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Cover photo: 767 engine and nacelle

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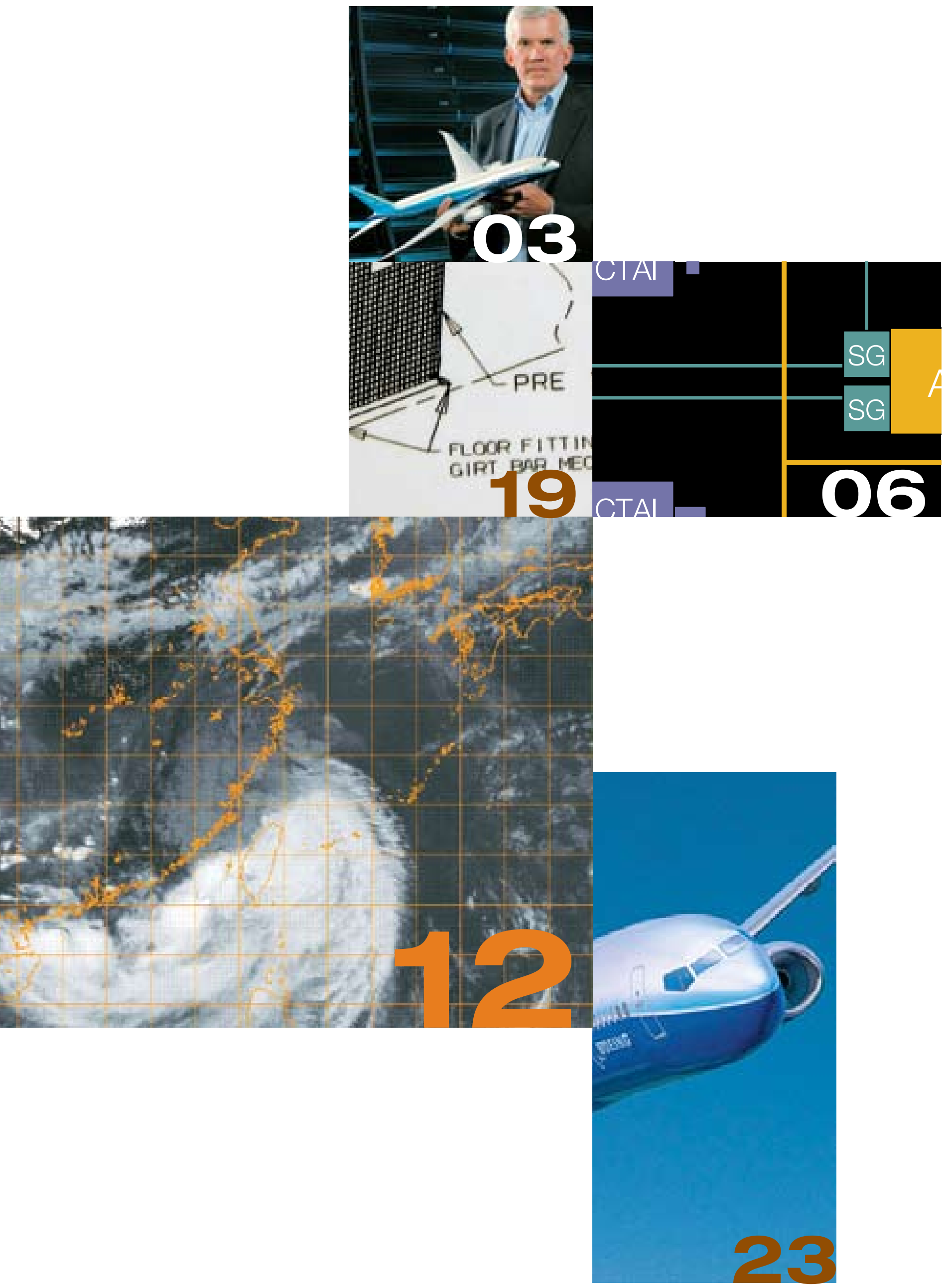

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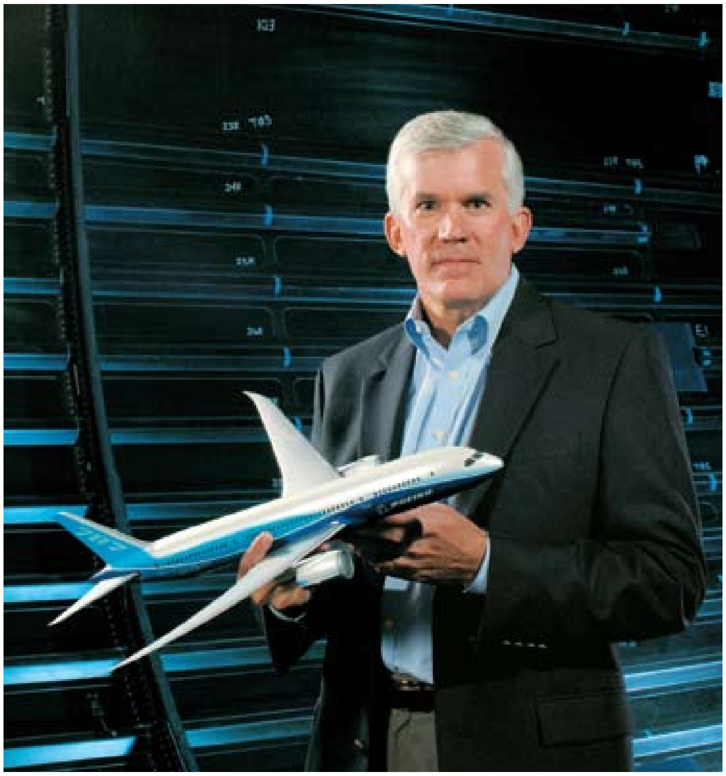
Building the Dream: Boeing 787

Mike Bair inside one of the first 787 composite fuselage test barrels, now on display at the Future of Flight Museum in Mukilteo, Washington.



MIKE BAIR
Vice President and General Manager, 787 Program

These are exciting times in the aviation industry. We're seeing increased use of composite material for airframe structure, one-piece fuselage sections, advanced systems capabilities, and global partnerships – just to name a few achievements. The Boeing Company is leading the way in leveraging these new technologies and business models – for both our airline customers and the passengers who will soon experience the super-efficient 787 Dreamliner.

By focusing hard on the right technologies and working with the best partners, we're delivering an airplane with breakthrough economics for airlines and a passenger experience superior to any airplane flying. The 787 offers a pleasing interior, unmatched fuel efficiency, and a 30 percent reduction in maintenance costs.

Our emphasis on environmental benefits has been very well received by our customers — beyond even our own expectations. Our new business model of getting design input from financiers allowed for early decisions that affect the lifecycle value of the airplane and will keep the 787 Dreamliner a good investment for many years. Designing and building this airplane with the best domestic and international partners has been key to making us competitive in the marketplace. And offering a family of 787 models (see accompanying chart) enables us to be flexible and meet the different needs of the airlines.

In April, our final assembly factory in Everett, Washington, received the first major 787 structures from our partners around the world. The nose and tail sections, wings, and center fuselage section for the first airplane were delivered using our new Dreamlifter, a modified 747-400 passenger airplane that hauls more cargo by volume than any airplane in the world.

Final assembly began in May, and on July 8, 2007, we premiered the first 787 Dreamliner with a wonderful event shared by employees, airlines, partners, and thousands of others around the world. Seeing the airplane at the Premiere for the first time was a reflection of the hard work of so many

people during the past five years. It's not every day we get to bring a new airplane to market and showcase it to the world!

Now our team is very focused on getting the 787 ready for first flight and flight test. We are installing final systems elements, interiors, and flight-test equipment. The flight-test program, which includes a total of six airplanes, will conclude in May 2008 with the certification of the airplane, followed shortly thereafter by the first delivery of a 787 to launch customer All Nippon Airways (ANA).

In addition to the visible work going on in the Everett final assembly factory, a lot of great work is going on behind the scenes to ensure that we meet our 787 commitments and promises to customers. We are working tirelessly to ensure the airplane is service-ready and the airlines are able to take full advantage of the new technology being built into the 787 to reduce operating costs and maximize revenue flights.

At a series of service-ready conferences recently held around the world, customers were given a detailed look at how to use 787 technology to maximize efficiencies within their maintenance, training, and flight operations. We've also issued the first release of the maintenance task cards, recommended spare parts lists, and preliminary flight operations manuals. And we've completed the first maintenance training class, which was attended by Boeing Flight Test mechanics.

As of July 31, 47 customers worldwide have ordered 683 airplanes worth more than $110 billion at current list prices, making the 787 Dreamliner the most successful commercial airplane launch in history. And there's more to come!

MIKE BAIR
Vice President and General Manager, 787 Program

THE 787 FAMILY
Flexibility to meet different airline needs

Description
Seating
Range
Configuration
Cross Section
Wing Span
Length
Height
Cruise Speed
Maximum Takeoff Weight
Total Cargo Volume
Entry into Service

Boeing 787-8 Dreamliner	Boeing 787-3 Dreamliner	Boeing 787-9 Dreamliner
Super-efficient airplane with new passenger-pleasing features. Brings the economics of large jet transports to the middle of the market, using 20 percent less fuel than any other airplane of its size.	Features a wing and structure optimized for shorter-range flights.	A slightly bigger version of the 787-8.
210–250 passengers	290–330 passengers	250–290 passengers
7,650 to 8,200 nautical miles (14,200 to 15,200 kilometers)	2,500 to 3,050 nautical miles (4,650 to 5,650 kilometers)	8,000 to 8,500 nautical miles (14,800 to 15,750 kilometers)
Twin aisle	Twin aisle	Twin aisle
226 inches (574 centimeters)	226 inches (574 centimeters)	226 inches (574 centimeters)
197 feet (60 meters)	170 feet (52 meters)	203 feet (62 meters)
186 feet (57 meters)	186 feet (57 meters)	206 feet (63 meters)
56 feet (17 meters)	56 feet (17 meters)	56 feet (17 meters)
Mach 0.85	Mach 0.85	Mach 0.85
484,000 pounds (219,540 kilograms)	364,000 pounds (165,100 kilograms)	540,000 pounds (244,940 kilograms)
4,400 cubic feet (1,341 cubic meters)	4,400 cubic feet (1,341 cubic meters)	5,400 cubic feet (1,646 cubic meters)
2008	2010	Late 2010

787 No-Bleed Systems: Saving Fuel and Enhancing Operational Efficiencies

by Mike Sinnett,
Director, 787 Systems

The Boeing 787 Dreamliner features a unique systems architecture that offers numerous advantages to operators. The new airplane's use of electrical systems reduces fuel usage and increases operational efficiency.

The primary differentiating factor in the systems architecture of the 787 is its emphasis on electrical systems, which replace most of the pneumatic systems found on traditional commercial airplanes.

One of the advantages of the no-bleed electrical systems architecture is the greater efficiency gained in terms of reduced fuel burn — the 787 systems architecture accounts for predicted fuel savings of about 3 percent. The 787 also offers operators operational efficiencies due to the advantages of electrical systems compared to pneumatic systems in terms of weight and reduced lifecycle costs.

This article explores the 787's no-bleed systems architecture and explains how the airplane's efficiencies are realized.

REASONS BEHIND THE MOVE TO A MORE ELECTRIC AIRPLANE

Recent advances in technology have allowed Boeing to incorporate a new no-bleed systems architecture in the 787 that eliminates the traditional pneumatic system and bleed manifold and converts the power source of most functions formerly powered by bleed air to electric power (for example, the air-conditioning packs and wing anti-ice systems). The no-bleed systems architecture offers operators a number of benefits, including:

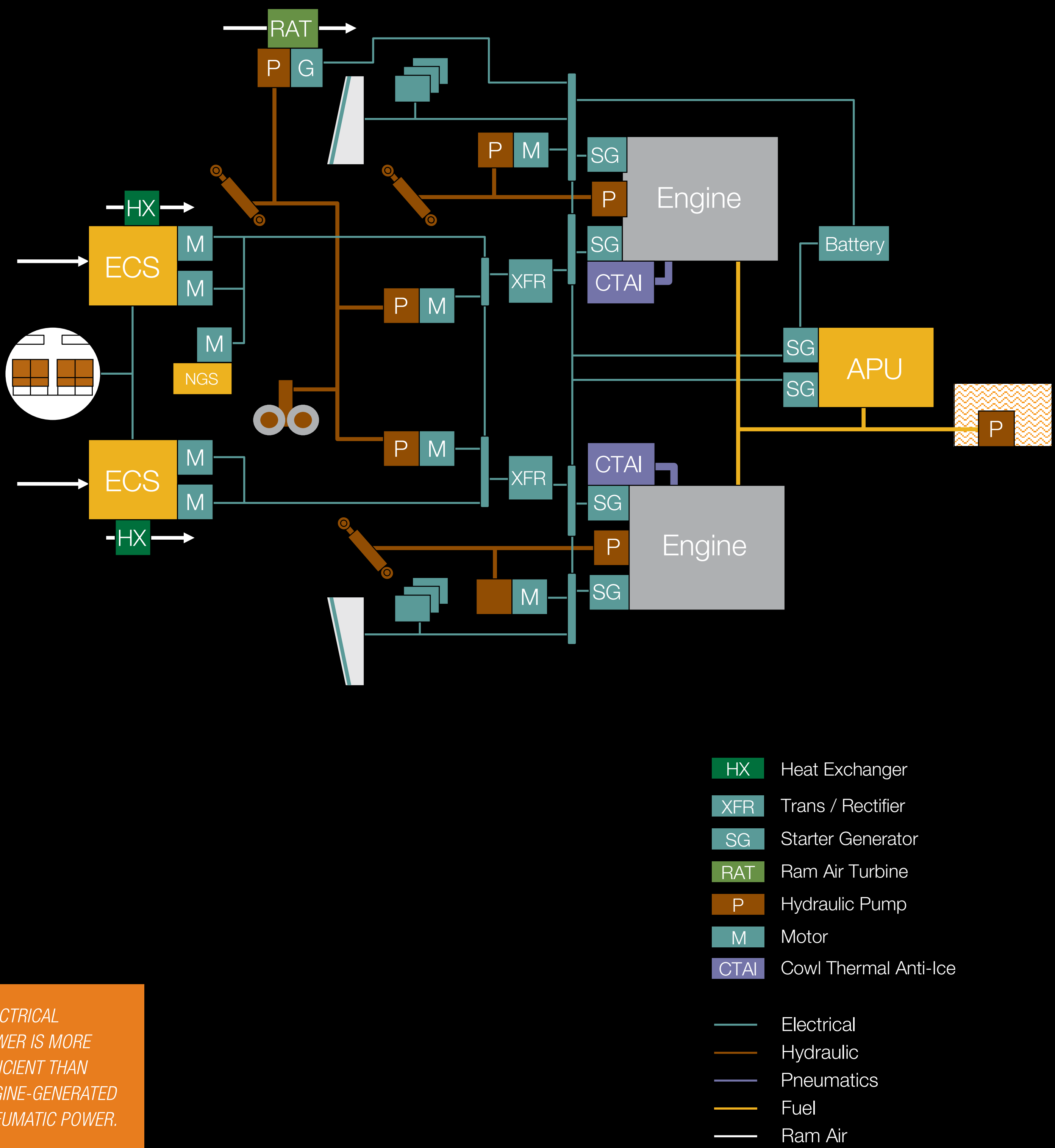
- Improved fuel consumption, due to a more efficient secondary power extraction, transfer, and usage.
- Reduced maintenance costs, due to elimination of the maintenance-intensive bleed system.
- Improved reliability due to the use of modern power electronics and fewer components in the engine installation.
- Expanded range and reduced fuel consumption due to lower overall weight.
- Reduced maintenance costs and improved reliability because the architecture uses fewer parts than previous systems.

The 787's no-bleed systems architecture will allow the airplane's engines to produce thrust more efficiently — all of the high-speed air produced by the engines goes to thrust. Pneumatic systems that divert high-speed air from the engines rob conventional airplanes of some thrust and increase the engine's fuel consumption.

Boeing believes that using electrical power is more efficient than engine-generated pneumatic power, and expects the new architecture to extract as much as 35 percent less power from the engines. Conventional pneumatic systems generally develop more power than is needed in most conditions, causing excess energy to be dumped overboard.

787 NO-BLEED SYSTEMS ARCHITECTURE
Figure 1

The 787's no-bleed systems architecture replaces the traditional pneumatic system and the bleed manifold with a high-power electrical system that, in addition to the traditional electrical system functions, supports a majority of the airplane functions that were traditionally performed via bleed air.

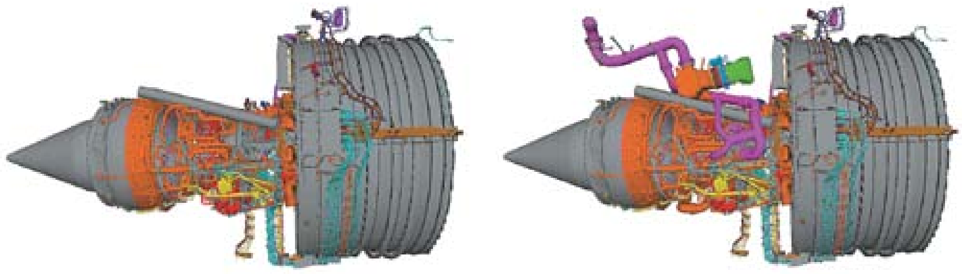


ELECTRICAL POWER IS MORE EFFICIENT THAN ENGINE-GENERATED PNEUMATIC POWER.

COMPARISON OF BLEED AND NO–BLEED ENGINE BUILDUP

Figure 2

A comparison of typical engine buildups of a no-bleed engine (left) and the traditional bleed engine.



The ducting used to pass the pressurized air around the airplane employs check valves and pre-coolers, and is itself made of titanium, which adds hundreds of pounds of weight to the airplane.

The electric system is also inherently easier to monitor and control, and produces only enough power as needed. The power, which comes off the generators at variable frequencies, is conditioned in the electronics bay before being distributed to the appropriate systems.

787 NO-BLEED SYSTEMS ARCHITECTURE

The 787 no-bleed systems architecture is shown schematically in figure 1. On the 787, bleed air is only used for engine cowl ice protection and pressurization of hydraulic reservoirs. The electrified functions are wing deicing protection, engine starting, driving the high-capacity hydraulic pumps, and powering the cabin environmental control system.

In this architecture, the power sources for the electrical system are engine-driven and auxiliary-power-unit (APU)-driven generators, while the power sources for the hydraulic system are engine-driven and electric-motor-driven hydraulic pumps. The engine-driven hydraulic power sources in the no-bleed architecture are similar to those in the traditional architecture.

In the no-bleed architecture, electrically driven compressors provide the cabin pressurization function, with fresh air brought onboard via dedicated cabin air inlets. This approach is significantly more efficient than the traditional bleed system because it avoids excessive energy extraction from engines with the associated energy waste by pre-coolers and modulating valves. There is no need to regulate down the supplied compressed air. Instead, the compressed air is produced by adjustable speed motor compressors at the required pressure without significant energy waste. That results in significant improvements in engine fuel consumption.

ENGINES

In the traditional architecture, the engines provide the majority of secondary airplane systems power needs in pneumatic form; in the no-bleed architecture, the engines provide the majority of airplane systems power needs in electrical form via shaft-driven generators. The traditional airplane pneumatic bleed system architecture results in less than optimum engine efficiency. Eliminating the pneumatic bleed results in a more efficient engine operation due to reduced overall airplane level power requirements — the airplane does not draw as much horsepower off the engine in cruise, so it doesn't burn as much fuel. The corresponding predicted improvement in fuel consumption, at cruise conditions, is in the range of 1 to 2 percent.

Moreover, the no-bleed architecture allows significant simplification in engine buildup due to the elimination of the pneumatic system and associated pre-coolers, control valves, and required pneumatic ducting. Figure 2 compares typical engine buildups of no-bleed engine and the traditional bleed engine.

HYDRAULIC SYSTEM

The hydraulic system in the 787 no-bleed architecture is similar to the one in the traditional architecture. There are three independent systems — left, center, and right — that collectively support primary flight control actuators, landing gear actuation, nose gear steering, thrust reversers, and leading/trailing edge flaps.

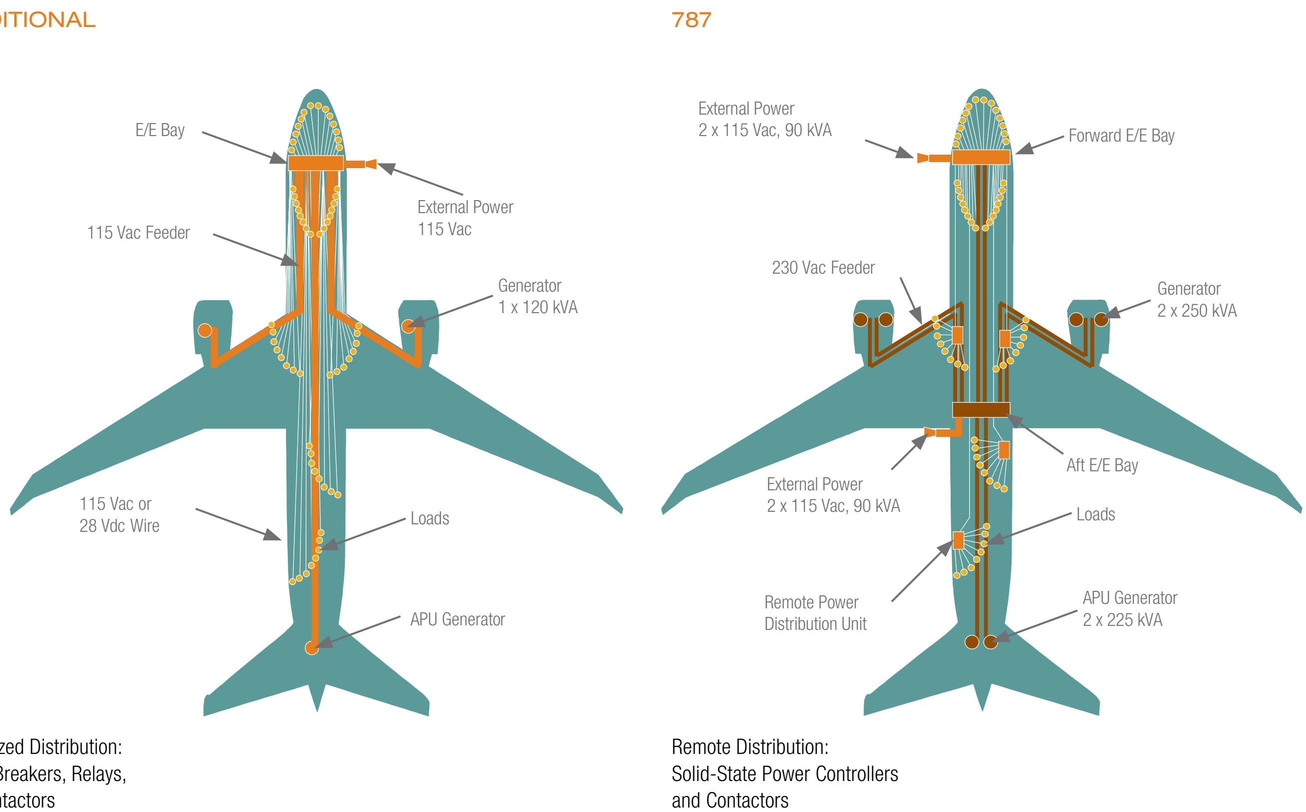
The primary power source for the left and right systems are engine-driven pumps mounted on the engine gearbox. In addition, the left and right systems are each powered by an electric-motor-driven hydraulic pump for peak demands and for ground operations.

The key difference between the traditional and 787 hydraulic system is the power source for the center system. In the traditional architecture, the center system is powered by two large air-turbine-driven hydraulic pumps, which operate at approximately 50 gallons per minute (gpm) at 3,000 pounds per square inch (psi) to meet peak hydraulic demands for landing gear actuation, high lift actuation and primary flight control during takeoff and landing. During the remainder of the flight, two small (approximately 6 gpm) electric-driven hydraulic pumps power the center system.

In the 787 no-bleed architecture, the center hydraulic system is powered by two large (approximately 30 gpm at 5,000 psi) electric-motor-driven hydraulic pumps. One of the pumps runs throughout the entire flight and the other pump runs only during takeoff and landing. The higher pressure of the 787's hydraulic system enables the airplane to use smaller hydraulic components, saving both space and weight.

Figure 3

The 787's electrical system uses a remote distribution system that saves weight and is expected to reduce maintenance costs.



ELECTRICAL SYSTEM

The 787 uses an electrical system that is a hybrid voltage system consisting of the following voltage types: 235 volts alternating current (VAC), 115 VAC, 28 volts direct current (VDC), and ±270 VDC. The 115 VAC and 28 VDC voltage types are traditional, while the 235 VAC and the ±270 VDC voltage types are the consequence of the no-bleed electrical architecture that results in a greatly expanded electrical system generating twice as much electricity as previous Boeing airplane models. The system includes six generators — two per engine and two per APU — operating at 235 VAC for reduced generator feeder weight. The system also includes ground power receptacles for airplane servicing on the ground without the use of the APU.

The generators are directly connected to the engine gearboxes and therefore operate at a variable frequency (360 to 800 hertz) proportional to the engine speed. This type of generator is the simplest and the most efficient generation method because it does not include the complex constant speed drive, which is the key component of an integrated drive generator (IDG). As a result, the generators are expected to be more reliable, require less maintenance, and have lower spare costs than the traditional IDGs.

The electrical system features two electrical/electronics (E/E) bays, one forward and one aft, as well as a number of remote power distribution units (RPDU) for supporting airplane electrical equipment. The system saves weight by reducing the size of power feeders. A limited number of 235 VAC electrical equipment is supplied from the aft E/E bay, while the majority of airplane electrical equipment, being either 115 VAC or 28 VDC, are supported by the forward E/E bay and RPDUs as shown schematically in figure 3. The RPDUs are largely based on solid-state power controllers (SSPC) instead of the traditional thermal circuit breakers and relays. The ±270 VDC system is supplied by four auto-transformer-rectifier units that convert 235 VAC power to ±270 VDC. The ±270 VDC system supports a handful of large-rated adjustable speed motors required for the no-bleed architecture. These include cabin pressurization compressor motors, ram air fan motors, the nitrogen-generation-system compressor used for fuel-tank inerting, and large hydraulic pump motors.

The system, as shown in figure 3, features two forward 115 VAC external power receptacles to service the airplane on the ground without the APU and two aft 115 VAC external power receptacles for maintenance activities that require running the large-rated adjustable speed motors.

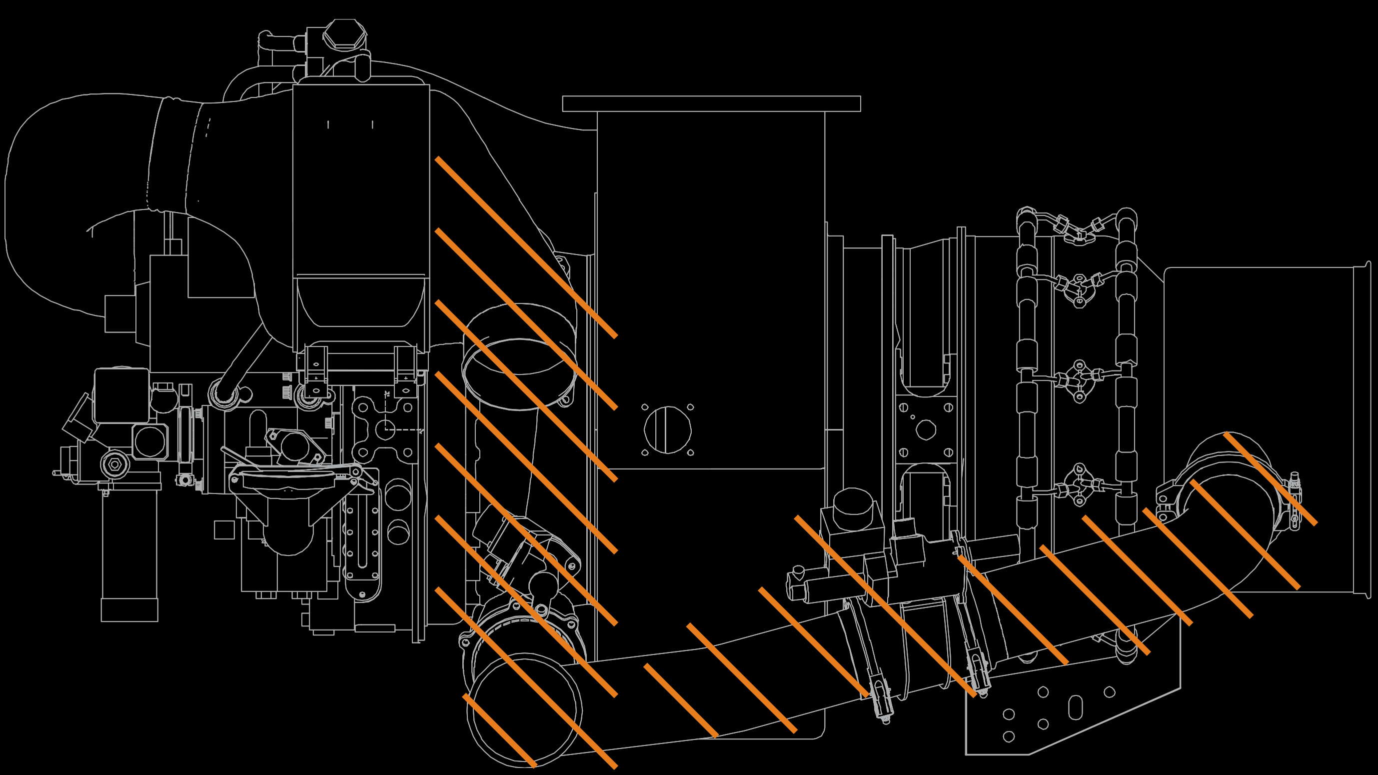
ENGINE AND APU START

The 787's engine-start and APU-start functions are performed by extensions of the method that has been successfully used for the APU in the

APU SYSTEMS ELIMINATED IN THE NO-BLEED ARCHITECTURE

Figure 4

This diagram of an APU for a 767-400 airplane shows the pneumatic portions that will be eliminated in a no-bleed architecture.



The 787 utilizes an electro-thermal ice protection scheme, in which several heating blankets are bonded to the interior of the protected slat leading edges.

Next-Generation 737 airplane family. In this method, the generators are run as synchronous starting motors with the starting process being controlled by start converters. The start converters provide conditioned electrical power (adjustable voltage and adjustable frequency) to the generators during the start for optimum start performance.

Unlike the air turbine engine starters in the traditional architecture that are not used while the respective engines are not running, the start converters will be used after the respective engine is started. The engine- and APU-start converters will function as the motor controller for cabin pressurization compressor motors.

Normally, both generators on the APU and both generators on the engine are used for optimum start performance. However, in case of a generator failure, the remaining generator may be used for engine starting but at a slower pace. For APU starting, only one generator is required.

The power source for APU starting may be the airplane battery, a ground power source, or an engine-driven generator. The power source for engine starting may be the APU generators, engine-driven generators on the opposite side engine, or two forward 115 VAC ground power sources. The aft external power receptacles may be used for a faster start, if desired.

ENVIRONMENTAL CONTROL SYSTEM

In the 787 electrical architecture, the output of the cabin pressurization compressors flows through low-pressure air-conditioning packs for improved efficiency. The adjustable speed feature of electrical motors will allow further optimization of airplane energy usage by not requiring excessive energy from the supplied compressed air and later regulating it down through modulating valves resulting in energy loss.

Avoiding the energy waste associated with down regulation results in improvements in engine fuel consumption, and the environmental-control-system air inflow can be adjusted in accordance with the number of airplane occupants to achieve the lowest energy waste while meeting the air-flow requirements.

WING ICE PROTECTION

In the traditional architecture, hot bleed air is extracted from the airplane bleed system and distributed through the areas of the wing leading edge that need ice protection. For each wing, one valve controls the flow of the bleed air to the wing leading edge, while a "piccolo" duct distributes the heat evenly along the protected area of the wing leading edge. In addition, should ice protection on the leading edge slats be required, a telescoping duct supplies bleed air to the slats in the extended position. The spent bleed air is exhausted through holes in the lower surface of the wing or slat.

The 787 utilizes an electro-thermal ice protection scheme, in which several heating blankets are bonded to the interior of the protected slat leading edges. The heating blankets may then be energized simultaneously for anti-icing protection or sequentially for deicing protection to heat the wing leading edge. This method is significantly more efficient than the traditional system because no excess energy is exhausted. As a result, the required ice protection power usage is approximately half that of pneumatic systems. Moreover, because there are no-bleed air exhaust holes, airplane drag and community noise are improved relative to the traditional pneumatic ice protection system.

APU

As in a traditional architecture, the APU in the no-bleed electrical architecture is mounted in the airplane tail cone, but it provides only electrical power. Consequently, it is much simpler than the APU for the traditional architecture because all of the components associated with the pneumatic power delivery are eliminated. This should result in a significant improvement in APU reliability and required maintenance.

Figure 4 shows the APU for a 767-400 airplane, identifying the pneumatic portions that will be eliminated in a no-bleed electrical architecture. Moreover, taking advantage of the variable frequency feature of the 787 electrical system, the APU operates at a variable speed for improved performance. The operating speed is based on the ambient temperature and will be within a 15 percent range of the nominal speed.

SUMMARY

A key benefit expected from the Boeing 787's no-bleed architecture is improved fuel consumption as a result of more efficient engine cycle and more efficient secondary power extraction, power transfer, and energy usage.

Eliminating the maintenance-intensive bleed system is also expected to reduce airplane maintenance needs and improve airplane reliability because there are fewer components on the engine installation; there are no IDGs, pneumatic ducts, pre-coolers, valves, duct burst protection, and over-temperature protection; and there is no compressed air from the APU, resulting in a simplified and more reliable APU.

The 787 no-bleed architecture also features modern power electronics and motors that will provide increased overall reliability, decreased costs, and improved performance. Finally, the architecture means reduced airplane weight, reduced part count, and simpler systems installation. For more information, please contact Lori Gunter at loretta.m.gunter@boeing.com

Engine Power Loss in Ice Crystal Conditions

by Jeanne Mason,
Senior Specialist Engineer,
Engine Performance and Operability,
Propulsion Systems Division

High-altitude ice crystals in convective weather are now recognized as a cause of engine damage and engine power loss that affects multiple models of commercial airplanes and engines. These events typically have occurred in conditions that appear benign to pilots, including an absence of airframe icing and only light turbulence. The engines in all events have recovered to normal thrust response quickly. Research is being conducted to further understand these events. Normal thunderstorm avoidance procedures may help pilots avoid regions of high ice crystal content.

ICE CRYSTAL ICING CAN OCCUR DEEP IN THE ENGINE, WHERE SURFACES ARE WARMER THAN FREEZING.

Since 1990, there have been at least 100 jet engine power-loss events on both commuter and large transport airplanes, mostly at altitudes higher than 22,000 feet, the highest altitude where airframe icing is expected to exist. "Power loss" is defined as engine instability such as a surge, stall, flame-out, or rollback that results in a sub-idle operating condition. High-altitude ice crystals are believed to have caused most or all of these events.

This article explains the ice crystal phenomenon, how ice crystals cause power loss, the types of power-loss events, where and when engine power-loss events have occurred, conditions associated with ice crystal formation, and recommendations for flight near convective weather. It also discusses the importance of pilot reporting of ice crystal power-loss events.

HIGH-ALTITUDE ICE CRYSTAL ICING

Several engine power-loss and damage events have occurred in convective weather above the altitudes typically associated with icing conditions. Research has shown that strong convective weather (thunderstorm activity) can lift high concentrations of moisture to high altitudes where it can freeze into very small ice crystals, perhaps

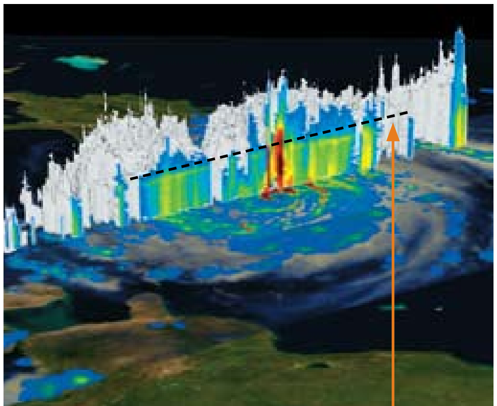


Photo Credit: NASA TRMM
image by Hal Pierce (SSAI/GSFC)

SATELLITE/RADAR IMAGE OF A HURRICANE CONVECTIVE STORM
Figure 1

This NASA Tropical Rainfall Measurement Mission (TRMM) combined satellite radar image shows a vertical cross-section of a convective storm. The image shows the freezing level clearly by the "bright band" where ice particles become coated with melted water and are excellent reflectors of radar energy. Below the freezing level, liquid water is highly reflective. Above the freezing level, while the concentration of moisture may still be high, the cloud is mostly composed of frozen ice particles with radar reflectivity below 20dBZ (units of radar energy). Small ice crystals are irregular in shape and poor reflectors of radar energy. These small ice crystals are believed to be associated with engine power-loss events.

as small as 40 microns (the size of flour grains). These are the crystals that can affect an engine when flying through convective weather. The industry is using the phrase "ice crystal icing" to describe these icing conditions, and to differentiate it from icing conditions due to supercooled liquid.

Ice crystals do not adhere to cold airframe surfaces because the ice crystals bounce off. However, the crystals can partially melt and stick to relatively warm engine surfaces.

"Glaciated conditions" refers to atmospheric conditions containing only ice crystals and no supercooled liquid. "Mixed phase conditions" refers to atmospheric conditions containing both ice crystals and supercooled liquid. Both glaciated and mixed phase conditions occur in convective clouds and have been present during engine power-loss and damage events.

On-board weather radar can detect large particles such as hail, rain, and large ice crystal masses (snowflakes). Small particles, such as ice crystals in high concentrations near thunderstorms, are invisible to on-board weather radar, even though they may comprise the majority of the total mass of a cloud (see fig. 1).

Sophisticated satellite radar technology has been used to detect crystals smaller than the lower limit of on-board weather radar. Above the freezing level, where icing can occur in a deep convective cloud, satellite radar has confirmed that large particles, which can be detected by on-board weather radar, are only found near the convective precipitation core. Away from the convective precipitation core, satellite radar has confirmed that small ice crystals, which are invisible to on-board weather radar, exist.

For this reason, flight in visible moisture near deep convective weather, even without radar returns, and at temperatures below freezing, is very likely to be in ice crystal conditions.

Ice building up on the inlet, fan, or spinner would likely shed outward into the fan bypass duct without causing a power loss. Therefore, in these power-loss events, it is reasonable to conclude that ice must have been building up in the engine core.

It is now believed that ice crystal icing can occur deep in the engine where surfaces are warmer than freezing (see fig. 2). Both older generation jet engines and the new generation of jet engines (high bypass ratio engines with electronic engine controls) can be affected by ice crystal icing.

TYPES OF POWER-LOSS EVENTS

The actual mechanism for ice crystal-related engine power loss takes many forms, depending on the design characteristics of each particular engine type (see table below).

WHERE AND WHEN ICE CRYSTAL POWER-LOSS EVENTS HAVE OCCURRED

About 60 percent of recorded ice crystal power-loss events have occurred in Asia. Researchers speculate that this may be due to the fact that the highest sea surface temperatures are also found

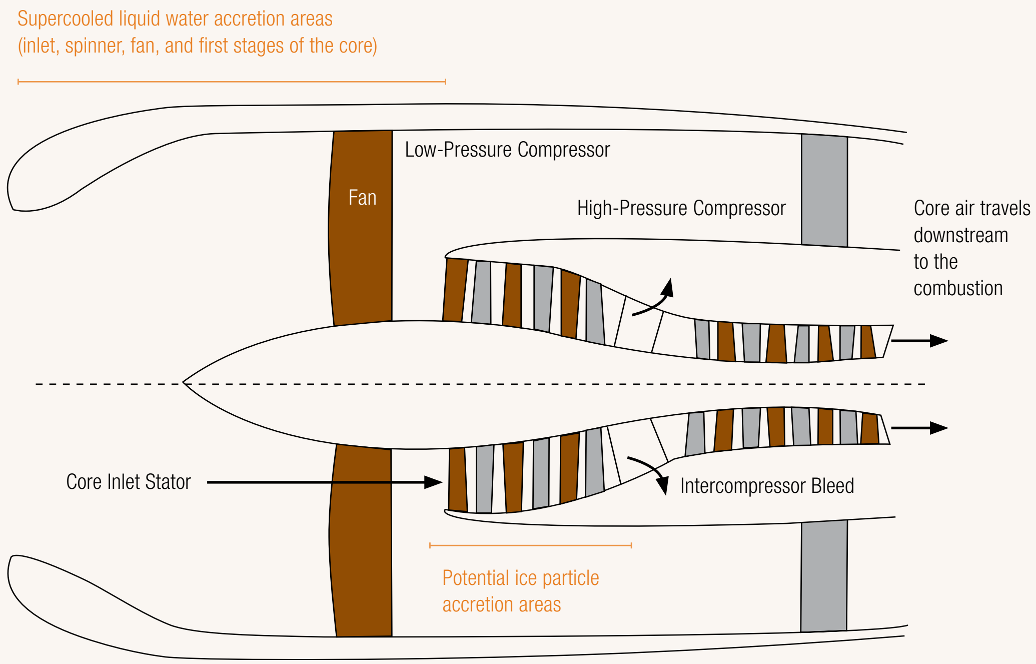
POWER-LOSS TYPE	DESCRIPTION	EFFECT	RECOVERY
Surge/Stall*	Ice shed into compressor drives engine to surge, then stall causes rotor speeds to decay, and reducing airflow while combustor remains lit.	Thrust loss and high exhaust gas temperature.	Throttle to idle. Cycling of the fuel switch may be required to clear some stalls.
Flameout*	Ice shed into the combustor quenches the flame.	Thrust loss and all parameters dropping.	Ignition. Many events self-recover due to auto-relight or having the ignition already on.
Engine Damage	Engine blades become damaged as shed ice impacts them.	Typically no effect at time of initial damage, but damaged blades may fail later causing vibration or engine stall.	As appropriate — refer to Quick Reference Handbook.

In every large transport power-loss event occurring due to stall and flameout that has been tracked to date, the engines were successfully restarted.

HOW ICE CRYSTALS ACCRETE IN A JET ENGINE

Figure 2

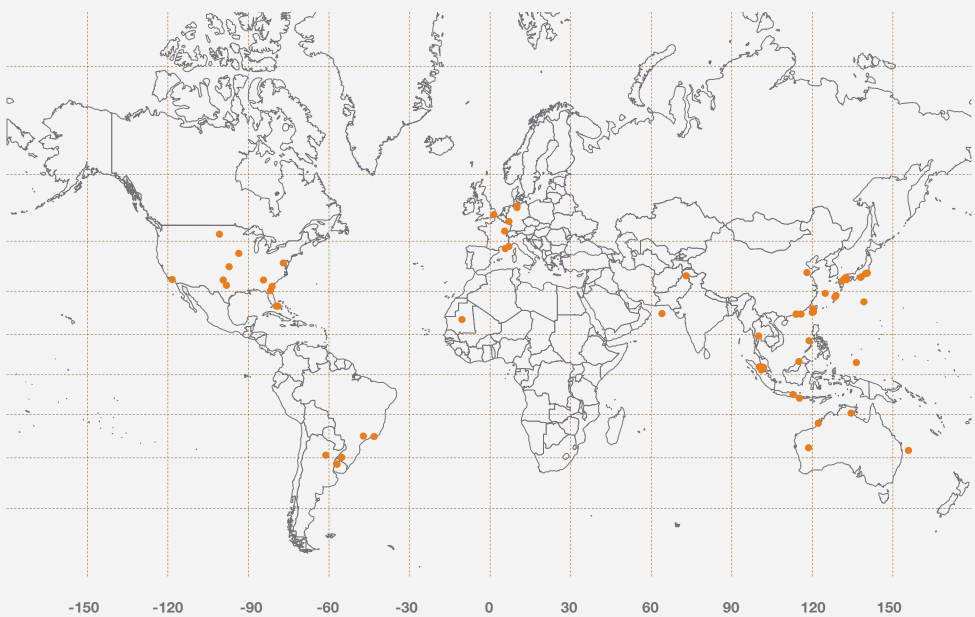
Researchers hypothesize that ice particles enter the engine and bounce off surfaces colder than freezing (inlet, fan, and spinner). Once reaching surfaces warmer than freezing in the core, some of the small particles can melt and create a film of water on the surface to which additional incoming ice crystals can stick. This process gradually reduces the temperature of the surface until ice can begin to build up.



LOCATIONS OF ICE CRYSTAL POWER-LOSS EVENTS

Figure 3

While most ice crystal power-loss events that have been studied to date have occurred in Asia, events have been noted in most parts of the world. Note: Latitude and longitude information is not available for all 100 events. This chart actually shows 67 events, some of which are overlaid. Not all events are Boeing airplanes.

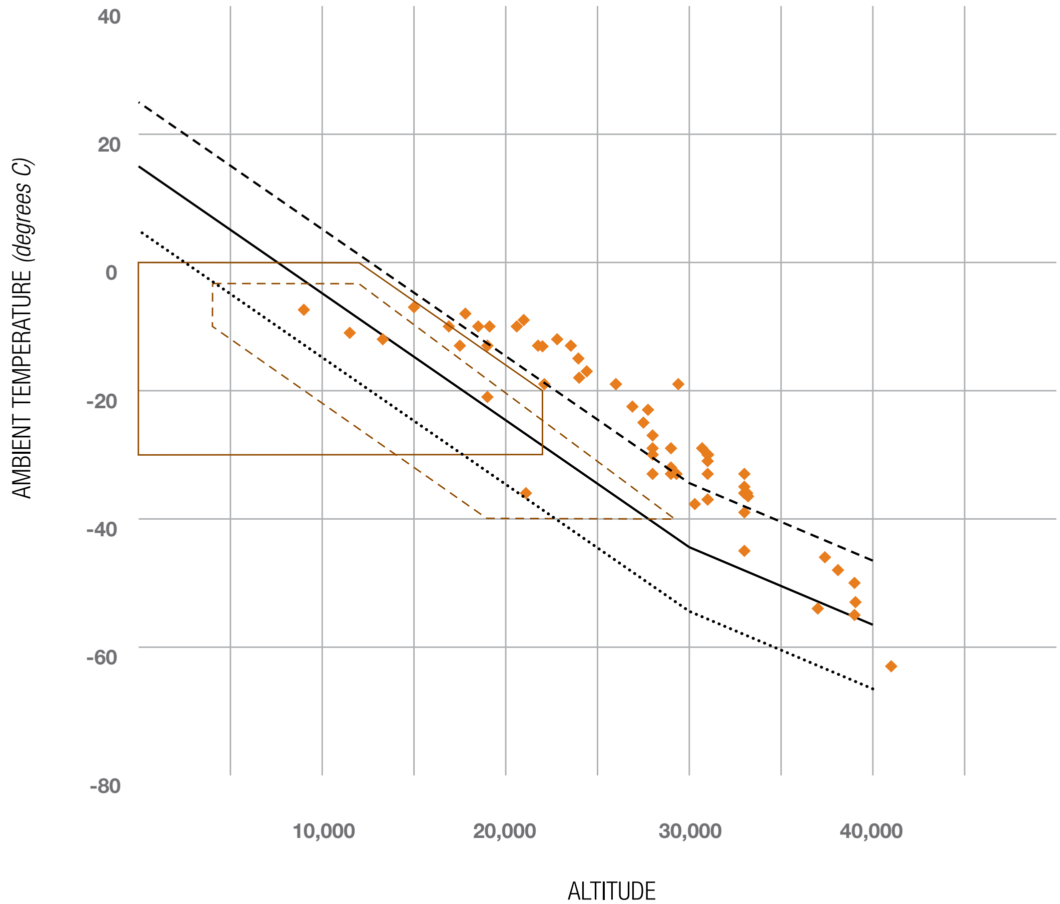


ALTITUDE AND TEMPERATURE OCCURRENCE OF ENGINE POWER LOSS

Figure 4

Temperatures for the majority of the events for which data is available are significantly warmer than standard day temperatures, and also fall outside of the current icing design envelopes for supercooled liquid water.

◆ = Power-Loss Event
— = Standard Atmosphere
-- = Standard Atmosphere +10C
··· = Standard Atmosphere –10C
— = Continuous Maximum — Stratiform Clouds
-- = Intermittent Maximum — Cumuliform Clouds



in this region. Higher temperature air can hold more water. There is a heavy concentration of ice crystal power-loss events between 20 and 40 degrees north latitude with a few events farther than 45 degrees from the equator (see fig. 3).

Engine power-loss events have occurred in three phases of flight: climb, cruise, and descent. However, most events occur during the descent phase, most likely because of a combination of two factors. First, for icing to occur, the ambient temperature must be below the freezing level, and therefore icing tends to occur at the higher altitude associated with the descent phase. Second, the engine is least tolerant to ice shedding at idle power, which occurs in the descent phase. Icing at high power and high altitude is possible due to the existence of high concentrations of ice crystals for long distances, such as in the anvil of a large convective storm, and the fact that ice can build up on warm engine surfaces.

RECOGNIZING HIGH ICE CRYSTAL CONDITIONS

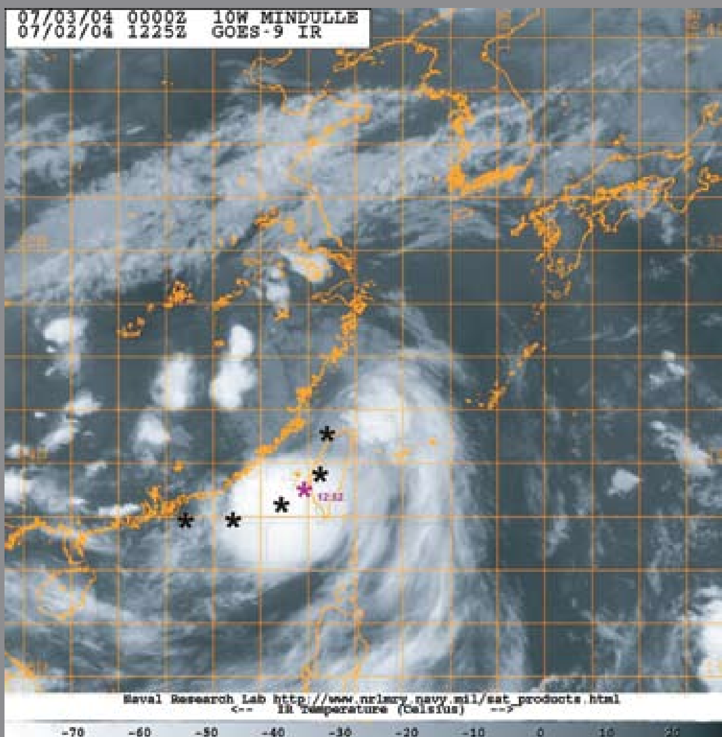
Researchers have identified several conditions that are connected to engine ice crystal icing events. The most important factors are:

- *High altitudes and cold temperatures.* Commercial airplane power-loss events associated with ice crystals have occurred at altitudes of 9,000 to 39,000 feet, with a median of 26,800 feet, and at ambient temperatures of –5 to –55 degrees C with a median of –27 degrees C. The engine power-loss events generally occur on days when the ambient temperature is warmer than the standard atmosphere (see fig. 4).
- *The presence of convective clouds.* Convective weather of all sizes, from isolated cumulonimbus or thunderstorms to squall lines and tropical storms, can contain ice crystals. Convective clouds can contain deep updraft cores that can lift high concentrations of water thousands of feet into the atmosphere, during which water vapor is continually condensed and frozen as the temperature drops. In doing so, these updraft cores may produce localized regions of high ice water content which spread downwind. Researchers believe these clouds can contain up to 8 grams per cubic meter of ice water content; by contrast, the design standard for supercooled liquid water for engines is 2 grams per cubic meter.
- *Areas of visible moisture above the altitudes typically associated with icing conditions.* This is indicated by an absence of significant airframe icing and the ice detector (when installed) not detecting ice, due to its ability to detect only supercooled liquid, not ice crystals.

These additional conditions are also typically found during engine ice crystal power-loss events.

- No pilot reports of weather radar returns at the event location.
- Temperature significantly warmer than standard atmosphere.
- Light-to-moderate turbulence.
- Areas of heavy rain below the freezing level.
- The appearance of precipitation on heated windshield, often reported as rain, due to tiny ice crystals melting.
- Airplane total air temperature (TAT) anomaly-reading zero, or in error, due to ice crystal buildup at the sensing element (see case study on following page).
- Lack of observations of significant airframe icing.

AN ICE CRYSTAL POWER-LOSS EVENT CASE STUDY



INFRARED IMAGE WITH AIRPLANE TRACK
In this infrared satellite image from about the time of an engine event, bright white indicates colder cloud, and therefore at high altitude. The airplane penetrated the upper altitudes of a fully developed typhoon, yet the pilot did not see any flight level radar returns.

The asterisks represent the aircraft path from left to right on descent into Taipei, with the event noted in purple.

- A commercial airplane on descent, flying in convection conditions, experienced a TAT anomaly. (The anomaly is due to ice crystals building up in the area in which the sensing element resides, where they are partly melted by the heater, causing a 0 degrees C reading. In some cases, TAT has stabilized at 0 degrees C during a descent, and may be noticeable to pilots. In other cases, the error is more subtle, and not a reliable-enough indicator to provide early warning to pilots of high concentrations of ice crystals.)
- At 38,000 feet (–42 degrees C), the pilot encountered moderate turbulence and noted some lightning in the vicinity.
- A brief power-loss event occurred at 30,000 feet — the engines restarted quickly.
- There were no radar echoes at the altitude and location of the airplane.
- An absence of a response from the ice detector indicated that no supercooled liquid was present.
- The pilot reported heavy rain at –25 degrees C.
- Initial report of rain on the windscreen was later determined to be ice crystals, and confirmed by the pilot to have a unique sound.

To view enhanced media associated with this article, visit AERO *online at www.boeing.com/commercial/aeromagazine.*

Pilots are advised to familiarize themselves with the conditions under which ice crystal icing typically occurs and follow the recommendations in related technical bulletins.

RECOMMENDATIONS FOR FLIGHT NEAR CONVECTION

Even when there are no radar returns, there may be significant moisture in the form of ice crystals at high altitudes. These are not visible to airborne radar. As a result, it is not possible to avoid all ice crystal conditions. However, normal thunderstorm avoidance procedures may help pilots avoid regions of high ice crystal content.

These avoidance procedures include:

- Avoiding flying in visible moisture over storm cells. Visible moisture at high altitude must be considered a threat since intense storm cells may produce high concentrations of ice crystals at cruise altitude.
- Flying upwind of storms when possible.
- Using the radar antenna tilt function to scan the reflectivity of storms ahead. Assess the height of the storms. Recognize that heavy rain below the freezing level typically indicates high concentrations of ice crystals above.
- Avoiding storm reflectivity by 20 nautical miles has been commonly used as a recommended distance from convection. This may not be sufficient for avoidance of high concentrations of ice crystals, as they are not visible on airborne radar.

These recommendations are included in flight operations technical bulletins Nos. 707-06-1, 727-06-1, 737-06-1, 747-15, 747-400-55, 757-75, 767-75, 777-21, 787-1 issued by Boeing on August 1, 2006: *Convective Weather Containing Ice Crystals Associated with Engine Power Loss and Damage.*

FURTHER RESEARCH

Today, knowledge of the nature of convective weather and the exact mechanism of ice crystal buildup and shedding in the engine is limited. A research program is being developed by an industry icing group to address these needs. It involves flights into convective clouds to measure their properties, as well as ground-based engine testing.

Most of what is currently understood about the environment associated with engine events is based on pilot reports and flight data. Additional pilot reports of high-altitude ice crystal encounters (with or without engine events) will help researchers understand the conditions associated with engine events, ensure that the flight program is directed into the appropriate flight conditions, and help develop cues for these flight conditions.

Pilots encountering conditions such as those described in this article are encouraged to provide as many details about the conditions as possible to their airlines for subsequent use by researchers.

SUMMARY

Ice crystal icing conditions have been recognized as a hazard to turbofan engines. Ice can build up deep in the engine core.

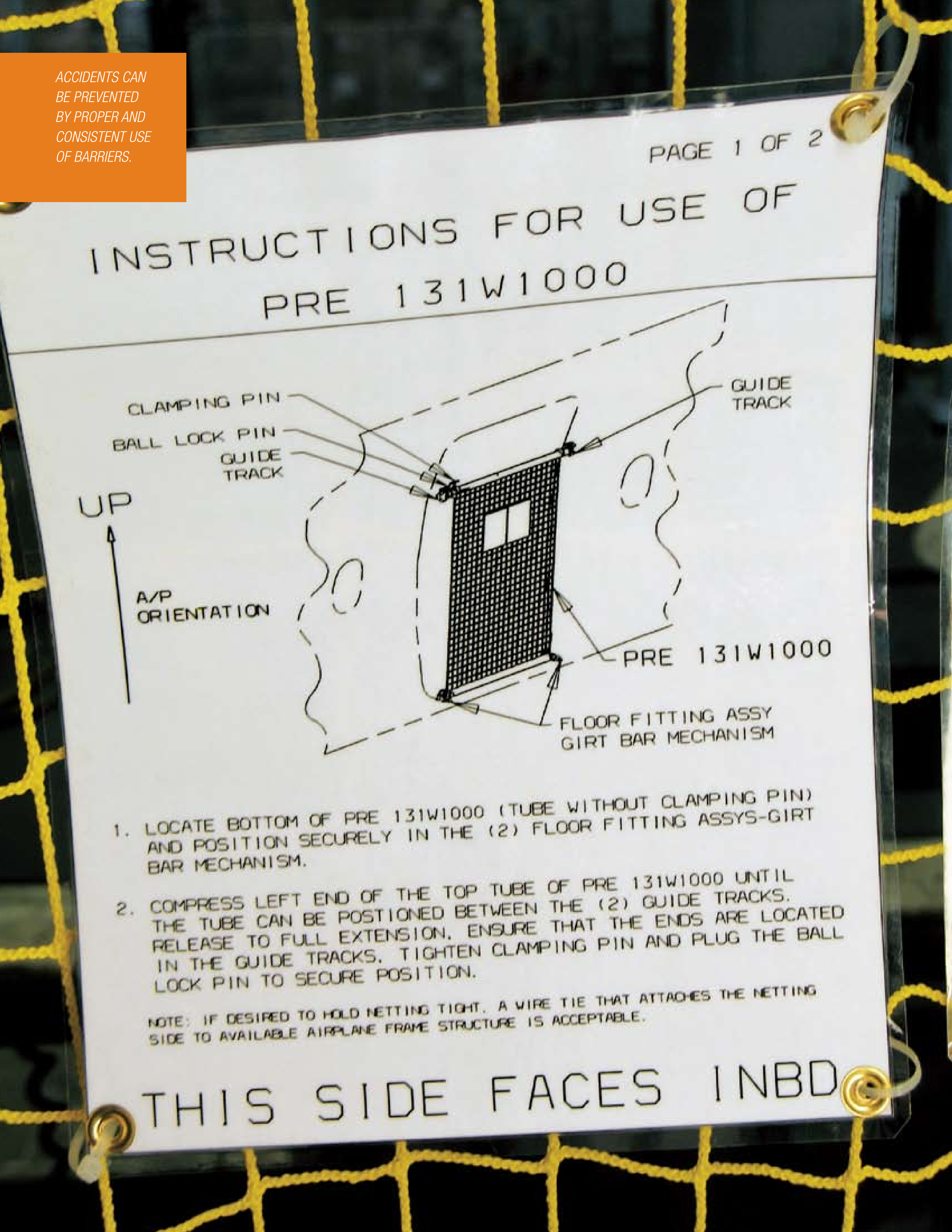
Pilots are advised to familiarize themselves with the conditions under which ice crystal icing typically occurs and follow the recommendations in related technical bulletins.

Airline awareness of the potential for ice crystal icing on all engine models/airplane types may provide additional information that will help Boeing and the industry better understand this phenomenon.

For more information, please contact Jeanne Mason at jeanne.g.mason@boeing.com.

Material for this article has been drawn from AIAA 2006-0206 "Ice Particle Threat to Engines in Flight," Mason, Strapp and Chow.

ACCIDENTS CAN BE PREVENTED BY PROPER AND CONSISTENT USE OF BARRIERS.



Protecting Airline Personnel from Falls

by William L. Rankin, Ph.D., Boeing Technical Fellow,
Maintenance Human Factors, and
William R. Carlyon, Program Management Specialist,
Environment, Health and Safety

Open doors, access panels, and hatches on parked airplanes can be potential safety hazards for airline personnel unaware of the opening. Flight attendants and servicing staff have suffered injuries as a result of falls through these openings. Investigations of these accidents by Boeing indicate that they are preventable by proper and consistent use of barriers and following airline policies and procedures.

Prior to pushback, flight attendants and servicing staff have suffered injuries by falling through unprotected airplane doors on all models and through internal access panels on 747, 767, 777, DC/MD-10, and MD-11 airplanes. On the 747, 767, and 777 models, this internal access panel is known as the electrical/electronics (E/E) bay main deck access panel. On the DC/MD-10 and MD-11 models, this internal access panel, located about mid-cabin, is known as the lower galley floor hatch or the center accessory compartment access door. Injuries can also result from tripping on open floor panels, hatches, and doors. This article explains these situations, recommends ways to guard against these injuries, describes equipment that Boeing has made available to operators to address these issues, and discusses the role of airline policies and procedures in helping to prevent falls.

THE DANGERS OF OPEN PANELS, DOORS, AND HATCHES

Flight attendants and servicing personnel have been injured on airplanes prior to departure by falling through an open E/E bay main deck access panel opening on 747, 767, and 777 airplanes (there is no such access panel on the 737, the 757, or on McDonnell Douglas products). The panel is removed from the passenger cabin floor and set aside while the opening is left unprotected by the mechanic.

On DC/MD-10/MD-11 airplanes with a lower galley, the lower galley floor hatch, as well as the center accessory compartment panel, can pose a danger if left open and unguarded.

Open, unprotected passenger entry doors on all models present another hazard. Many times during servicing of airplanes between flights, passenger entry doors are left open to allow access by caterers and servicing personnel. The danger occurs when a catering vehicle or air stairs move away from the opening while the door is still open. Also, doors are left open in hot weather to cool the aircraft interior. In this situation, there is nothing to stop someone onboard the airplane from falling to the ground through the open door.

PREVENTING FALLS ASSOCIATED WITH THE E/E BAY MAIN DECK ACCESS PANEL

Accidents involving the E/E bay main deck access panel can be prevented by following correct procedures. According to the Boeing airplane maintenance manuals (AMM), the E/E bay main deck access panel is to be used for “access to the E/E bay while in flight.” This access is potentially needed for extreme emergencies, such as by the cabin crew to fight an E/E bay fire. During hangar maintenance, the internal access panel may be used by operators to accommodate extensive airplane maintenance or modification activity. However, the internal access panel was never intended for the purpose of line maintenance in which flight crew, cabin crew, catering personnel, and passengers might be endangered. The Boeing AMM maintenance procedure does not direct a mechanic into the E/E bay using the internal main deck access panel. When entry to the E/E bay is needed, the AMM maintenance procedure directs the mechanic to enter the E/E bay via the external access door.

To help prevent accidents and injuries related to this panel, all 777s now being delivered have a hinged, self-closing access panel, and all 747s now being delivered have a safety net attached. For retrofitting purposes, all three airplane models have a hinged, self-closing access panel available, and the 747 and 767 models have a safety net available. Since 1982, Boeing has released a number of service bulletins related to methods available on the various models to block access to this panel. (Please refer to service bulletins Nos. 747-53-2434, 767-53-0092, and 777-53-0021.)

If an operator elects not to install a self-closing access panel or safety net, Boeing recommends the installation of an E/E access opening safety guard around the exposed opening in the floor or the installation of a safety barrier in the cabin across the access door panel whenever the panel is removed. Examples of safety barriers are shown in figures 1 and 2.

During line maintenance on the 747, 767, and 777 airplanes, Boeing recommends the use of the external access door at the bottom of the fuselage instead of the internal access door (i.e., E/E bay main deck access panel) in order to gain access to the electrical equipment bay.

BLOCKING OPEN CABIN AND CARGO DOORS

Passenger and cargo doors should be closed when access to the airplane cabin or cargo compartment is no longer needed. Many airlines state this explicitly in their policies and procedures.

On occasions when doors are left open deliberately, such as to air out an airplane during cleaning, steps should be taken to block the door. Some operators use a simple strap to provide a visual signal that a door is open. However, the strap is not designed to stop a fall. Boeing recommends the use of a net any time a passenger or cargo door is left open and unprotected. This recommendation is also included in the 27th edition of the International Air Transport Association's *Airport Handling Manual,* which became effective Jan. 1, 2007. Boeing ground-support-equipment safety nets are available for use in cases in which the passenger door must be open or whenever a passenger door is being replaced.

FLOOR HATCHES AND PANELS ON DC/MD-10, MD-11 AIRPLANES

Operators have reported instances of flight attendants inadvertently stepping into an open and unguarded floor hatch. In response, warning placards have been installed adjacent to main deck floor access hatches. If a lower galley is installed, these placards are located near the lower galley escape hatch, as well as near the center accessory compartment access panel.

Boeing recommends that operators further protect the safety of their personnel by erecting a barricade, such as those shown in figures 1 and 2 around any open floor access hatch or panel.

THE ROLE OF AIRLINE POLICIES

If operators elect not to purchase and install the recommended hinged access panels or safety nets, or choose not to use the recommended safety barriers, they should use local procedures to provide for the safety of the flight attendants and servicing personnel. These procedures include specific policies dictating how open floor panels, hatches, and doors should be protected. For example, an employee can be assigned to guard the panel or door while it is open.

SUMMARY

Open doors, access panels, and hatches can present safety hazards, but falls through them can be prevented by proper and consistent use of barriers and following airline policies and procedures.

For more information, please contact William L. Rankin at william.l.rankin@boeing.com or William R. Carlyon at william.r.carlyon@boeing.com.

EXAMPLES OF SAFETY BARRIERS

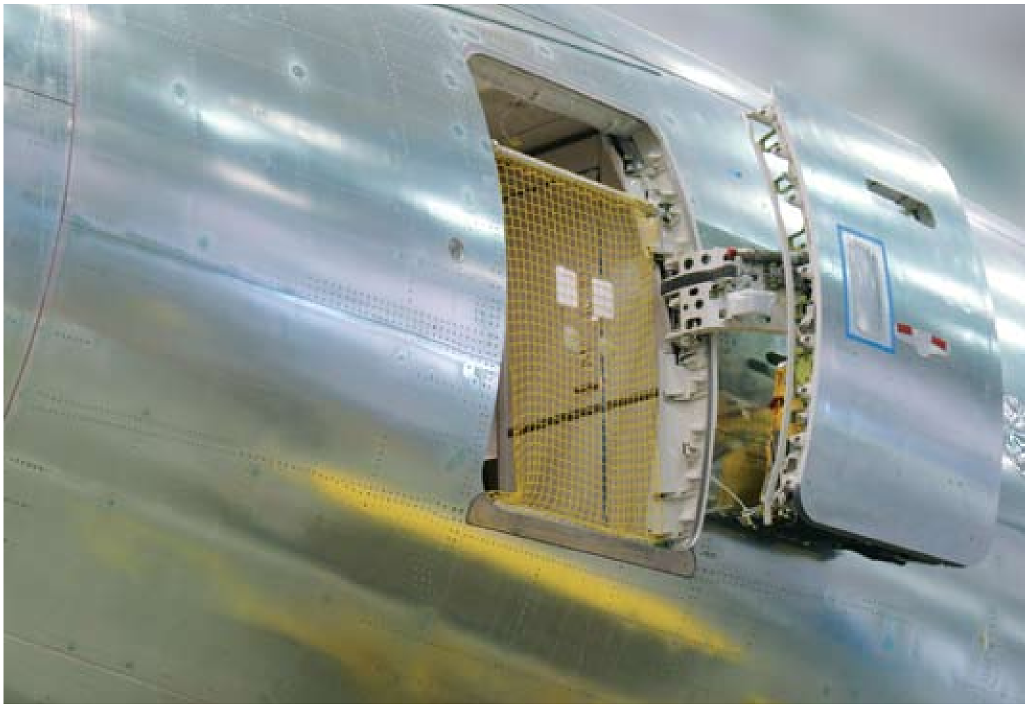
Figure 1

Folding manhole guard safeguards open manholes or areas up to 33 inches square. This 42-inch-high guard folds to 33-by-4 inches for easy transport and compact storage. It has a strong, tubular steel frame with a yellow powder-coated finish.

Figure 2

Highly visible, this four-panel barrier alerts everyone in the area to the presence of a work zone. It features durable, lightweight orange polypropylene panels. Each barrier panel is 30 inches high by 34½ inches wide. Panels have quick-release snap hinges for easy setup. Two panels can be used together as an A-frame barricade or two or more barriers can be joined together to create a larger work zone.

Door safety nets such as these are used on the 777 during production.



This hinged, self-closing E/E bay main deck access panel is used during 777 production. Note that the panel is connected to a red light, which flashes any time the access panel is open.

CRUISE FLIGHT IS THE PHASE OF FLIGHT BETWEEN CLIMB AND DESCENT.

Fuel Conservation Strategies: Cruise Flight

by William Roberson, Senior Safety Pilot, Flight Operations;
Robert Root, Flight Operations Engineering; and
Dell Adams, Flight Operations Engineer

This article is the second in a series exploring fuel conservation strategies.

A good understanding of cruise flight can not only help crews operate efficiently and save their companies money, but can also help them deal with low fuel situations. As an additional benefit, the less fuel consumed, the more environmentally friendly the flight.

This article defines cruise flight, presents various cruise schemes, and outlines the effects of wind on cruise speed calculations. It also discusses the relationship between cruise flight and cost index (CI) which was discussed in the first article in this series, "Fuel Conservation Strategies: Cost Index Explained" in the second-quarter 2007 *AERO*.

Used appropriately, the CI feature of the flight management computer (FMC) can help airlines significantly reduce operating costs. However, many operators don't take full advantage of this powerful tool.

CRUISE FLIGHT DEFINED

Cruise flight is the phase of flight that falls between climb and descent. The largest percentages of trip time and trip fuel are consumed typically in this phase of flight. As an aside, unanticipated low altitude maneuvering, which also impacts trip time and fuel significantly, can often be avoided through appropriate cruise planning.

The variables that affect the total time and fuel burn are speed selection, altitude selection, and, to some degree, center of gravity (CG). This article focuses on speed selection.

A number of high-level objectives may influence speed selection. These objectives, which depend on the perspective of the pilot, dispatcher, performance engineer, or operations planner, can be grouped into five categories:

1. Maximize the distance traveled for a given amount of fuel (i.e., maximum range).
2. Minimize the fuel used for a given distance covered (i.e., minimum trip fuel).
3. Minimize total trip time (i.e., minimum time).
4. Minimize total operating cost for the trip (i.e., minimum cost, or economy [ECON] speed).
5. Maintain the flight schedule.

The first two objectives are essentially the same because in both cases the airplane will be flown to achieve optimum fuel mileage.

Pilots are often forced to deal with shorter-term restraints that may require them to temporarily abandon their cruise strategy one or more times during a flight.

CONSIDERATIONS AFFECTING CRUISE STRATEGIES

In addition to one of the overall strategic objectives listed above for cruise flight, pilots are often forced to deal with shorter term constraints that may require them to temporarily abandon their cruise strategy one or more times during a flight. These situations may include:

- Flying a fixed speed that is compatible with other traffic on a specified route segment.
- Flying a speed calculated to achieve a required time of arrival (i.e., RTA) at a fix.
- Flying a speed calculated to achieve minimum fuel flow while holding (i.e., maximum endurance).
- When directed to maintain a specific speed by air traffic control.

POSSIBLE CRUISE SCHEMES

There are two theoretical speed selections for the cruise phase of flight. The traditional speed is long-range cruise (LRC). LRC speed is interrelated with maximum-range cruise (MRC) speed, which is the speed that will provide the furthest distance traveled for a given amount of fuel burned and the minimum fuel burned for a given cruise distance.

LRC has been historically defined as the speed above MRC that will result in a 1 percent decrease in fuel mileage in terms of nautical miles per kilogram or pound of fuel burned. The classic text, *Aerodynamics for Naval Aviators*, revised in 1965, states: “Most long-range cruise operation is conducted at the flight condition which provides 99 percent of the absolute maximum specific range. The advantage is that 1 percent of range is traded for 3 to 5 percent higher cruise velocity. Since higher cruise speed has a great number of advantages, the small sacrifice of range is a fair bargain.” This concept is graphically illustrated in figure 1.

Because fuel is not the only direct cost associated with a flight, a further refinement in the speed for most economical operation is ECON speed, based on the entered CI. This speed, which includes some tradeoffs between trip time and trip fuel, is based on an estimation of the time-related operating expenses that are specific to each airline’s operation. CI is defined as the ratio of time-dependent costs to fuel costs.

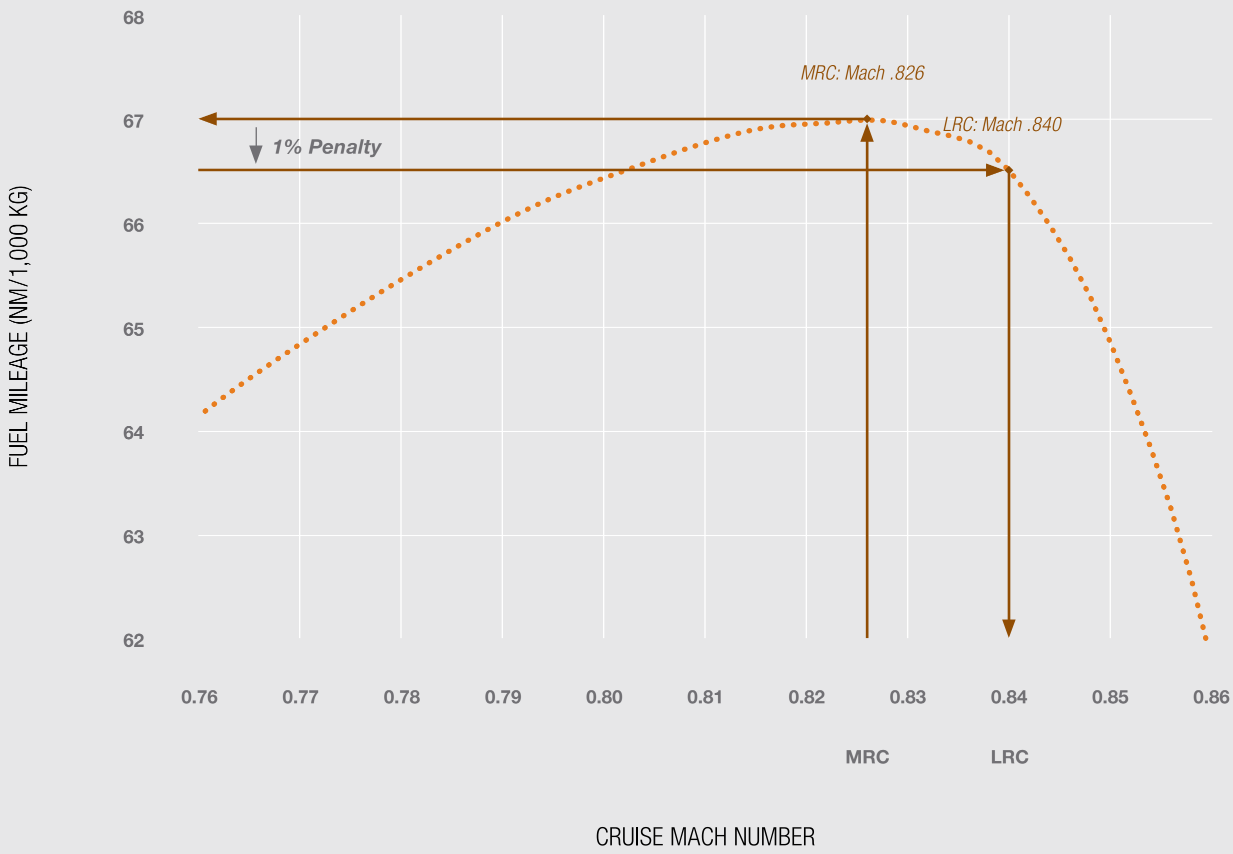
$$CI = \frac{\text{Time cost} \sim \$/\text{hr}}{\text{Fuel cost} \sim \text{cents/lb}}$$

LONG-RANGE CRUISE AND COST INDEX

The relationship between LRC speed and ECON speed is different for each Boeing airplane model. As stated, LRC is based on a 1 percent penalty on fuel mileage, while the ECON speed uses CI as an input that is based on a more detailed accounting of actual costs. However, it is possible to derive a CI for normal cruise conditions that approximates

REPRESENTATIVE COMPARISON OF MRC AND LRC
Figure 1

Modern flight management systems automatically adjust LRC speed throughout cruise for weight change due to fuel burn, as well as changes in cruise altitude.



LRC in terms of the cruise speed that results. Figure 2 shows the approximate relationship for Boeing commercial airplanes.

It is very important to note that the LRC speed is almost universally higher than the speed that will result from using the CI selected by most carriers. If faced with a low fuel situation at destination, many pilots will opt to fly LRC speed thinking that it will give them the most miles from their remaining fuel. As shown in figure 2, the best strategy to conserve fuel is to select a very low cost index, with zero providing the maximum range. Any pilot can easily demonstrate this during cruise flight by inputting different CIs into the FMC and comparing with LRC by observing the predicted fuel at destination.

EFFECTS OF WIND ON CRUISE SPEED

In addition to more accurately optimizing costs, there is one other benefit of flying ECON instead of LRC with most Boeing airplanes. The LRC speed calculated by the FMC is typically not adjusted for winds at cruise altitude but the ECON speed is. As a result, LRC is ideal only for zero wind conditions, while the ECON speed is optimized for all cruise wind conditions.

For example, in the presence of a strong tailwind, the ECON speed will be reduced in order to maximize the advantage gained from the tailwind during the cruise. Conversely, the ECON speed will be increased when flying into a headwind in cruise to minimize the penalty associated with the headwind (see example in fig. 3).

THE RELATIONSHIP BETWEEN OPERATING COSTS AND COST INDEX

If fuel prices increase relative to other costs, a corresponding reduction in CI will maintain the most economical operation of the airplane. If, however, an airline experiences rising hourly costs, an increase in CI will retain the most economical operation. In either case, the changing CI will result in changes to the cruise speed calculated by the FMC. Even calculating a cost index based on approximate time costs and flying ECON speed can yield significant cost benefits to the airline.

To be used most effectively, CI should be based on a comprehensive evaluation of an operator's specific operating costs. For this reason, flight crews typically receive a recommended CI value from their flight operations department, and it is generally not advisable to deviate from this value unless specific short-term constraints demand it.

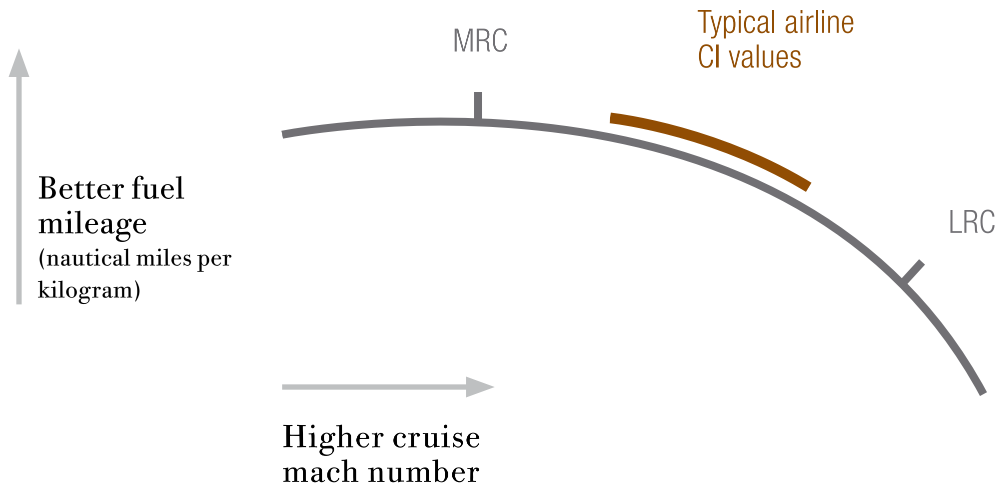
SUMMARY

In order for flight crews to achieve optimum cruise operation, it is necessary to first understand the flight's strategic objectives, and then to select the cruise speed that best meets these objectives. It is equally important to recognize that real-world situations may result in the need for deviations from the overriding strategy. Appropriate use varies with each airline, and sometimes even for each flight.

Boeing Flight Operations Engineering assists airlines' flight operations departments in computing an accurate CI that will enable them to minimize costs on their routes. For more information, please contact FlightOps.Engineering@boeing.com.

RELATIONSHIP OF COST INDEX TO LRC FOR BOEING AIRPLANES
Figure 2

The LRC-equivalent cost index varies for different airplane models and engines.



Entered Cost Index (CI)

AIRPLANE MODEL	MRC	TYPICAL AIRLINE CI VALUES	APPROXIMATE LRC EQUIVALENT
717	0	40 to 60	70
737-3/4/500	0	5 to 25	25
737-6/7/800	0	10 to 30	35
757	0	15 to 50	85
767	0	15 to 55	70
777	0	90 to 150	180
MD-11	0	80 to 120	200
747-400	0	25 to 80	230

ECON SPEED IS OPTIMIZED FOR CRUISE WIND CONDITIONS
Figure 3

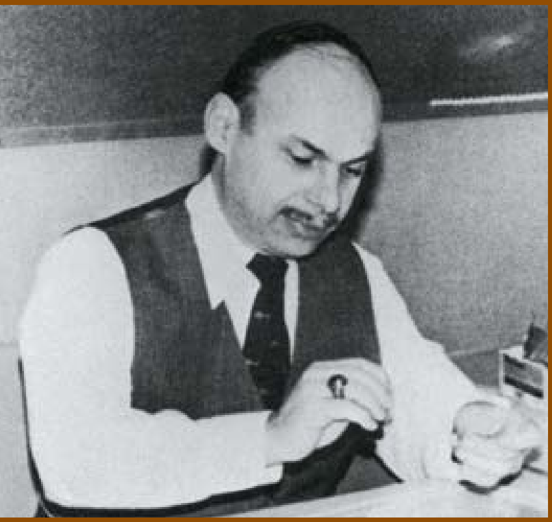
ECON Cruise Mach

COST INDEX	100 KT TAILWIND	ZERO WIND	100 KT HEADWIND
0	0.773*	0.773	0.785
80	0.787	0.796	0.803
Max**	0.811	0.811	0.811

*FMC will not slow down below still air CI=0 ECON speed.

**At maximum CI, FMC will fly at envelope limit in all wind conditions.

In memoriam:
Al Lloyd



A man who loved airplanes and firmly believed that going the extra mile for a customer was just the way we do business at Boeing, Alwyn “Al” Lloyd passed away Tuesday, May 29, 2007.

Al was a top-notch engineer with an encyclopedic knowledge of Boeing products, a combination that proved invaluable when he was editor of the *Boeing Airliner* (predecessor of *AERO*) and more recently as a senior service engineer for Boeing Commercial Aviation Services and a member of the Boeing Corporate History Council.

Al’s motto of “we do the difficult immediately but the impossible may take a bit longer” endeared him to the airline customers that he supported and helped to keep those customers loyal to Boeing.

Outside of his work at Boeing, Al was a highly respected aviation historian and very successful author to a worldwide audience of aviation professionals, enthusiasts, historians, and modelers.

Al served in the U.S. Air Force and was a former president of the Air Force Association. He wrote many books and articles on Air Force history including a comprehensive history of the Strategic Air Command, *A Cold War Legacy,* which is considered to be the best history of that famous organization.

Al’s enthusiasm for aviation and dedication to Boeing and its customers will be greatly missed.

— Michael Lombardi, Boeing Corporate Historian