

**The 9th Israeli Symposium on
Jet Engines and Gas Turbines (Oct 7, 2010)**

All/More Electric Aircraft Engine & Airframe Systems Implementation

Presented by:

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Objectives

- Assess the benefits and implications of adopting the All Electric and More Electric Aircraft (AEA/MEA) concepts relative to conventional secondary power systems on Boeing (B767) and Airbus (A330) baseline aircraft,
- B787 and A380 more electric aircraft design approach,
- Quantify fuel and mass changes on aircraft level,
- IAI implications of MEA concept.

Evolution of the All/More Electric Aircraft Concepts

- First proposed by Woodford, GCA. “Electrics for Aircraft” Journal of the Royal Aeronautical Society, Volume 49, PP 518-565, September 1945,
- June 1981 NASA Workshop on “Electric Flight Systems”,
- January 1985 NASA contractor report “Integrated Digital/Electric Aircraft (IDEA)”, studies the efficiency of a 250-300 seater replacement by Boeing (derivative 767) and Lockheed (advanced 1011 Tristar),
- 1988-1989 Cranfield College of Aeronautics study based on hypothetical RB211-524D4 powered A300-600 and Allison 501-M80F-3 propfan powered BAe 146-300.

“Conventional” Philosophy

- Secondary power systems (SPS) are the power distributed around the engine and airframe systems and not used for propulsion (this being the primary power). On most aircraft SPS are distributed in three forms:
 - Electric (avionics, lights, instruments, entertainment, etc.),
 - Hydraulic (primary & secondary flight controls, landing gears, brakes, steering, doors, other actuation functions),
 - Bleed air or pneumatic (environmental control system ECS, cabin pressurization, engine cowl and wing ice protection, engine starting).

“Conventional” Philosophy (Cont.)

- Past and current turbofan and turbojet engines are capable of supplying SPS in two forms:
 - Shaft power is extracted from the engine’s high pressure shaft to drive a gearbox on which SPS components are mounted in addition to the engine’s fuel and oil pumps,
 - Hot, pressurized air is extracted from the engine’s compressors.

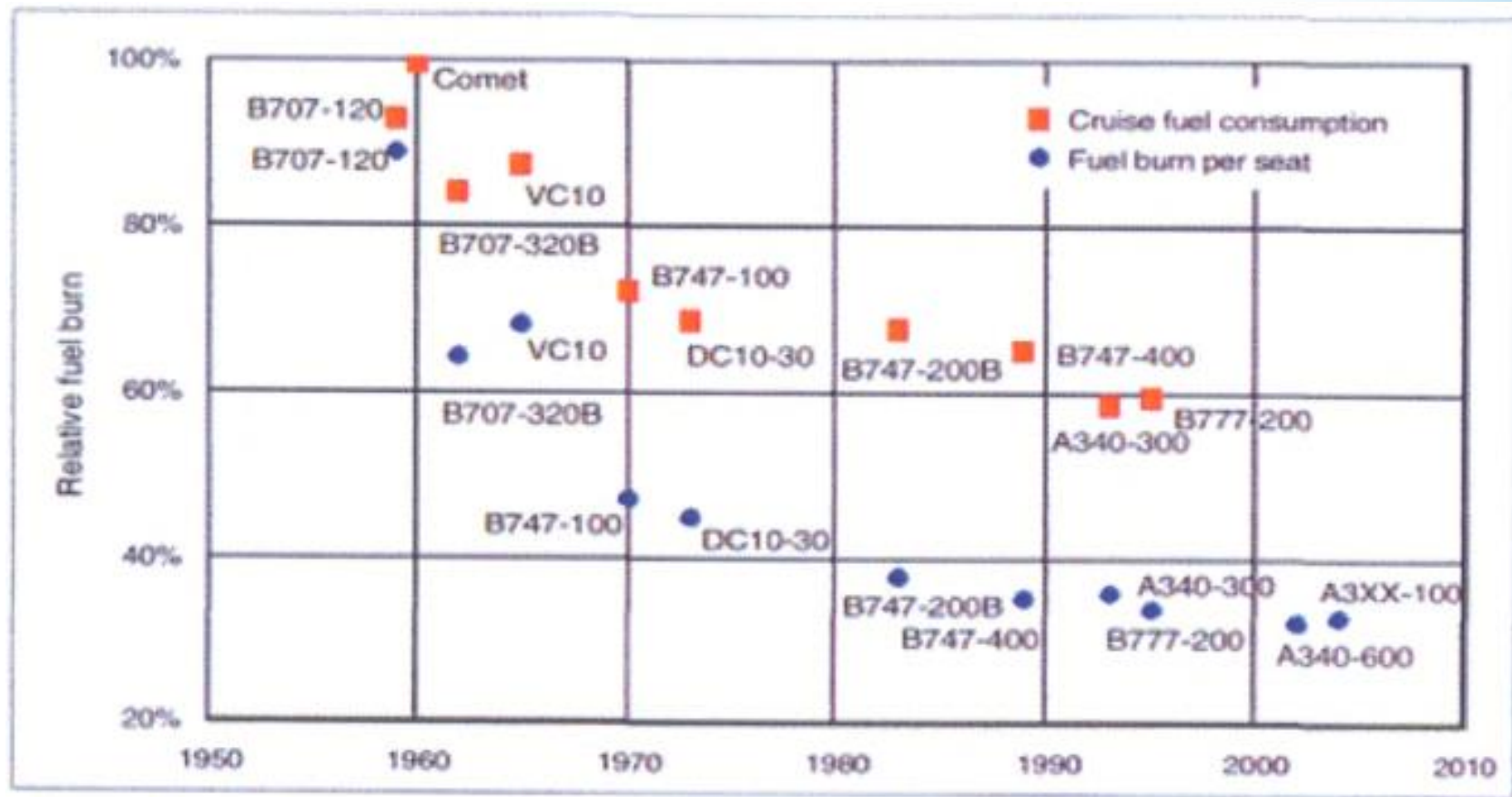
“Conventional” Philosophy (Cont.)

- Extraction and distribution of secondary power systems affect the design and performance of the engine:
 - Increase both complexity and weight,
 - Increase maintenance and operational costs,
 - Increase aircraft drag (profile and induced),
 - Increase turbine entry temperature (TET),
 - Increase sfc,
 - Reduce thrust.

“Conventional” Philosophy (Cont.)

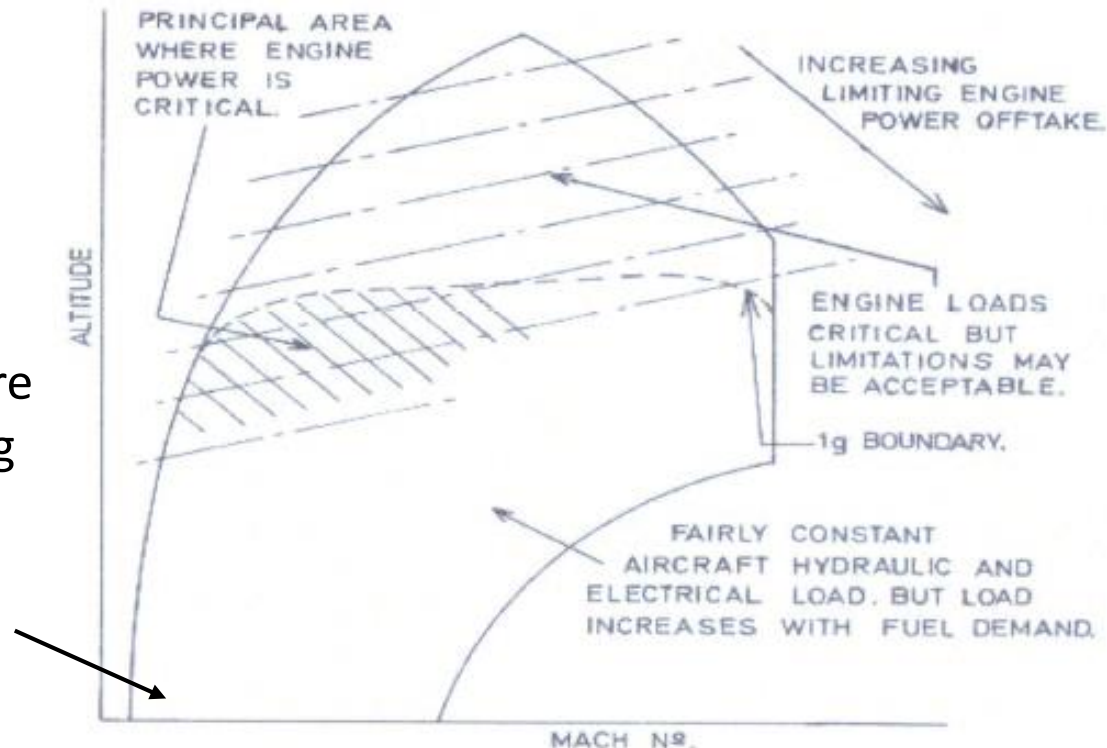
- Alternative secondary power sources while on ground and/or emergencies may include an auxiliary power unit (APU), ground connections and the use of ram air turbine (RAT).
- Bleeding air from the engine is largely inefficient and a large amount of power is wasted for no useful purpose. Hydraulic systems are often sized for loads that are small in duration thus increasing the mass and power requirements of the systems.
- Conventional secondary power systems were developed during the years that fuel was relatively inexpensive and flight envelope have not been optimized for maximum efficiency.

Aircraft Fuel Burn Reduction



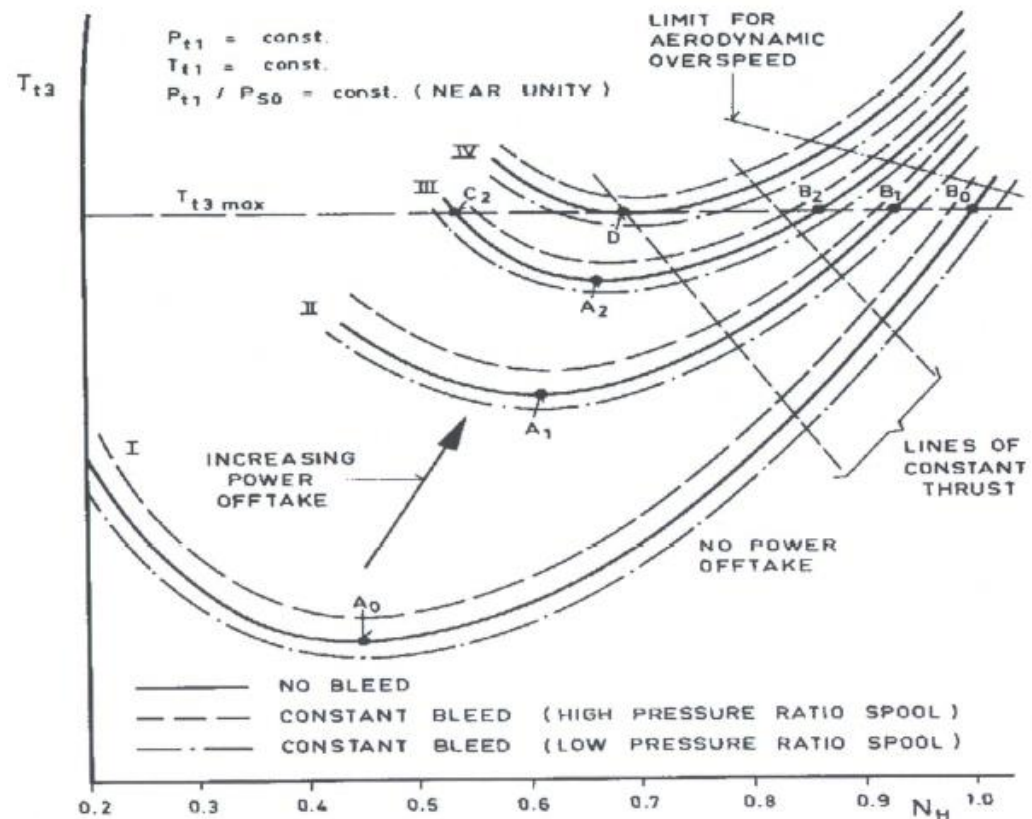
Effects of Takeoff on Aircraft Operational Characteristics

Area where large amount of hydraulics loads and bleeding air are required for small duration (landing gear, flaps, cabin and electronic equipment cooling)



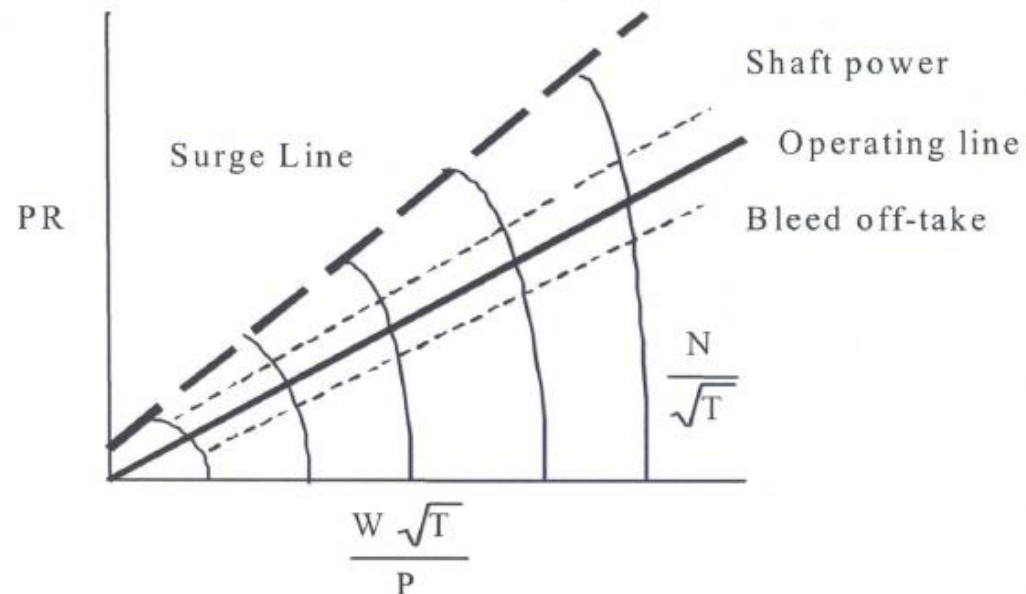
Effects of Takeoff on Turbine Entry Temperature (TET)

TET increases in proportion to the percentage of takeoff power relative to the total power within the core of the engine



Effects of Bleed Air and Shaft Power on Compressor Characteristics

- Taking bleed air from the compressor requires an increase in fuel flow and hence temperature.
- When shaft power is extracted the turbine has to deliver extra work at a given speed and this can occur by increasing TET.



“Electric Aircraft” Philosophy

- All electric aircraft (AEA) - Integration of all secondary power systems (SPS) into a single electric source. Present hydraulic and pneumatic actuation functions would be eliminated together with the extraction of bleed air for the supply of the environmental control and ice protection systems.
- More electric aircraft (MEA) - Majority of SPS would be electrically powered. However, present forms of hydraulic, mechanical or pneumatic power would be retained. Dedicated or localized hydraulic systems may be incorporated together with the extraction of bleed air.

“Electric Aircraft” Philosophy (Cont.)

- All electric engine (AEE) - Engine bleed air would be eliminated. Large generators would be mounted on the core of the engine to supply power to both engine and airframe accessories. Hydraulic systems could be retained, though the pumps would be electrically driven as opposed to the present system that utilizes mechanically driven pumps. The engine's oil system and accessory gearbox (AGB) would be eliminated and electromagnetic bearings would replace conventional bearings. Electric fuel pump and metering system provide only the required fuel flow. Electric actuators would be used for range of applications.

“Electric Aircraft” Philosophy (Cont.)

- More electric engine (MEE) - Large generators supply power to the majority of engine and airframe accessories. Accessories gearbox (AGB) could be retained or modified to accept the generators and/or some mechanically driven accessories. The oil systems could be reserved along with the conventional bearings.

“Electric Aircraft” Philosophy (Cont.)

- The all/more electric aircraft airframe systems consist of:
 - Electric wing ice protection,
 - Electric environmental control system (ECS),
 - Electric engine starting system,
 - Electric power distribution and management systems (power on demand),
 - Electro-mechanical actuators (EMAs), electro-hydrostatic actuators (EHA) / electrical backup hydraulic actuators (EBHAs)
 - Electric nitrogen-generation-system compressor used for fuel-tank inerting,

“Electric Aircraft” Philosophy (Cont.)

■ The all/more electric aircraft airframe systems consist of (cont.):

- Electric braking,
- Electro-mechanical thrust reversing actuation,
- Electro-mechanical variable stator vanes (VSVs) actuation,
- Electric fuel pump, metering and control system,
- Electric oil pump and scavenge system,
- Distributed engine control using deterministic CAN buses,
- Advanced diagnostics and prognostics.

“Electric Aircraft” Philosophy (Cont.)

- Adoption of a single form of secondary power systems and implementation of all or more electric technologies offers number of distinct advantages over conventional secondary power systems.
- Improved airframe systems utilization and implementation of more efficient power units.
- Reduced engine core size and an increase in engine bypass ratio, overall pressure ratio and the turbine inlet temperature, thus improving engine performance which lead to more efficient aircraft.

“Electric Aircraft” Philosophy (Cont.)

- Elimination of conventional hydraulic and bleed air systems leads to mass reduction. However, the mass and size of the electrical equipment would also increase and these changes must be accounted for.
- Studies evaluate that adoption of more electric technologies would introduce a small mass penalty. However, if the all electric concept is adopted, bleed air systems are eliminated and the conventional hydraulic systems are replaced by local electro-hydrostatic / electro-mechanical actuators, then the operating empty weight (OEW) for twin-engine wide-body aircraft (A330, B767) could be reduced by at least 0.5% and total fuel saving can reach 4.5%.

“Electric Aircraft” Philosophy (Cont.)

- Improved reliability and life cycle costs,
- Reduced maintenance,
- Adoption of all or more electric technologies will enable the designers:
 - to meet more severe takeoff requirements,
 - to enhance passenger comfort.

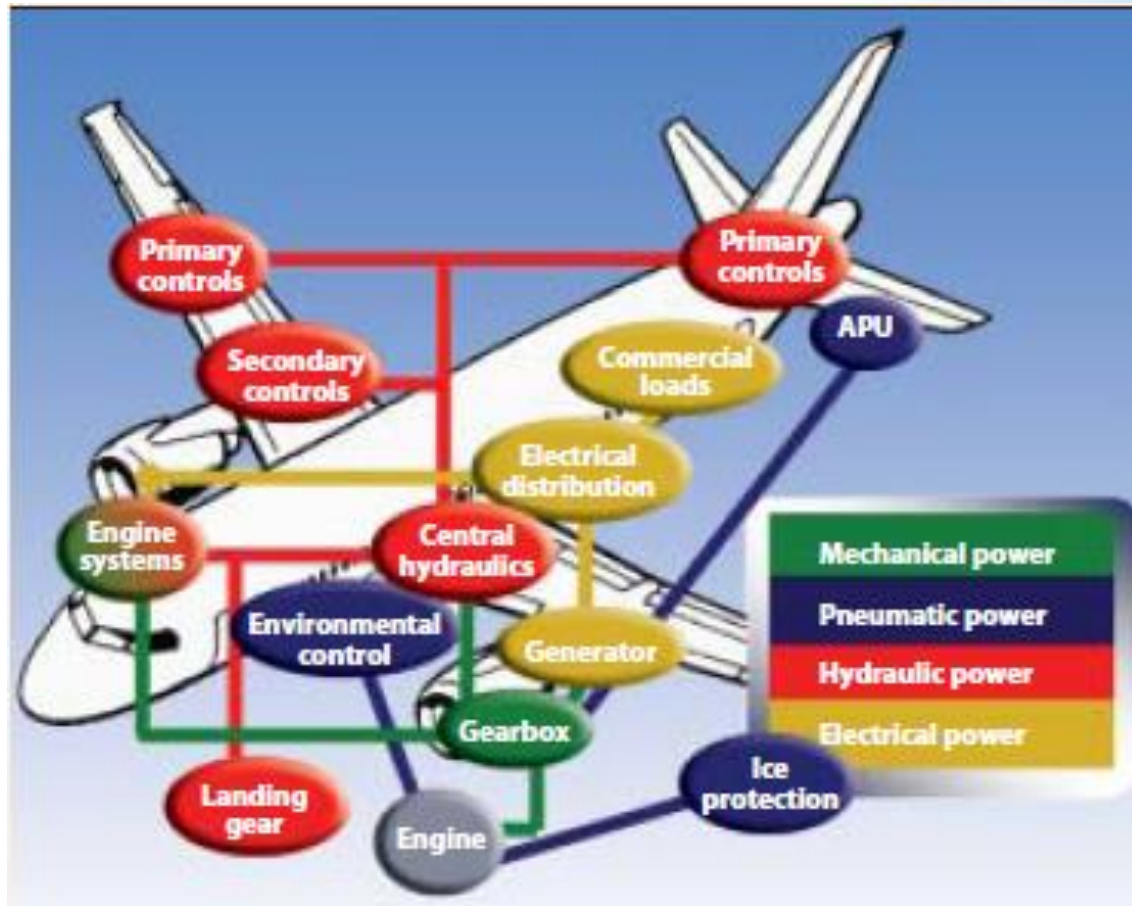
Environmental Control System Mass Changes for Electrically Driven Compressors

Electrically Driven System / Components	Twin Engine Wide-Body Aircraft (A330, B767)
Ground Hot Day / PR 5:1	2 x 250 KW
Added Generators	+150 Kg
Motors	+150 Kg
Controllers	+340 Kg
Compressors	+60 Kg
Removed (ducted, pre-cooler, air starting, etc.)	-603 Kg
Total	+97 Kg

“Electric Aircraft” Philosophy (Cont.)

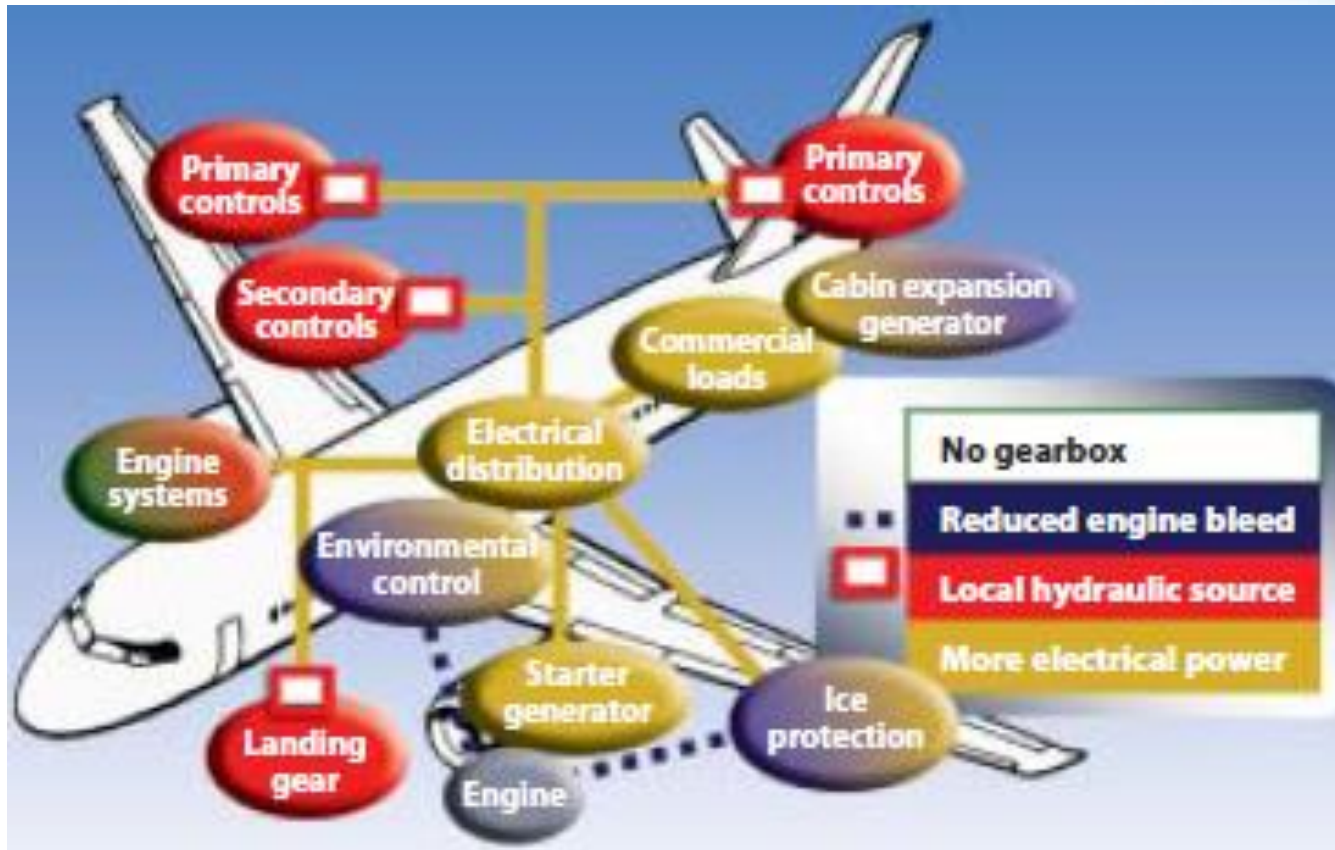
- Airframe electrical systems can be switched on and off as needed, resulting with “consequential effects”, thus conserving power. Adoption technologies of generation and distribution of variable voltage variable frequency (VVVF) would increase mass savings.
- The VVVF system power output varies with engine/generator rotational speed. The generators are designed to supply constant voltage to frequency ratio, thus improving the performance of electric motors and eliminating the need to use controllers.

Secondary Power Systems (SPS) Distribution



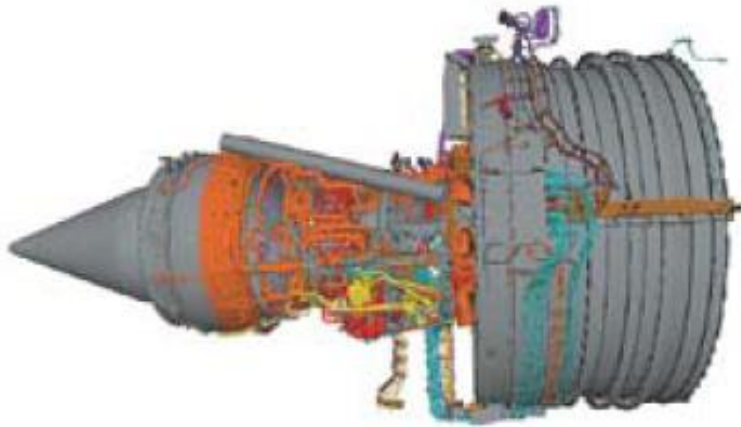
Conventional

Secondary Power Systems (SPS) Distribution (Cont.)

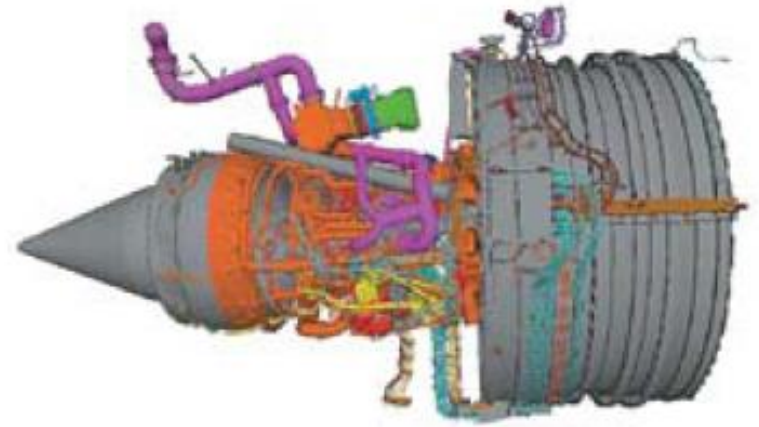


All/More Electric

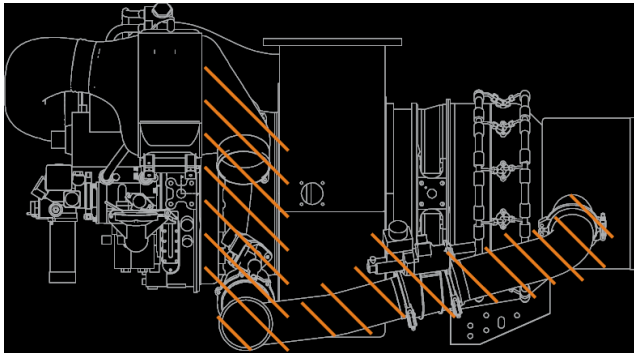
Conventional Vs. “Bleedless” Engine



More Electric Engine
(Bleed Ducting Removed)

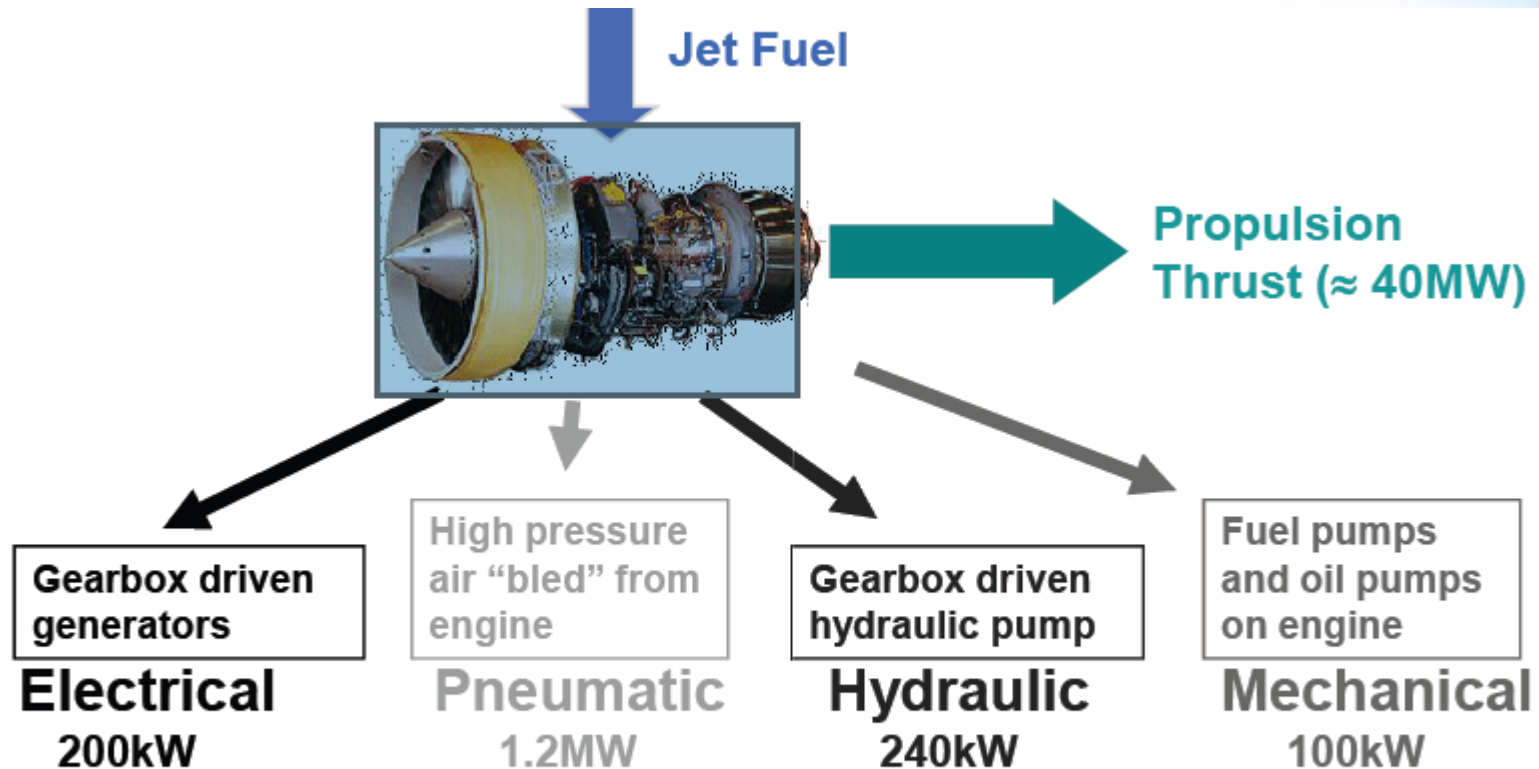


Conventional Engine
(Bleed Air for Airframe Systems)



APU pneumatic portions are eliminated in the “bleedless” architecture

Conventional Secondary Power Systems Distribution

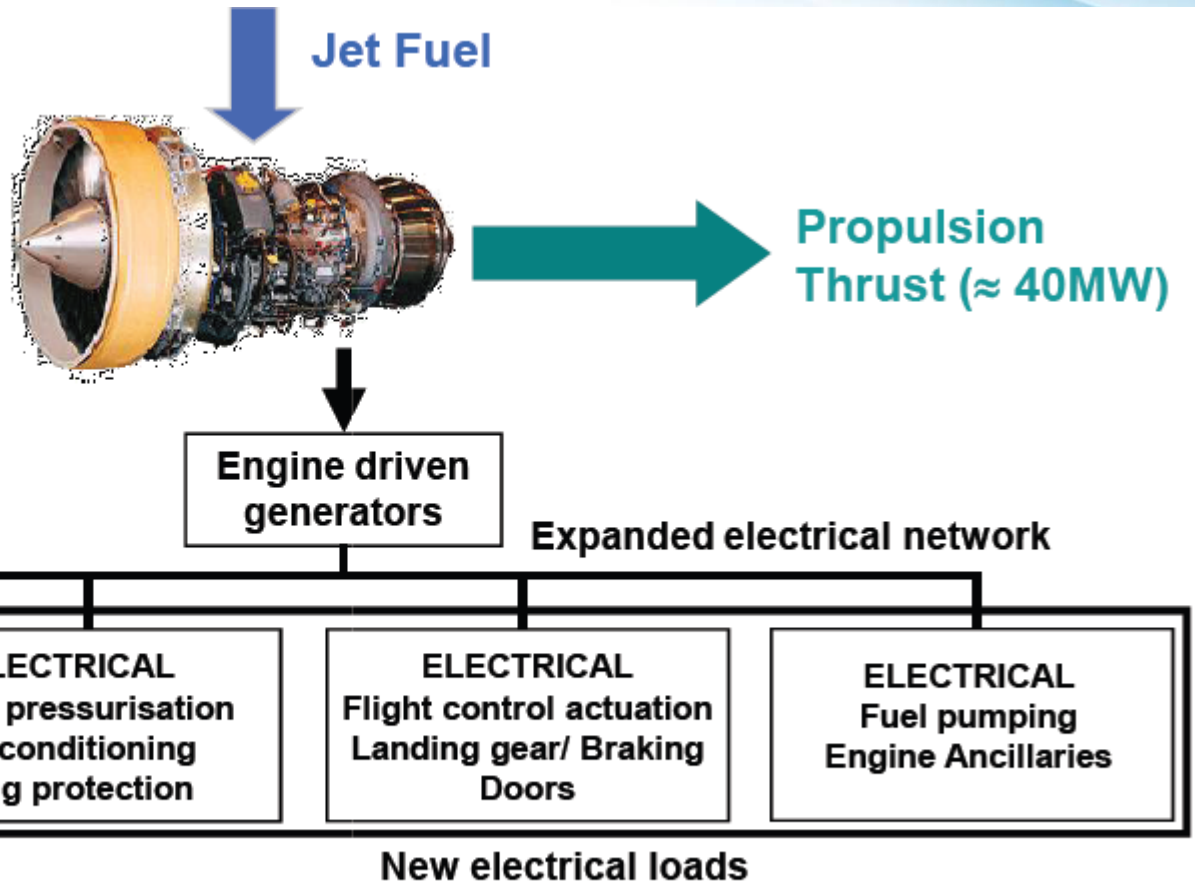


Total "non-thrust" power $\approx 1.7\text{MW}$ (4.25%)

All/More “Electric Aircraft” Architecture

Rationalisation of
power sources and
networks

“Bleedless” engine

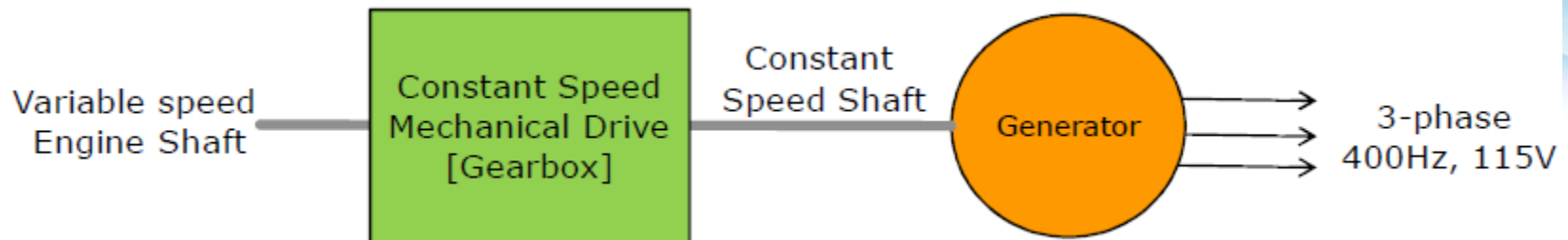


Electrical system power ≈ 1MW (2.5%)

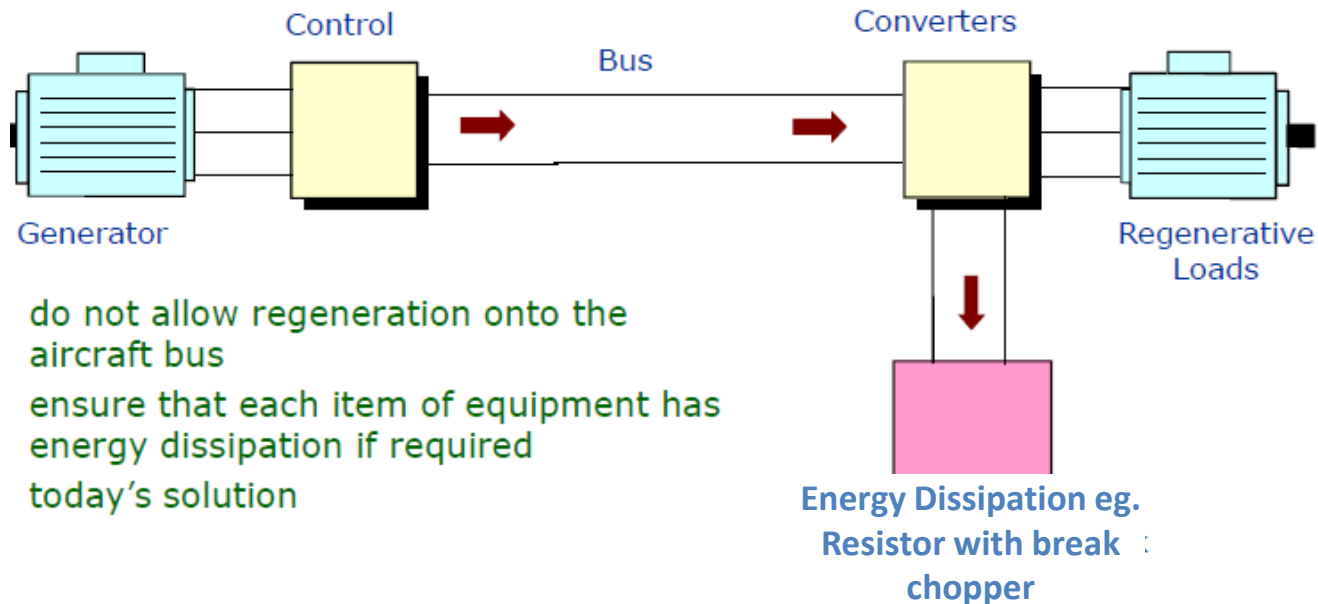
Typical Power Level of Electrical Loads

Power User	Comments	Typical Power Level
Air Conditioning	ECS	4 x 70 kW+
Flight Controls	Primary & Secondary	3 kW to 40 kW short duration at high loads
Fuel Pumps		About 10 kW
Wing Ice Protection	Thermal mats or similar	250 kW+
Landing Gear	Retraction, steering and braking	25 kW to 70 kW short duration
Engine Starting	May be used for additional applications	200 kW+ Short duration

AC Power Generation & Regenerative Energy Management

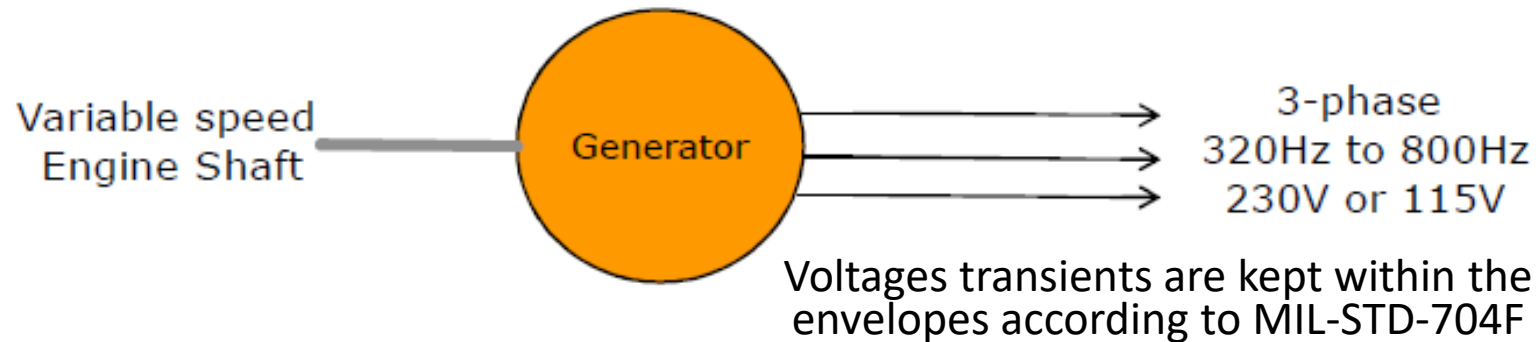


Conventional Mechanical Constant Frequency Generator



Local Energy Dissipation

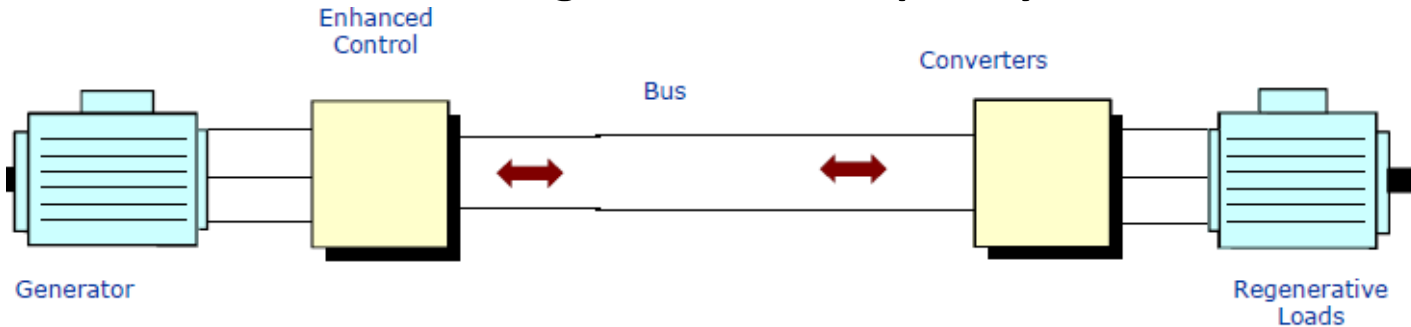
AC Power Generation & Regenerative Energy Management (Cont.)



New Aircraft Variable Voltage Variable Frequency Generation



**130 kW / 200 kVA
Starter-Generator**



allow regeneration onto the aircraft bus
use the generator as a motor if required
the regenerative power would be returned to the engine inertia
only possible if there is no auxiliary gearbox

Return Energy to Source

Mass Changed for Variable Voltage Variable Frequency (VVVF) System vs. ones of Constant Speed System

Equipment	All Electric Aircraft	More Electric Engine
ECS Removed		
Ducts, Precooler, Valves, etc	-293 Kg	-293 Kg
ECS Added		
4 Compressors	+104 Kg	+104 Kg
4*155KW Motors (0.3-0.5 Kg/KW)	+186 Kg (+310Kg)	+186 Kg (+310Kg)
Power Generation Removed		
4*75 KVA IDG (0.5-1 kg/KW)	-150 Kg (-300Kg)	-150 Kg (-300Kg)
APU Gen 125KVA (0.27 Kg/KVA)	-32 Kg	-32 Kg
Power Generation Added		
4*250 KVA IDG	+500 Kg (+1000Kg)	+500 Kg (+1000Kg)
2*180 KVA APU Generators	+97 Kg	+97 Kg
Elimination of Hydraulics		
Net Mass Saving	-750 Kg	
Electro Impulse De-Icing		
4*60 KVA Electric Hydraulic		-144 Kg
Pumps		
4 * 50 KVA Electric Fuel Pumps	+60 Kg (+100 Kg)	+72 Kg (+120 Kg)
Overall Mass Changes		
	-422Kg (+84)	+400 (+962 Kg)

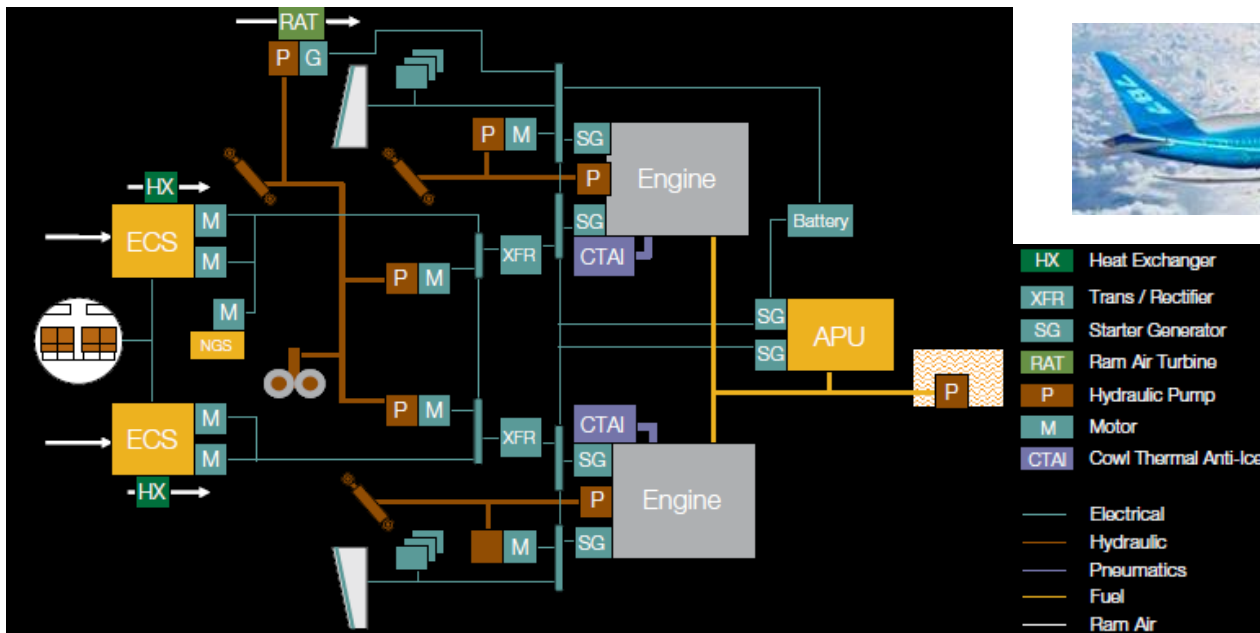
Mass Changes for a Constant Speed System

Equipment	All Electric Aircraft	More Electric Aircraft/Engine
ECS Removed		
Ducts, Precooler, Valves, air starting	-783 Kg	-783 Kg
ECS Added		
4 Compressors	+104 Kg	+104 Kg
4*155KVA Motors (0.3-0.5 Kg/KW)	+186 Kg (+310Kg)	+186 Kg (+310Kg)
4* 155 KVA Converters Controllers (0.68-1 Kg/KVA)	+421 Kg (+620 Kg)	+421 Kg (+620 Kg)
Power Generation Removed		
4*75 KVA IDG (0.5-1 kg/KW)	-150 Kg (-300Kg)	-150 Kg (-300Kg)
APU Gen 125KVA (0.27 Kg/KVA)	-32 Kg	-32 Kg
Power Generation Added		
4*200 KVA PMG (0.3 Kg/KVA)	+240 Kg	+240 Kg
2*180 KVA APU Generators	+97 Kg	+97 Kg
4*40 KVA 400Hz DC Link (0.68-1 Kg/KVA)	108 Kg (+160Kg)	108 Kg (+160Kg)
Elimination of Hydraulics		
Net Mass Saving	-750 Kg	
Electro Impulse De-Icing		
4*60 KVA Electric Hydraulic		-144 Kg
Pumps		
4 * 50 KVA Electric Fuel Pumps	+60 Kg (+100 Kg)	+72 Kg (+120 Kg)
Overall Mass Changes		
	-643 Kg (-346Kg)	+179 Kg (+492 Kg)

Mass Changes for a VVVF System

B787 “Bleedless” System Architecture

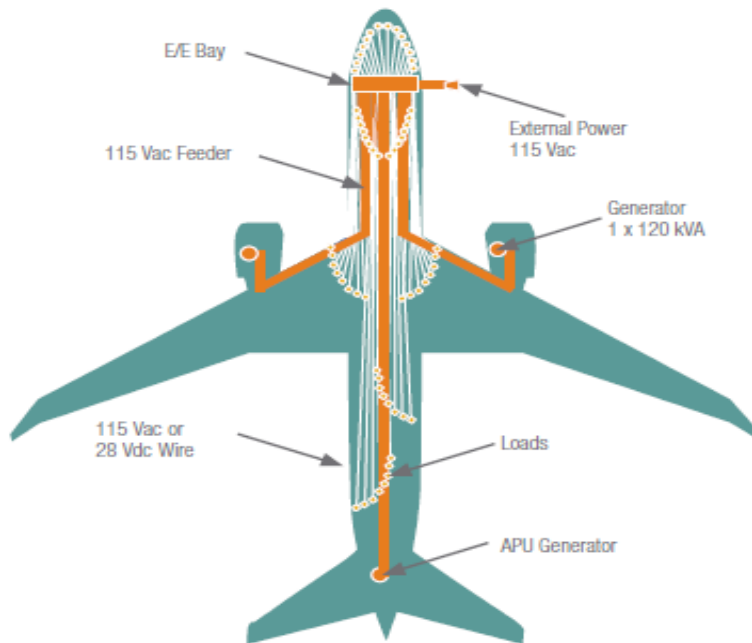
The 787’s “bleedless” systems architecture replaces the traditional pneumatic system and the bleed manifold with a high-power electrical system that, in addition to the traditional electrical system functions, supports a majority of the airplane functions that were traditionally performed via bleed air.



Airframe systems architecture accounts for fuel savings of 3%

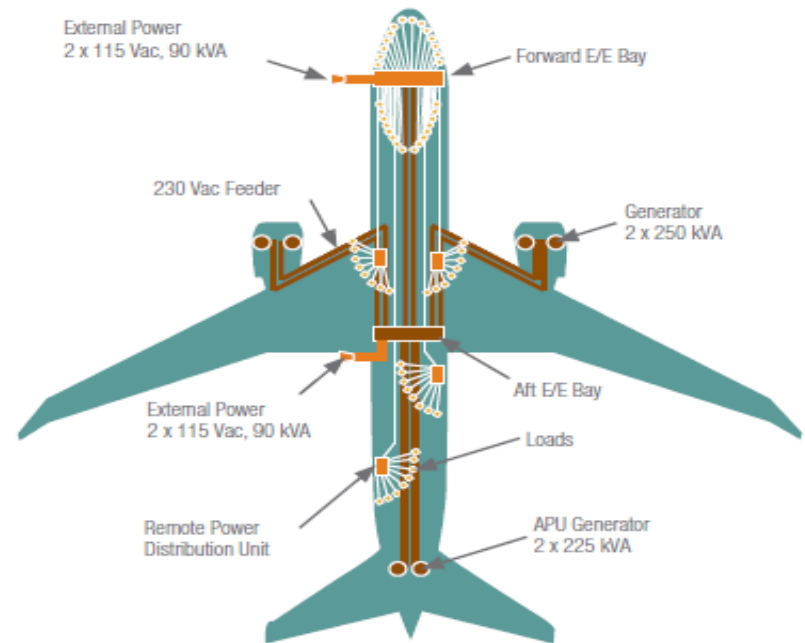
B787 Hybrid Electrical Power Distribution System

Conventional (B767)



Centralized distribution:
circuit breakers, relays
and contactors

B787



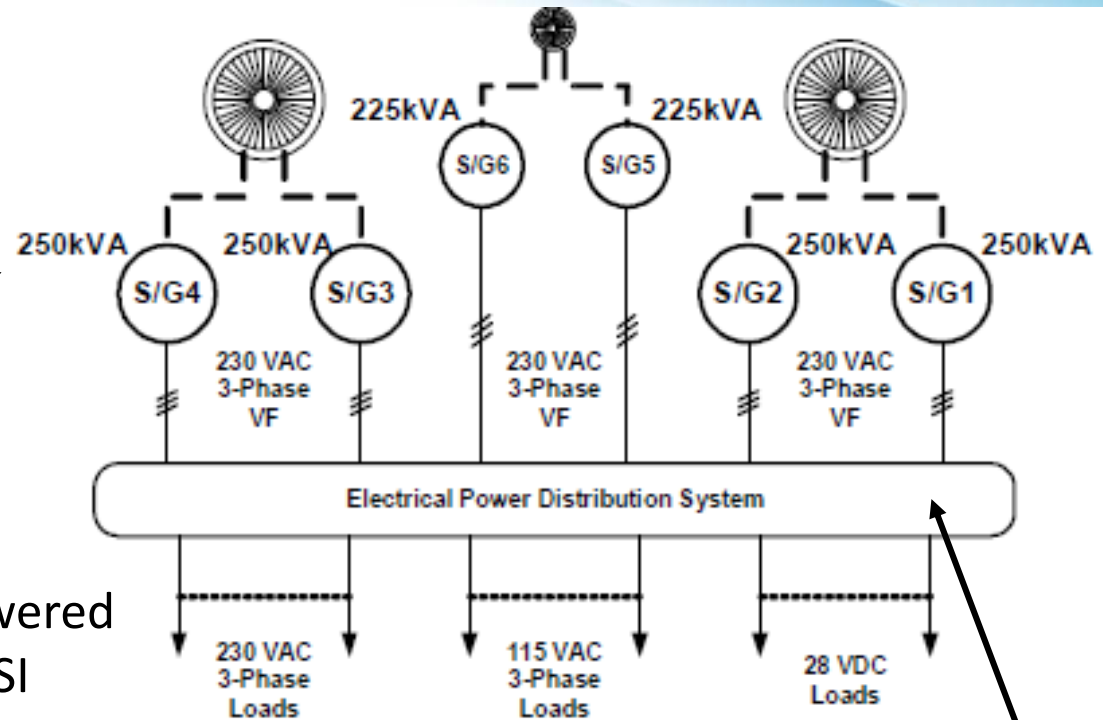
Remote distribution:
solid-state power controllers
and contactors

B787 Hybrid Electrical Power Distribution System (Cont.)

The level of power of the B787 ram air turbine (RAT) has increased dramatically

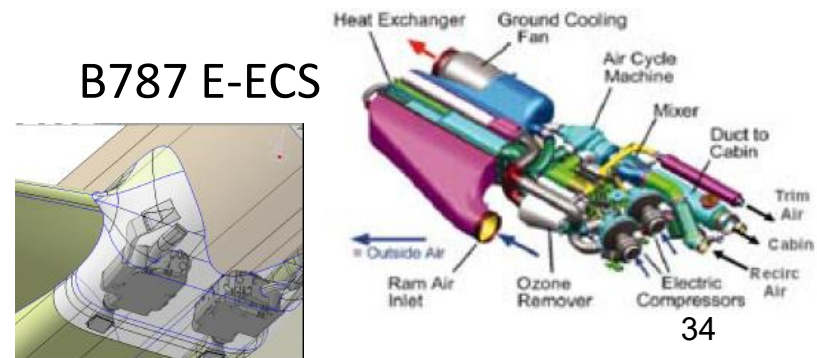
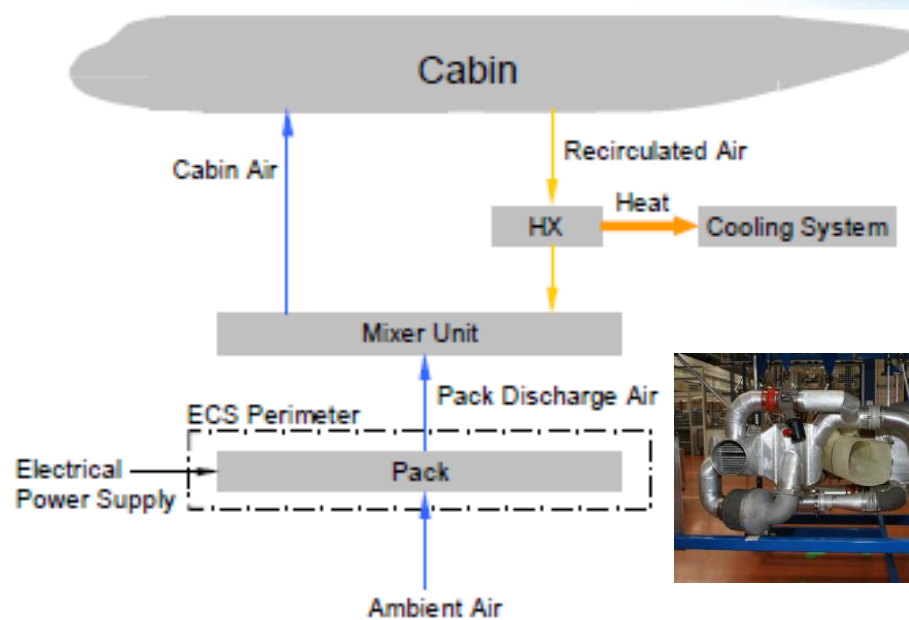
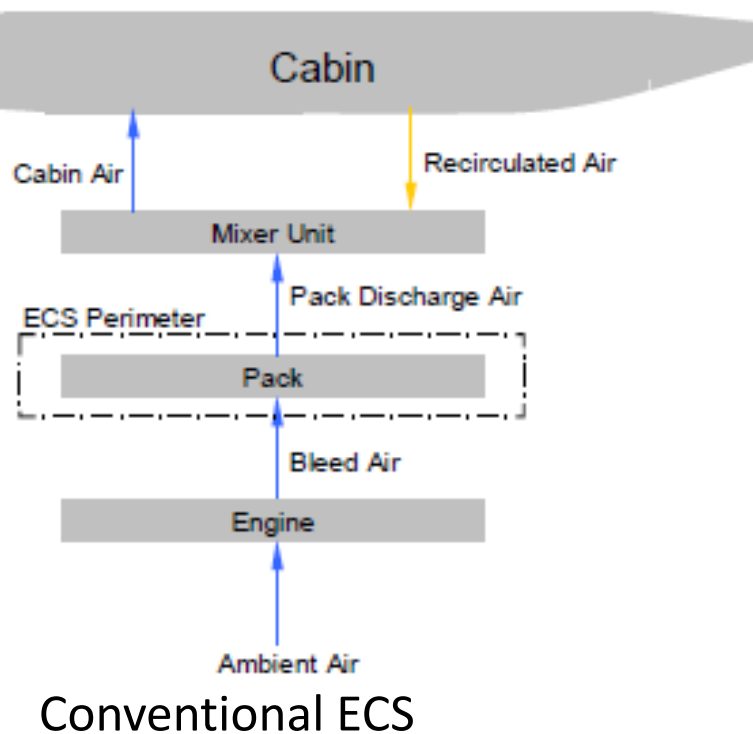
Compared with B767 single 90 to 120 kVA per engine

Center hydraulic system is powered by two large 30 GPM / 5000 PSI electric-motor driven hydraulic pumps (230 VAC), compared with B767 two 7 GPM / 3000 PSI electric-motor driven pumps + 37 GPM / 3000 PSI single air driven pump (ADP)



Expanded electrical system generating twice as much electricity than conventional aircraft

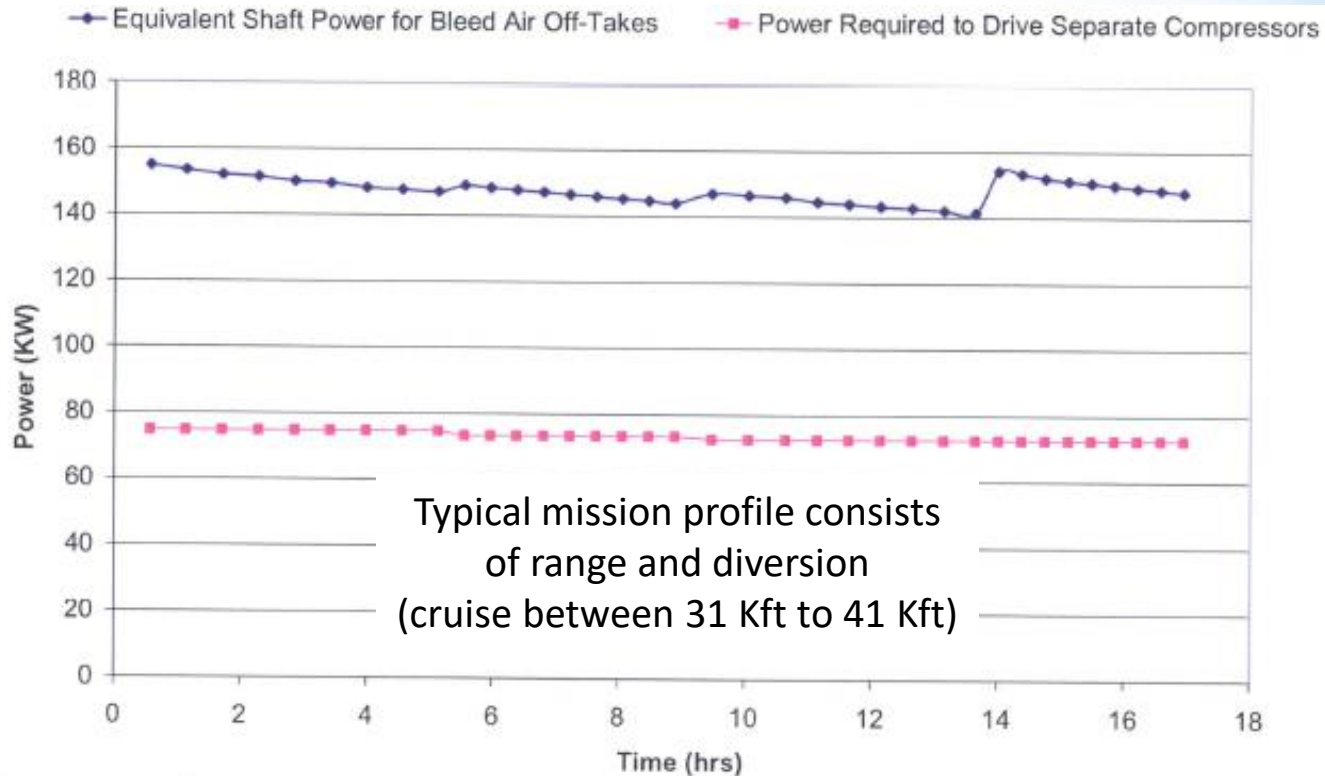
B787 Air Systems Design



Conventional Vs. Electric ECS

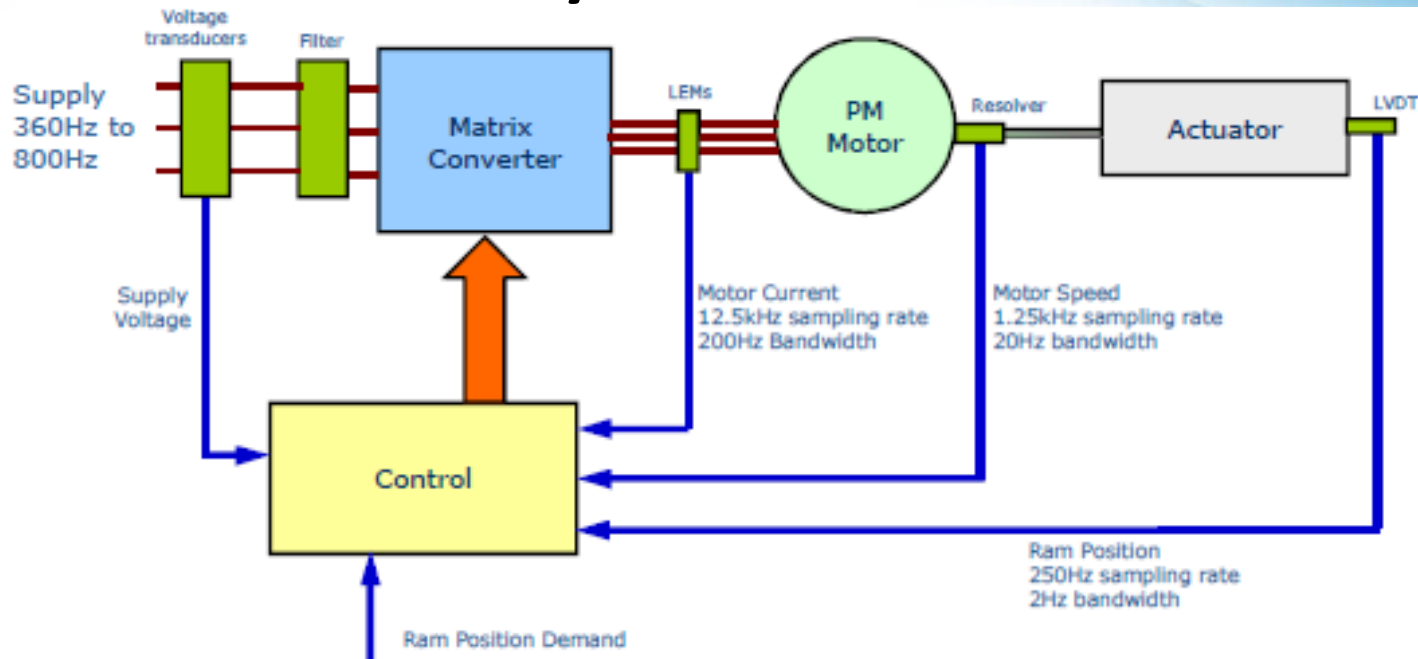
Conventional ECS	Electric ECS
Engine bleed air delivered at 30 PSI / 400 °F.	Electrical compressors delivered at 15 PSI / 200 °F determined by minimum temperature of ozone converter.
Air cooled by air conditioning pack [pri & sec HEx + Air Cycle Machine (ACM)].	Air cooled by air conditioning pack [pri & sec HEx + Air Cycle Machine (ACM)], requires greater ram air mass flow.
Cooled air enters cabin at 11.8 PSI / 60 °F. Much energy wasted as bleed air is delivered at excessive pressure and temperature.	Cooled air enters cabin at 11.8 PSI / 60 °F. System only delivers the necessary air - temperature limited by ozone converter characteristics. <u>Note</u> : ozone converters used only at Altitudes > xx,000 feet.
Physical interface with engine and potential for distributing air flow.	Reduced interface with engine.

Conventional Vs. Electric ECS (Cont.)



Power Required for the Operation of the ECS
for Twin-Engine Wide-Body Aircraft (A330, B767)

Actuation System



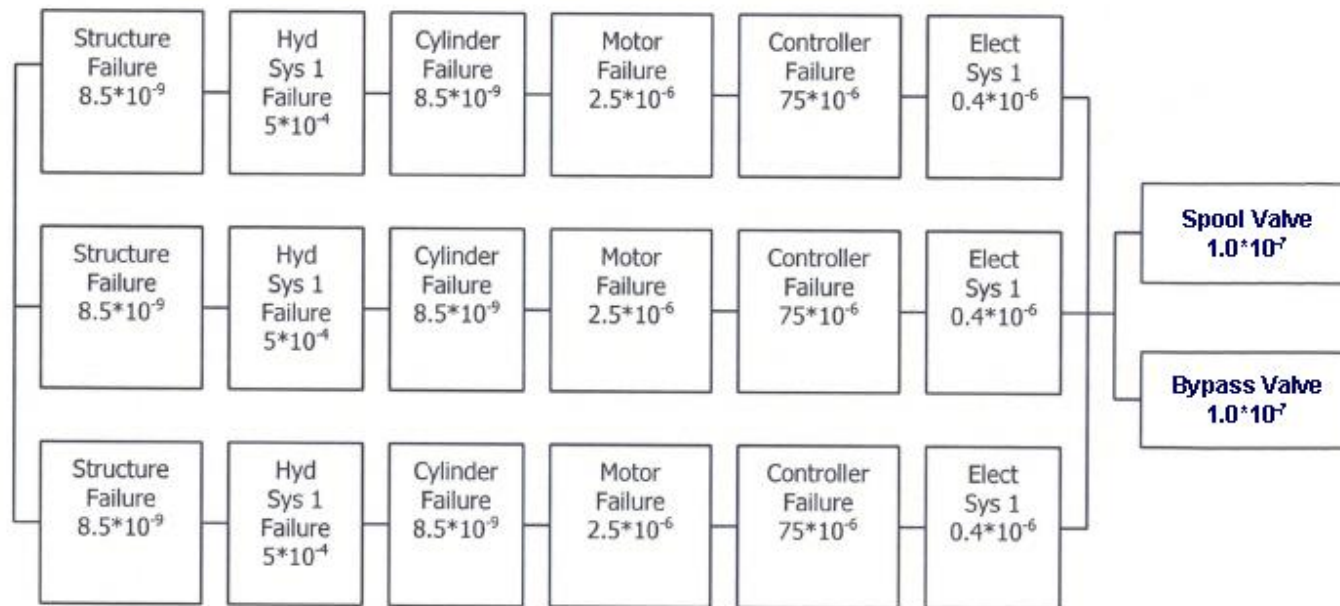
The four-engine A380 adopted the “2H + 2E” concept using EHAs and EBHAs. The twin-engine B787 adopted the three channel hydraulic system approach which is more conservative. Both aircraft utilize 5000 PSI hydraulic systems.



A380 Electro-Hydrostatic Actuator (EHA)

Unclassified

Reliability Block Diagram for Electro-Hydrostatic Primary Flight Control Actuation System



The additional components are the electric system power supply, the electric motors and the controllers. Twin-engine aircraft primary flight control actuation system reliability requirements of 1.00 E-9 / flight-hour, can be met by two separate electrical power systems out of three.

Impact of Aircraft and Engine Design on the AEA Concept Implication

The impact of the all or more electric technologies depends on the aircraft configuration, i.e.:

- Number of engines,
- Bypass ratio,
- Engine pressure ratio (PR),
- Turbine entry temperature (TET),
- Number of passengers,
- Aircraft range,
- Size of the aircraft.

Impact of Aircraft and Engine Design on the AEA Concept Implication (Cont.)

- In theory, fuel saving increases with number of passengers, aircraft range, engine bypass ratio and reduced number of engines. Significant decrease in specific fuel consumption is observed for long range high capacity aircraft.
- Twin-engine aircraft engines are oversized in order to correspond to the take-off conditions with one engine inoperative. At cruise conditions, the engines operate at significantly lower power setting and as a result the power extracted in the form of shaft power and bleed air, constitutes a larger percentage of power waste.

Impact of Aircraft and Engine Design on the AEA Concept Implication (Cont.)

- The elimination of shaft power and bleed air reduces the overall specific fuel consumption.
- For four engine all-electric aircraft, the engine can be sized accordingly to minimize the effect of takeoff, such an action becomes more difficult in the case of twin-engine aircraft.
- For flight safety, the design point of the electrical system would be the one engine inoperative condition and meeting 1309 regulations, which may lead to relative more generators and higher mass penalties in twin-engine aircraft than in four-engine aircraft.

Impact of the AEA Concept Implication on Aircraft Aerodynamic Efficiency

- Adoption of all electric technologies could reduce the operating empty weight of the aircraft and could lead to reduction in fuel load, thrust required, maximum takeoff weight, etc.
- Reductions in maximum aircraft take-off weight could reduce the wing area, which in turn could allow for reduced wing span and increased aspect ratio, thus improving the aerodynamic efficiency of the aircraft.

Impact of the AEA Concept Implication on Aircraft Aerodynamic Efficiency (Cont.)

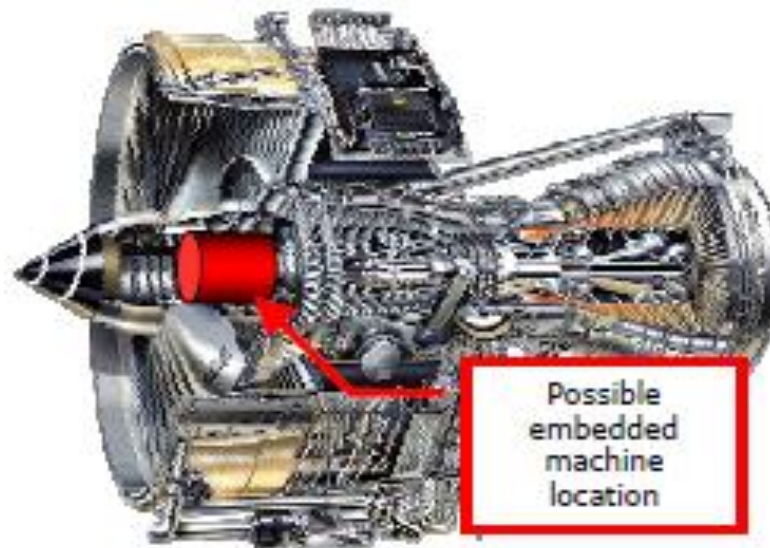
- Reductions in thrust requirements and turbine entry temperature could reduce jet velocity and noise as well as NO_x emissions.
- Reduced sfc, aircraft mass and improved aerodynamic efficiency would lead to reduced fuel consumption thus CO₂ emissions.

More Electric Engine (MEE)

- In addition to the More Electric and All Electric Aircraft (MEA/AEA) concept, there is another research direction towards satisfaction of the increasing demand for electrical power in the aircraft - More Electric Engine (MEE).
- A More Electric Engine takes the engine control elements of the engine, such as fuel pumping, oil pumping and engine actuation that are conventionally powered through mechanical and/or fuelhydraulic means and converts them to electrically powered operation.
- In spite of obvious benefits of the MEE it is still under investigation since MEE implementation meets a lot of problems.

More Electric Engine (MEE) Challenges

Embedded generator

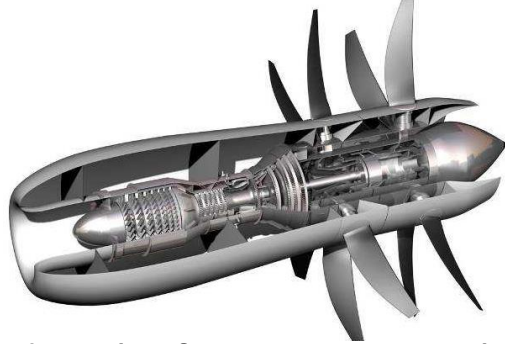


The embedded electrical machine and associated control provide electrical generation capabilities and the engine start function via electrical means.

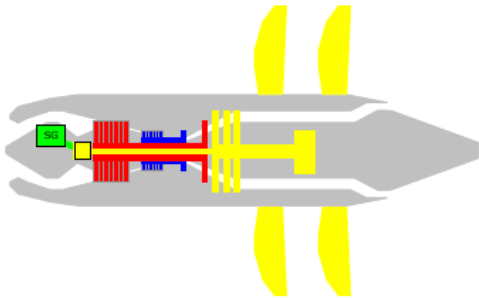
However, the embedded machine installation increases the engine length and consequential increase in drag due to nacelle length increase, as well as increase in engine weight due to additional bearing requirements and therefore would be detrimental to the overall efficiency.

More Electric Engine (MEE) Challenges (Cont.)

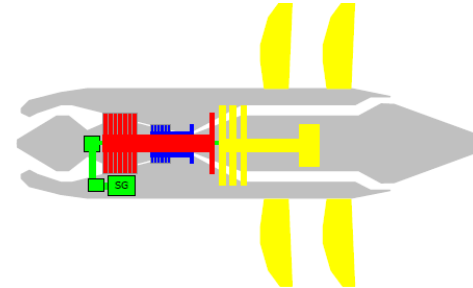
Open rotor engine or propfan



The propfan is a modified turbfan engine with the fan placed outside the engine nacelle on the same axis as the compressor blades. The design is intended to offer the speed and performance of a turbfan, with the fuel economy of a turboprop. Two main alternatives for starting and generating configurations.



Nose mounted - lack of space within the nose cone for electrical machine installation.



Radial shaft driven- complex clutching mechanism to allow connection to both Low power (LP) shaft (start) and free power (FP) shaft (generation).

IAI More “Electric Aircraft”

B737, B747, B767

IAI Bedek’s Freighter Conversions

- Replace main & lower cargo compartment smoke detection system “ducted” type (pneumatic) by electrical multi-criteria “open-air” ambient smoke detectors with CAN bus communication technologies.
- Pre and post conversion flight test procedures and results approved that aircraft aerodynamics performance remains unchanged.

B767-200ER

IAI Bedek’s Multi-Mission Tanker Transport (MMTT)

- Fly-by-wire (FBW) refueling boom ruddervator*
- Electric refueling boom hoist and telescope*

* Under development

IAI More “Electric Aircraft” (Cont.)

New Super Mid-Size Business Jet G250

- Digital fly-by-wire spoilers and rudder with electro-hydrostatic actuation.
- Digital auto brake-by-wire system.
- Superior cockpit avionics and instrumentation [Rockwell Collins ProLine Fusion Architecture (PlaneView250)].
- Improved cabin altitude pressurization system 7000 ft at FL450.
- Conventional Honeywell HTF7250 turbofan engine provides the required platform for the more electric airframe systems.