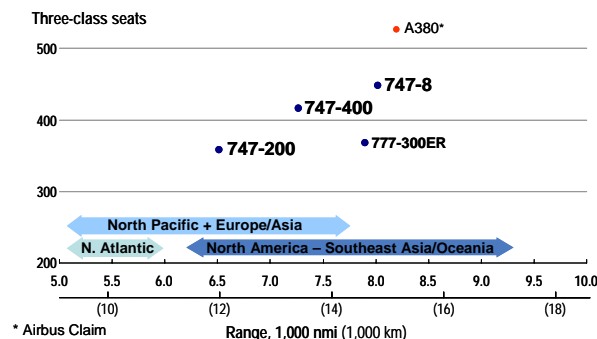


Fig. 10. 747-8 Payload Range

As is commonplace in airplane design, the final decision was a compromise. A range target of

8,000 NM was set, which opens up new routes from Asia to North America, but not as many as some operators would desire. Capacity then grew by 51 seats, the greatest amount that the range target would allow. This places the 747-8 approximately halfway between the A380 and the 777-300ER in payload, nicely filling a niche in the marketplace (see Figure 10).

For the engines, the early design work centered on reducing engine size. The 787 fan diameter of 111 inches was too large for the 747 in many ways – too much thrust, not enough ground clearance and too much drag in flight. For the 747-8, the size of the fan was reduced to 105 inches, but commonality with the 787 engine core was maintained to keep development costs and risk down to a minimum.

While the reduction in engine diameter was beneficial overall, it did increase noise. To address that, two other items on the engine installation were changed to meet the program goals for community noise. Chevrons were added to the fan case and the engine exhaust nozzle (see Figure 11). The size and shape of these were optimized for the 747-8 through extensive wind tunnel testing. In addition, a new inlet design developed during the 2nd quiet technology demonstrator program [QTD2] was added.

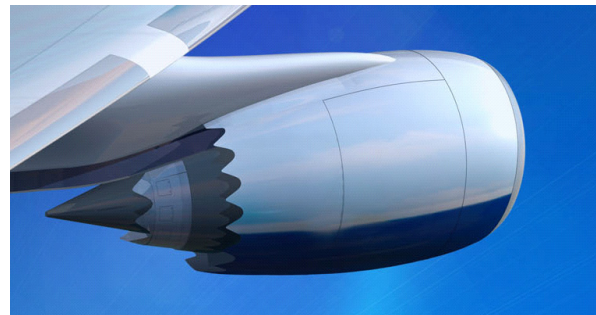


Fig. 11. Chevrons

The new engine installation also included nacelle chines (not pictured) for low speed performance, which helped enable the flap configuration changes discussed below.

Engine bleed air capability was retained for the 747-8 so that the systems architecture from the 747-400 could be retained. GE had already designed the core with bleed in mind even though the 787 wouldn't use it.

With the engine fan sized for the 747-8 airplane and an engine package more or less in place, the work to integrate the new engine installation began. It was clear that a significant amount of L/D (lift/drag) improvement would be required to make the payload range goals of the program, given the additional drag of the new engines. However, to keep the airplane workstatement in line with a derivative program, it was important to minimize change to the wing, particularly to the center section and to the landing gear. In addition, from an analysis point of view it was desirable not to change the structural arrangement of the wingbox.

Initial work focused on the wingtip and loft changes to the outboard wing. It quickly became clear that much of the L/D improvement gained by changing the outboard wing would either be offset by wing washout at the tips or by weight inboard (stiffness required to prevent washout). See Figure 12.

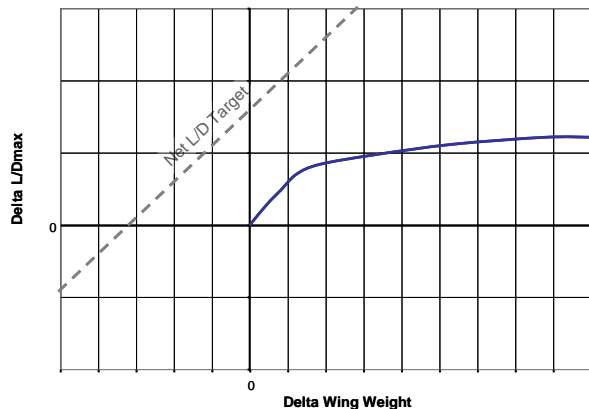


Fig. 12. Weight vs. Outboard Wing Efficiency

Wing stiffness aside, the airfoil changes outboard were resulting in much better L/D. So to help with the stiffness issue a reloft of the wing from the side of body outboard was the next logical idea for study. This had the advantage of adding lift inboard where less weight would be required to carry it and allowed thicker airfoils to be used to help structural efficiency. The thicker airfoils also had no aerodynamic penalty as advances in aerodynamics since the 1960s offset the additional thickness. With the new airfoils, the structural arrangement of the wing stayed the

same and at the side of body the new loft was smoothed into the old loft shape, thus protecting the center section geometry, the landing gear and the fuselage interface. Another benefit of the thicker airfoils was addressing the fuel volume limit of the 747-400 wing. The 747-8 would now be off of the fuel volume limit, thus opening up the design space. See Figure 13 for an illustration of wing thickness and planform.

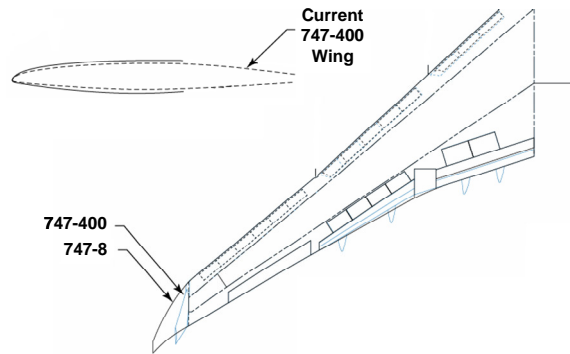


Fig. 13. Wing Comparison

The trailing edge had already been improved prior to the wing loft change. The triple-triple (inboard-outboard) slotted flap arrangement on the 747-400 had been replaced with a double-double (inboard-outboard) slotted flap arrangement to reduce community noise.

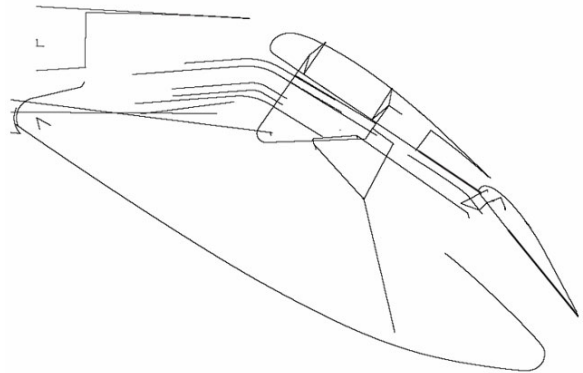


Fig. 14. Inboard Flap Configuration

Early wind tunnel testing showed that a single outboard, double inboard flap arrangement could be used (see Figures 14 and 15) and approach speed targets could still be met, with a catch – a change to the inboard leading edge was required.

In order to go to a single slotted outboard flap without impacting low speed performance, the inboard leading edge was gapped rather than sealed as it is on the 747-400 (see Figure 16).

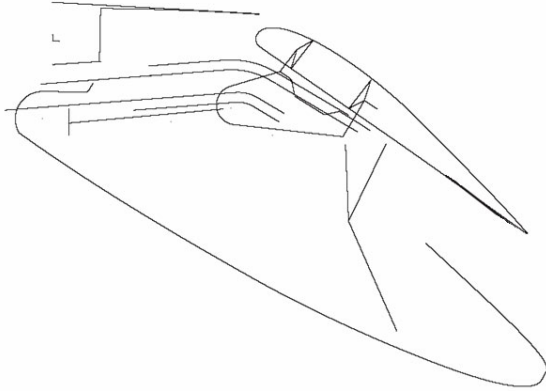


Fig. 15. Outboard Flap Configuration

Adding the gap showed a significant approach speed benefit. As for the mid and outboard leading edge, the variable camber kreugers [VCKs] from the 747-400 were retained, but were modified for the new engine installations. Aileron droop was also added for additional low speed performance.

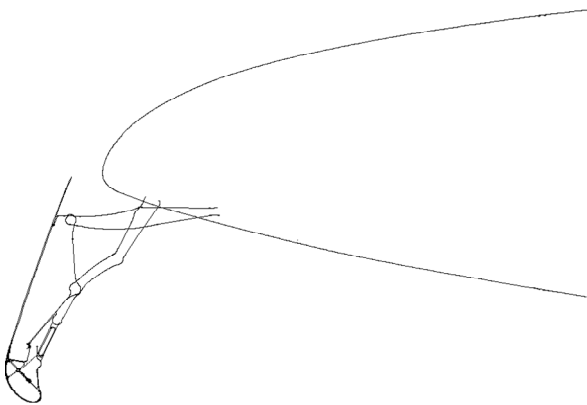


Fig. 16. Gapped Kreuger Flaps

With the new airfoils, stability and control was addressed to give the 747-8 the same or better handling qualities than the 747-400. This resulted in changes to flight control systems.

The outboard aileron was changed to fly by wire [FBW]. This was driven by the desire to optimize aileron droop at any flap setting, something the 747-400 aileron control system could not do. In turn, this maximized the community noise benefit seen on both departure

and approach. The FBW outboard aileron also allows for tuning of low speed roll response resulting in improved handling characteristics.

The spoilers were also changed to fly by wire in what was originally a decision made to reduce weight. Naturally, the decision to tune the spoiler controller to improve airplane response in the lateral axis soon followed. Fly by wire control surfaces also allowed for the addition of maneuver load alleviation [MLA] to the airplane. This capability actuates control surfaces to 'unload' the wing during certain maneuvers, in turn making ultimate wing loads lower and allowing gage to be taken out of the wing. The 747-8 MLA capability uses different control surfaces depending on the flight condition.

Along with the fly by wire controls, an electronic tail strike protection system was added. This works to prevent tail strikes by adding the appropriate elevator movement if an impending tail strike is sensed. Along with the obvious benefit of avoiding damage to the airplane, this also creates a low speed performance improvement by allowing additional rotation during normal takeoff and landing.

Increased rudder power was needed due to the increase in engine thrust. Though the aft body of the airplane was stretched 60 inches, this increase in moment arm was not enough to offset the thrust. An improved version of the double hinged lower rudder from the 747SP was added to get the additional rudder authority needed for engine out scenarios (see Figure 17).

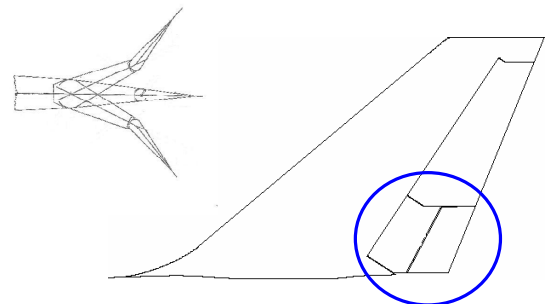


Fig. 17. Double Hinged Lower Rudder

Changes outside of flight controls while integrating the new wing were also made. For instance, the hydraulic power system was

inadequate due to higher loads on the wing. Additional capability was added by using the engine driven pumps and air driven pumps from the 777 on each of the (4) hydraulic systems (see Figure 18). The wing anti ice system was also optimized for where ice forms on the new wing, including the deletion of wing anti ice in front of the outboard most VCK (see Figure 19).

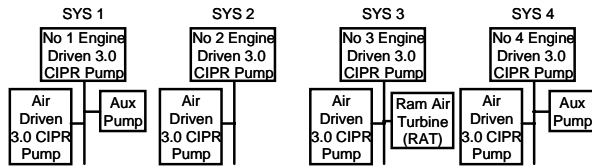


Fig. 18. Hydraulic Power System

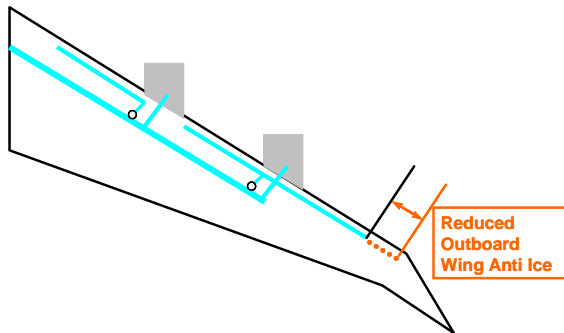


Fig. 19. Wing Anti Ice

Many advanced materials were studied for use in the new 747-8 wing, as well as the body and floor of the airplane. Much of the focus was on using advanced aluminums, including aluminum lithium. 777 and 787 alloys were studied as well.

	747-400	747-8
Wing Skins	7150 and 2324-T39, Type I	7055 and 2324-T39, Type II
Flaps and Supports	Fiberglass Composite and Stainless Steel	Carbon Composite and Custom 465 Steel
Ailerons, Spoilers, Rudders	Fiberglass Composite	Carbon Composite
Fuselage Skins	2024 and 7075 Aluminum	2524 and 7055 Aluminum
Floors	7075	7150

Fig. 20. Materials Comparison

After all of the trades were run, it was concluded that overall the 777 and 787 alloys were as good or better than the more advanced alloys. This is due to two factors – material properties consistency and cost. While the latest alloys offer improvements in certain properties, almost all of the alloys also show a

degradation in other properties. For example, 7056 aluminum shows an improvement in toughness, but its static strength is actually worse than a 777 generation alloy, thereby significantly limiting its applicability. The latest alloys are also much more expensive, making their application detrimental to airplane cost. The major material improvements are outlined in Figure 20.

The flight deck philosophy for the 747-8 was established early on by balancing the need for new capability against the need for operational commonality with the 747-400 fleet. The best functionality from 737, 777 and 787 was brought over to the architecture of the 747-400 flight deck. So while the look and feel of the 747 flight deck is unchanged, the pilots get the latest capabilities:

- Electronic Checklists,
- Vertical Situation Display [VSD] which shows the airplane's vertical path,
- Quiet Climb which minimizes community noise,
- Global Positioning System [GPS] Landing System [GLS] which is the latest in precision instrument approaches,
- Navigation Performance Scales [NPS] which gives the pilot both lateral and vertical guidance along a preset path,
- Integrated Approach Navigation [IAN] which makes all instrument approaches (Non-Directional Beacon [NDB], VHF Omnidirectional Range [VOR], Instrument Landing System [ILS], etc) look and feel the same,
- Airport Moving Map which increases situational awareness on the ground and
- An optional class III Electronic Flight Bag (EFB).



Fig. 21. Side by Side Flight Deck Comparison

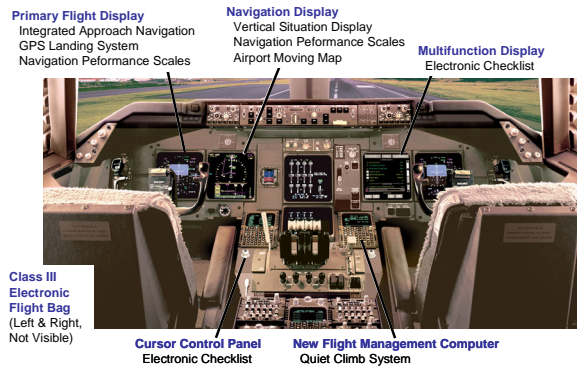


Fig. 22. Flight Deck Capabilities

These capabilities are shown in Figure 22 and a comparison of the two flight decks is shown in Figure 21.

The major advantage to maintaining the flight deck architecture was to keep the same type rating as the 747-400 fleet, as well as common segment currency. Many airlines will be flying a mixed fleet of 747-400s and 747-8s in the years to come, so this approach is best in terms of pilot pools, training and safety as pilots switch between 747-400s and 747-8s.

The development of the interior started slowly, but eventually gained momentum as the popularity of the 787 interior grew.



Fig. 23. Door 2 Entryway

Initial changes to the interior centered around the Door 2 entryway, lighting and the windows. The Door 2 entry was re-architected with a new staircase and surround structure. See Figure 23 for an illustration. The motive behind this change was a desire to communicate to the passenger as soon as they board the airplane it is a new 747, not a 747-400.

The windows were also changed to the 777 elliptical type (see Figure 24). These windows

give the cabin a more open feel, cost less to produce and weigh less. 787 windows were considered, but with an aluminum fuselage their size imposed too much of a weight penalty.

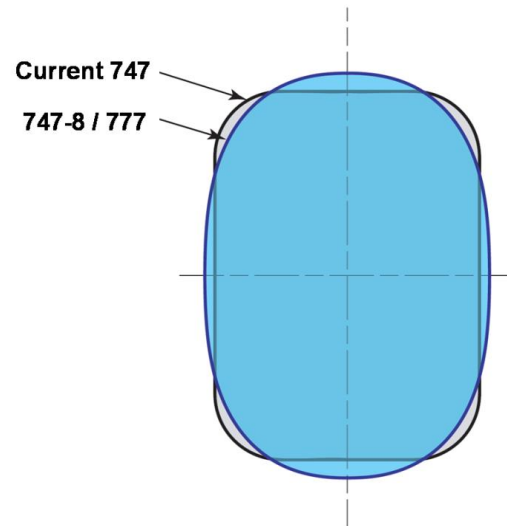


Fig. 24. Elliptical Windows

The cabin lighting system was revised to be an Light Emitting Diode [LED] hybrid (part LED, part florescent) – taking some of the 787 system advantages without revising all of the interior lighting.

These decisions were all in made by mid 2005. During this time, the 787 was continuing its rapid growth in popularity amongst both the airlines and the flying public. It became obvious that the 747-8 interior needed to be more in line with the latest interior from Boeing. Thus, the decision was made to go with a new, more 787 like interior. This included going to new stowbins, ceilings and a full LED lighting system. See Figure 25 and Figure 26 for illustrations of the new interior.

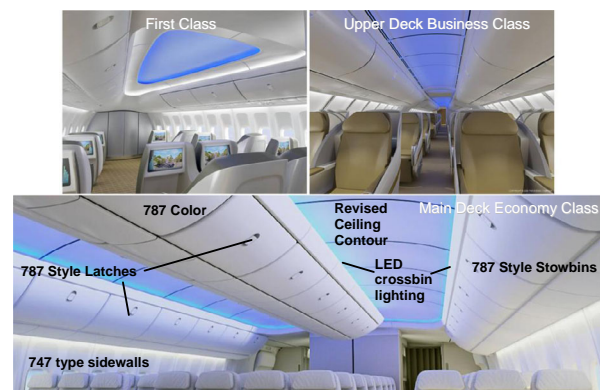


Fig. 25. New "787 Style" Interior



Fig. 26. New Interior – Business Class

The space above the main deck between door 3 and door 5 has long been identified as an area that can be utilized to make the 747 interior better. On the 747-8 this area has been cleared of systems and structurally provisioned for overhead monuments (see Figure 27).

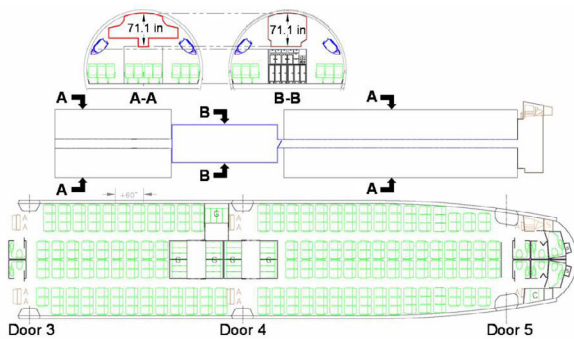


Fig. 27. Sky Loft Provisions

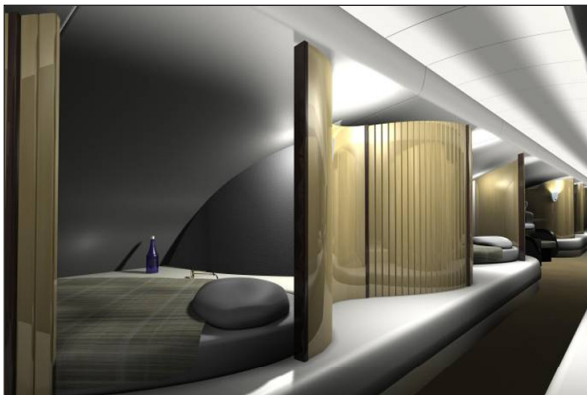


Fig. 28. Sky Loft Suite Concept

Many concepts were considered for the Sky Loft area including suites, lounges and business centers. While none of these generated enough interest to be offered on the production

airplane, the area between door 3 and door 5 was still cleared of systems so that monuments like these could be installed in the future (see Figure 28). This is an important consideration for the Very Important Person [VIP] version of the airplane where a completion center may install accommodations in the crown of the airplane after delivery.

6 What's Next?

With the future of the 747 now in good shape with the 747-8, what lies ahead for the 747 as the market changes and that airplane platform ages?

Given the desire of some Asian airlines for additional range on the 747-8 passenger, any near term improvements will likely be applied to address this. This includes engine improvements currently slated for the 787 that will apply to the 747-8 engine, additional material improvements and continued interiors refinements.

The 747-8 and these improvements are ready to keep the 747 going strong past its 50th birthday. What lies ahead then only time will tell. Will it be the 4th generation of the 747?

7 Acknowledgements

The author would like to thank the following people for their contributions to this paper: Paul Dees, David Loffing, Eric Kaduce, Roy Eggink, Steve Wald and Bob Michael all of whom are from Boeing Commercial Airplanes. In addition, thanks to the thousands of people on the 747-8 team who helped make the airplane a reality.

Copyright Statement

The authors confirm that they, and/or their company or institution, hold copyright on all of the original material included in their paper. They also confirm they have obtained permission, from the copyright holder of any third party material included in their paper, to publish it as part of their paper. The authors grant full permission for the publication and distribution of their paper as part of the ICAS2008 proceedings or as individual off-prints from the proceedings.