Johan Hellsing

2024-11-20

Innovations and safety implications of electrified aircraft

- Heart Aerospace and our mission
- The electric propulsion system
- Heart X1 propulsion system (EPS)
- Heart X2 propulsion system (EHPS)
- Certification of ES-30 and EHPS

Johan Hellsing

Chalmers - MSc in Electrical Engineering (1994)
Chalmers - Lic Eng in Electric Machine Design (1998)

Volvo Car Corporation (1998-2007)
Volvo Technology/Volvo Group (2007-2013)
CEVT/Geely (2013-2023)
Heart Aerospace (2023-)

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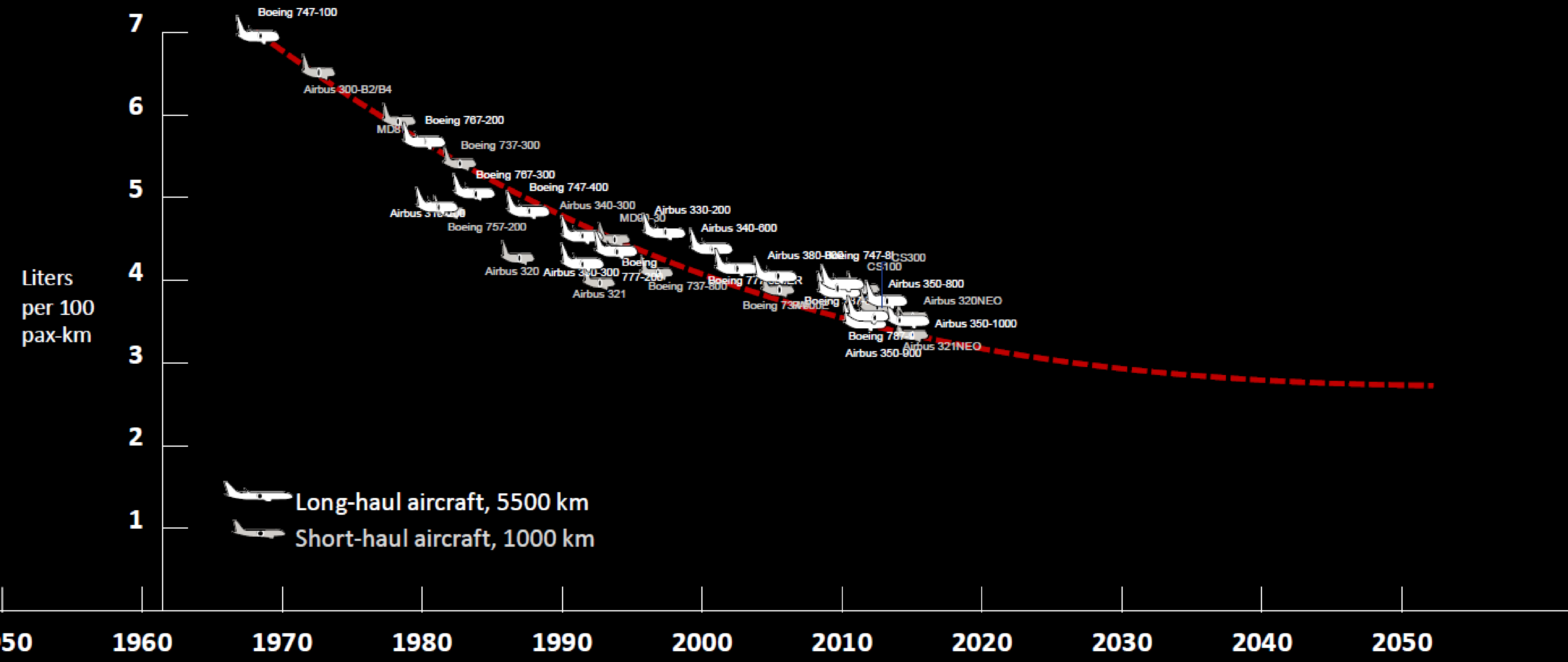
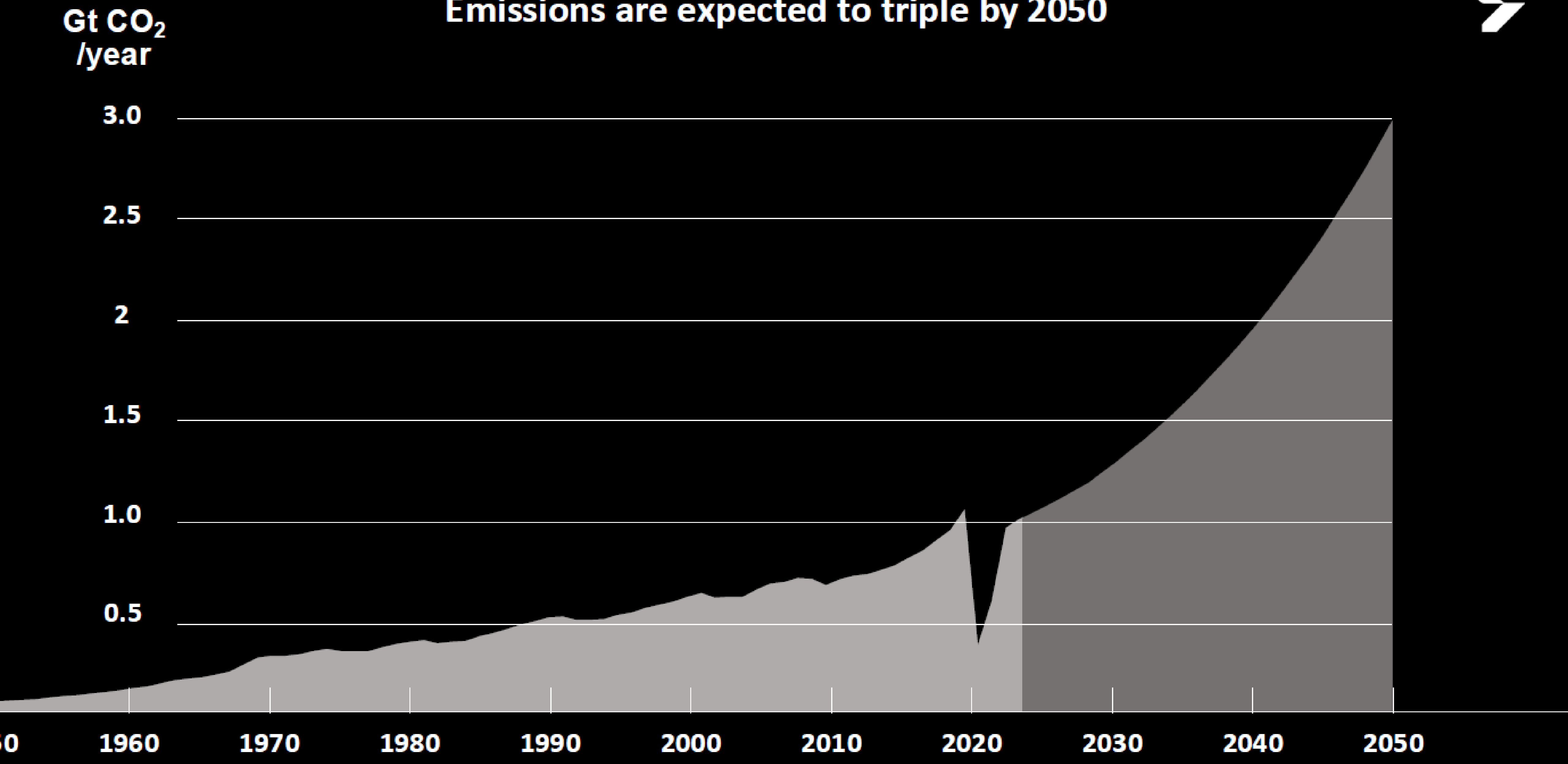
Today, jet engines can't be pushed much further



Emissions are expected to triple by 2050



A paradigm shift in aviation

Propulsion

Novel architectures to push propulsive efficiency further

Product development

New methodologies to reach market faster

Production

New facilities adapted to build next-gen aircraft at scale


Heart
Aerospace


Heart Aerospace
ES-30
30 passengers
25 kg luggage/ passenger
200 km all-electric range
800 km hybrid range (25 PAX)
1100 m runway length
30 min charge time

Sector Distance	CO_2 emissions reduction per seat ES-30 vs. ATR42
100 km	-100%
200 km	-98%
300 km	-69%
400 km	-53%
500 km	-42%
600 km	-33%
800 km	-22%

Certification Roadmap

Experimental			Conforming		
2024	2025	2026	2027	2028	2029

Heart X1

First Flight

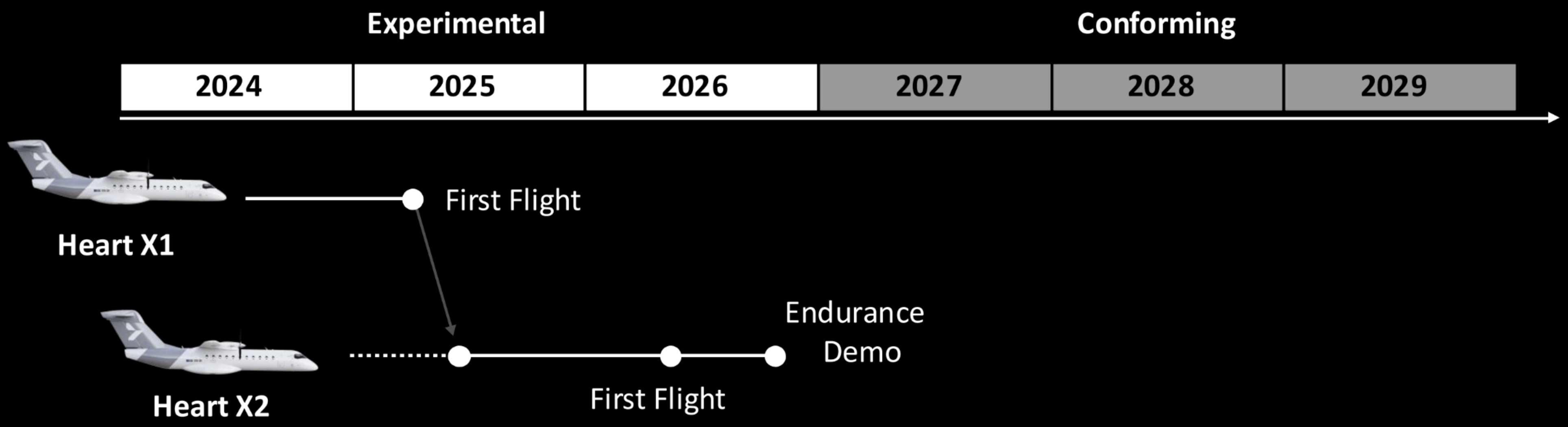
The Heart X1

On September 12, 2024, Heart Aerospace unveiled its first full-scale demonstrator airplane, the Heart X1.

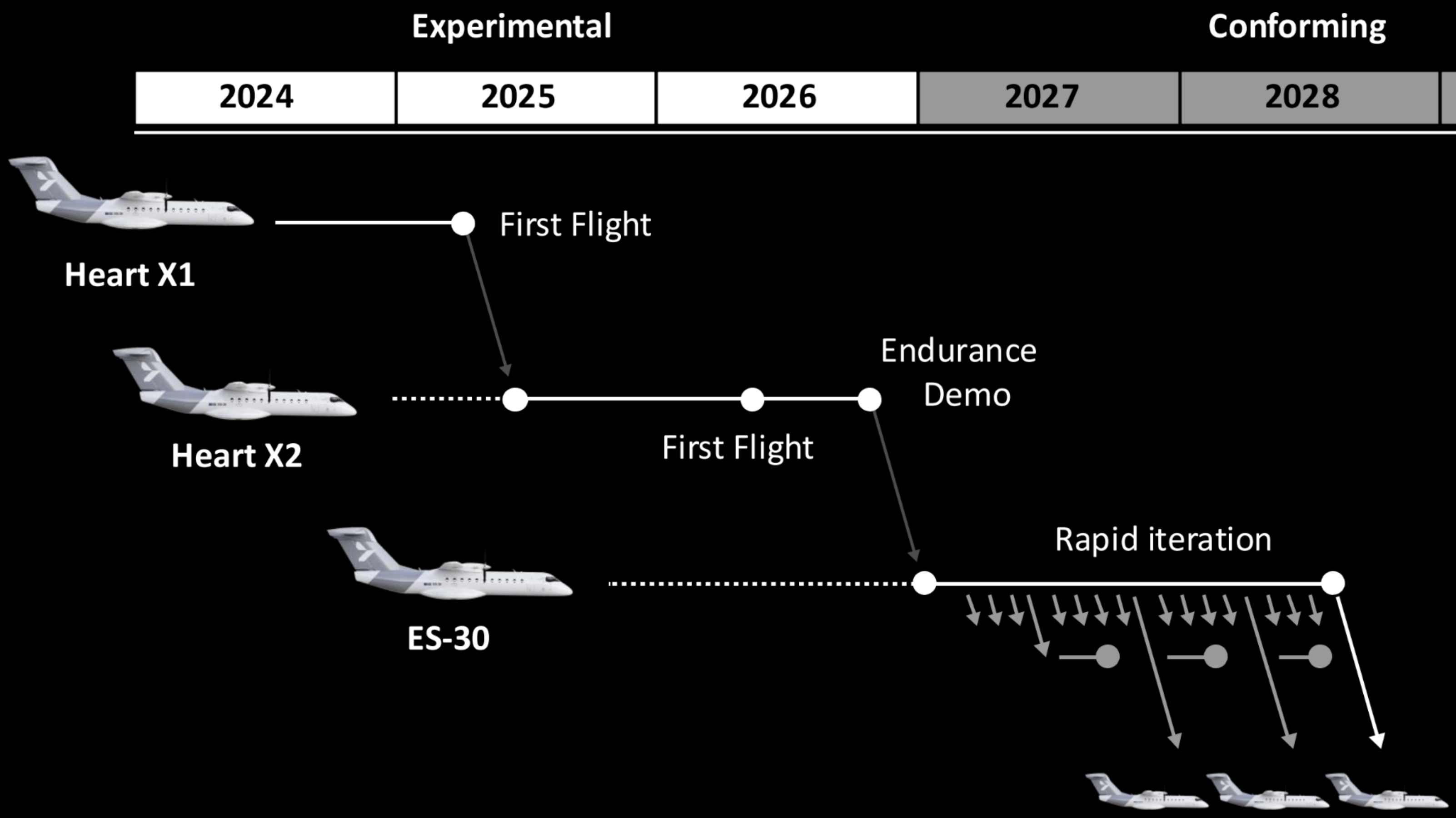
Listen to our CTO Ben Stabler describe why this is such a major milestone for the company and sustainable aviation

[Heart Aerospace, CTO Benjamin Stabler - Heart X1]

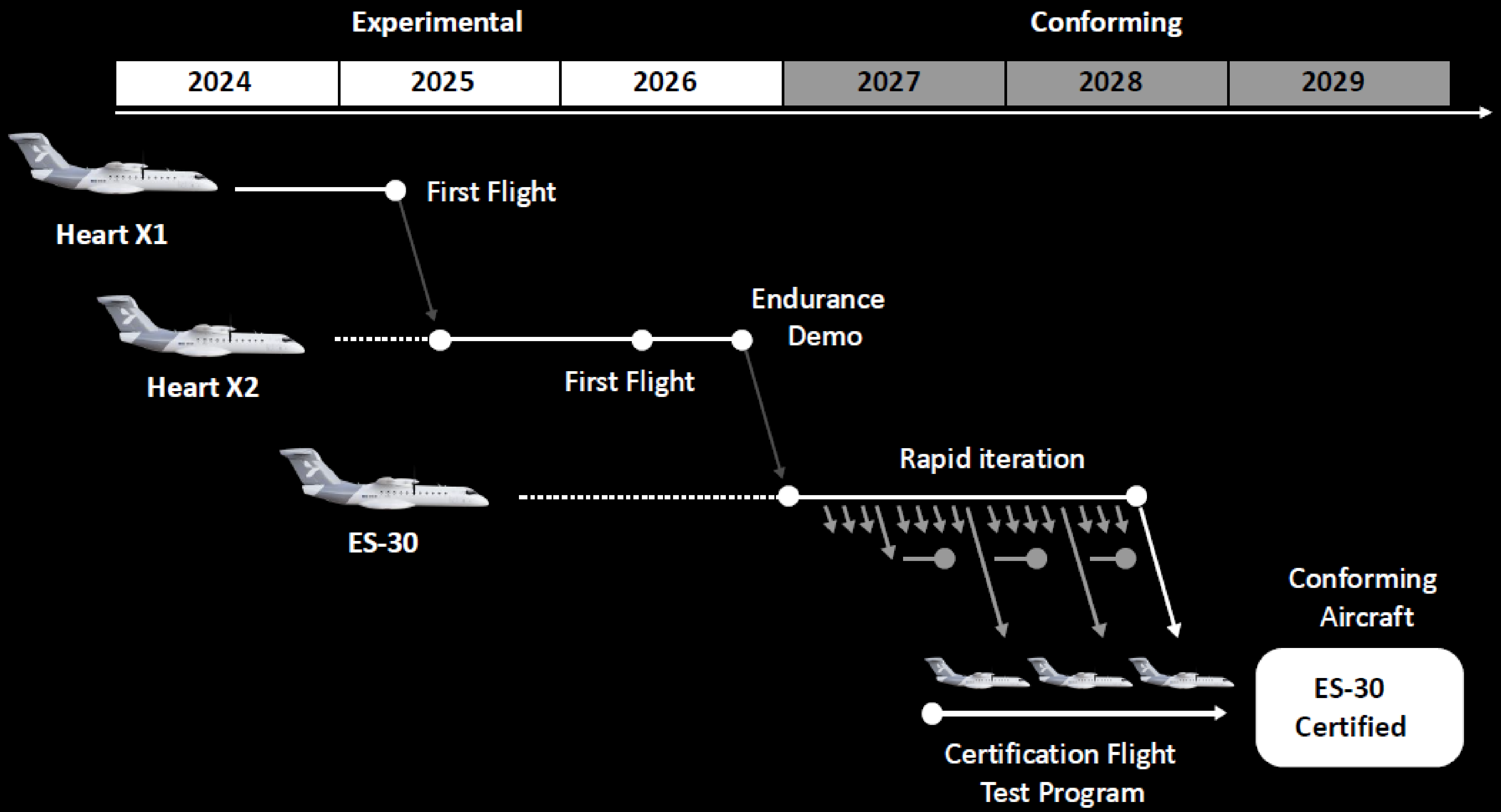
Certification Roadmap



Certification Roadmap



Certification Roadmap



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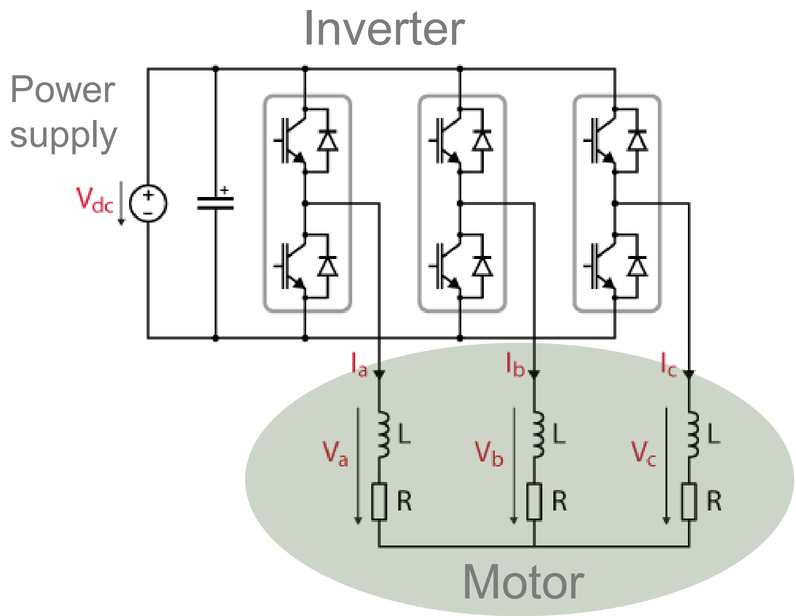
The electric propulsion system

- Operate in 4 quadrants (both directions of speed & torque)
  - Electric-to-mechanical – “motor” or “actuator”
  - Mechanical-to-electrical – “generator”
- Highly efficient (~90-95%)
- Torque at zero speed
- Require control of frequency and amplitude
- Performance limited by temperature/cooling

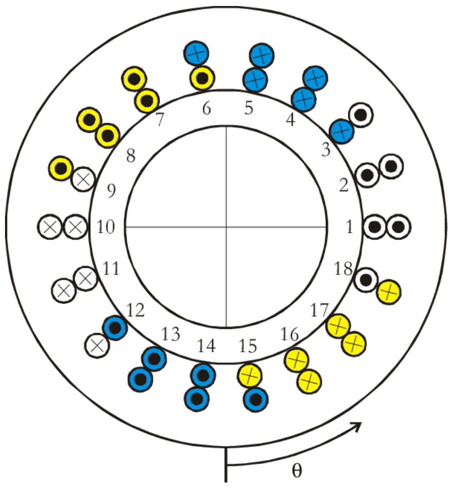
- Motor type PMSM dominate in the area of high-power actuators and vehicle traction
- Power transistor development ongoing
  - Si - IGBT → SiC - MOSFET

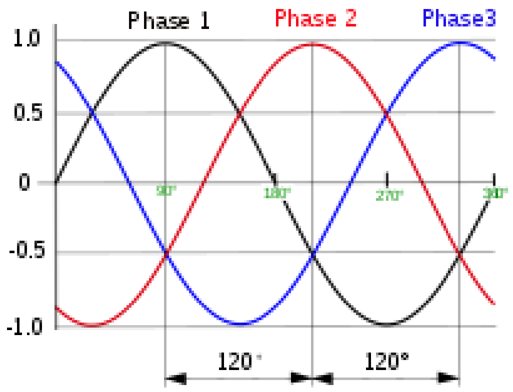
PMSM = Permanent Magnet Synchronuous Motor



Means of operation

- A single winding fed by alternating current (AC) will produce an <u>alternating</u> magnetic field
- A 3-phase winding fed by 3-phase alternating currents will produce a <u>rotating</u> magnetic field with constant amplitude
- A magnet will align with this rotating magnetic field and create the rotary motion

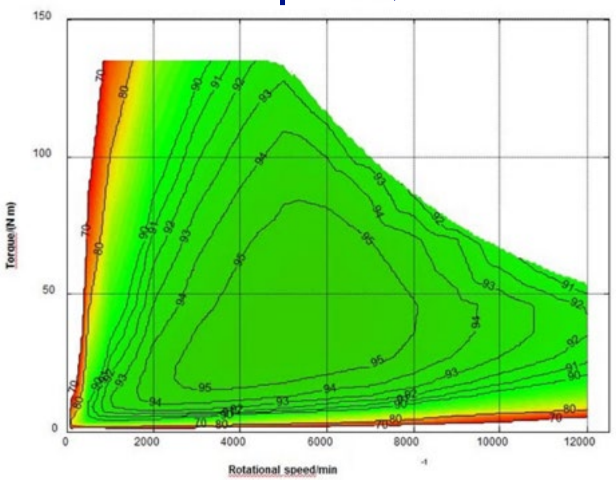




Field weakening operation to reach beyond ”knee”

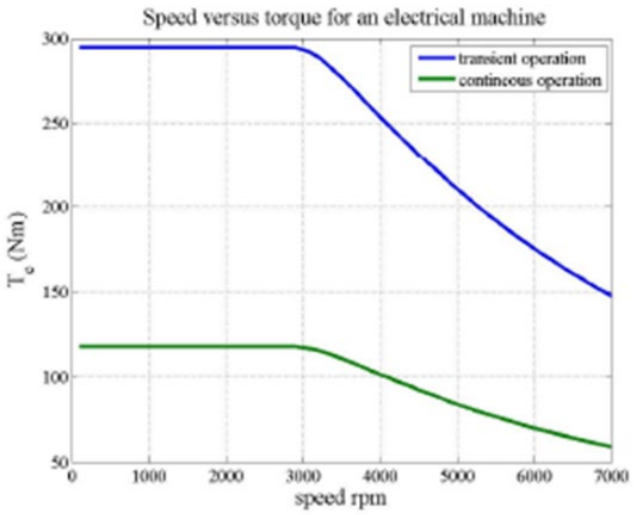
High efficiency in a large area

Similar efficiency in all 4 quadrants

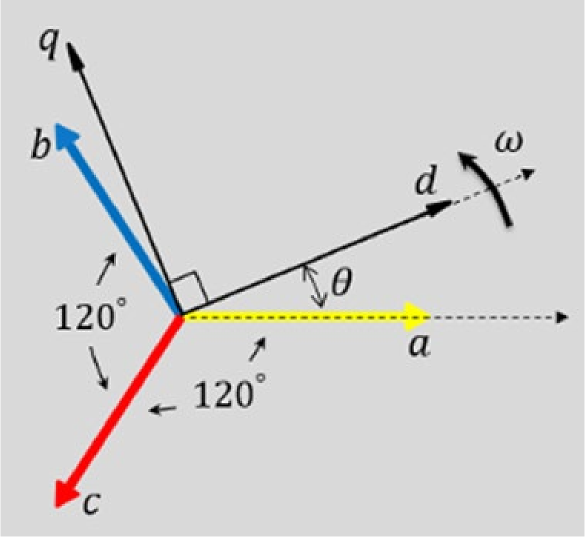


Transient performance limited by electromagnetic design

Continuous performance limited by heat rejection capability

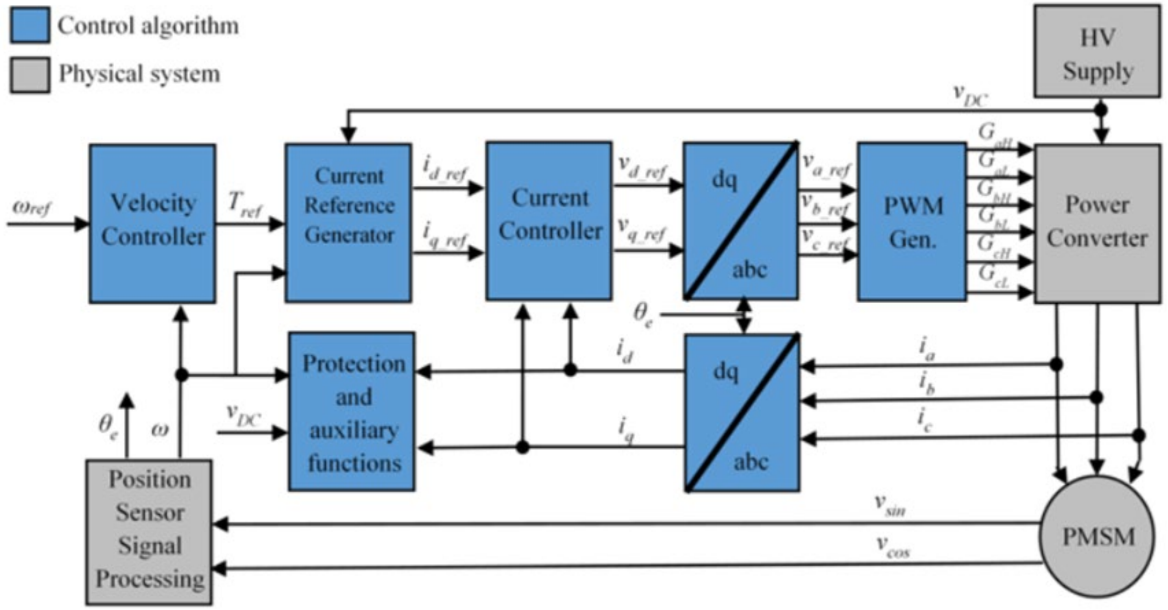


Field-oriented Control



MathWorks: "Field Oriented Control decouples torque and flux by transforming the stationary phase currents to a rotating frame aligned with the rotor magnetic poles. Use this control strategy when rotor speed and rotor position are known, and your application requires:

- High torque and low current at startup
- High efficiency"



Challenges for electric powertrains in aircrafts

ASCEND Program Description (35 M$ under ARPA-E within DOE):

The ASCEND program supports the development of innovative lightweight and ultra-efficient electric motors, drives, and associated thermal management systems (collectively referred to as the all-electric powertrain) that will help enable net-zero carbon emissions in 150-200 passenger commercial aircrafts. The ASCEND program sets a benchmark of the fully integrated all-electric powertrain system at a power density of ≥ 12 kW/kg* with an efficiency at ≥ 93%. Currently, these targets, among others, are beyond the capability of state-of-the-art technologies and will require creative thinking and innovation in the electric motor and power electronics space. The ASCEND performers will work in two phases:

1. Conceptual designs and computer simulations
2. Development, fabrication, and testing of an integrated sub-scale all- electric powertrain (≥ 250 kW)

It is anticipated that the developed lightweight and high efficiency all-electric powertrains will find direct application in the emerging urban air mobility, unmanned aircraft aerial vehicle, and selected regional aircraft markets.

* Continuous performance

Challenges for electric powertrains in aircrafts

Low weight/ High power density	ASCEND program propose 12 kW/kg (motor+inverter) We aim at 6 kW/kg and 40 Nm/kg – as we avoid a gearbox
High efficiency	ASCEND program propose 93% We aim at 96%, as battery weight has greater impact than motor weight
Safety/reliability	Loss of power may be accepted once during 100 million flight hours Partial loss of power may occur ”more often” Redundant inverters and stator windings are becoming standard Heart Aerospace avoid gearbox for reliability – not for weight
Environmental conditions	No performance impact related to altitude Lower breakdown voltage at higher altitude More atmospheric radiation at higher altitude Lower temperatures at higher altitude Immunity to HIRF (high-intensity radiated fields) and lightning

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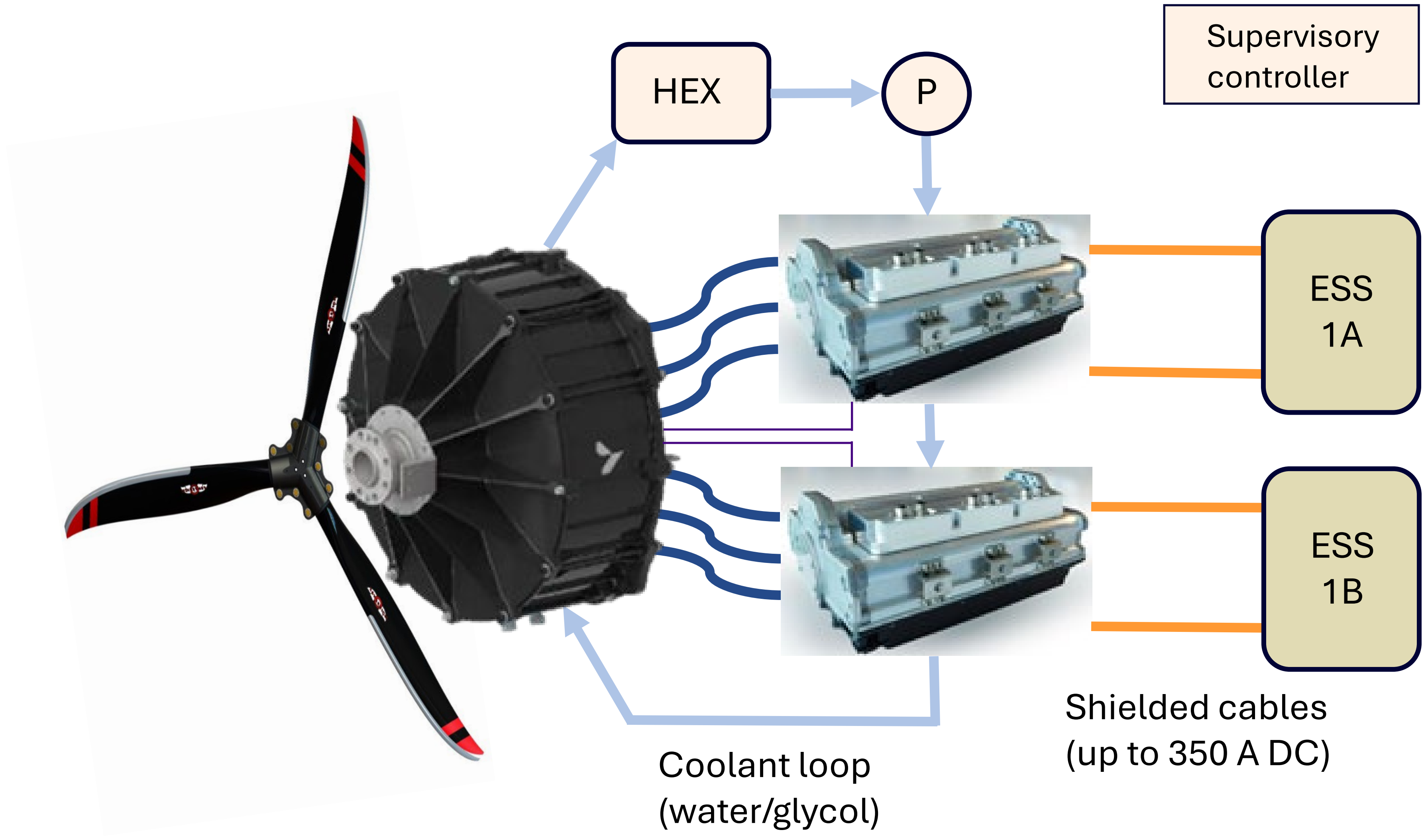
Heart X1 propulsion system (x4)



<u>Motor</u>
PMSM 400 kW
Dual 3-phase windings
64 poles
Speed 1800 rpm
Torque 2100 Nm

<u>Inverter</u>
Si IGBT, 600 A
300 A cont. AC current
Coolant temp 0-60°C

<u>Motor control</u>
CAN communication
Field-oriented Control
16 kHz PWM
Sensorless operation

<u>Energy Storage</u>
High Power Li-ion
720 V nominal
90 kWh per motor

Propulsion Control System requirements

Functional Requirement: The Control System shall, under normal conditions, provide complete and automatic control of the Electric Propulsion Unit, ensuring safe operation for all flight phases

- Motor acceleration/deacceleration
- Propeller speed tracking
- Ability to start and shutdown the motors independently
- Fault detection, monitoring and logging

Safety Requirement: The Control system shall detect and monitor/log:

- Degraded power loss due to inverters or motor.
- Loss of communication between the EPU and the supervisory controller
- Inverter/Motor overtemperature
- Uncommanded High Power/Thrust.

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Aviation Hybrid Architectures

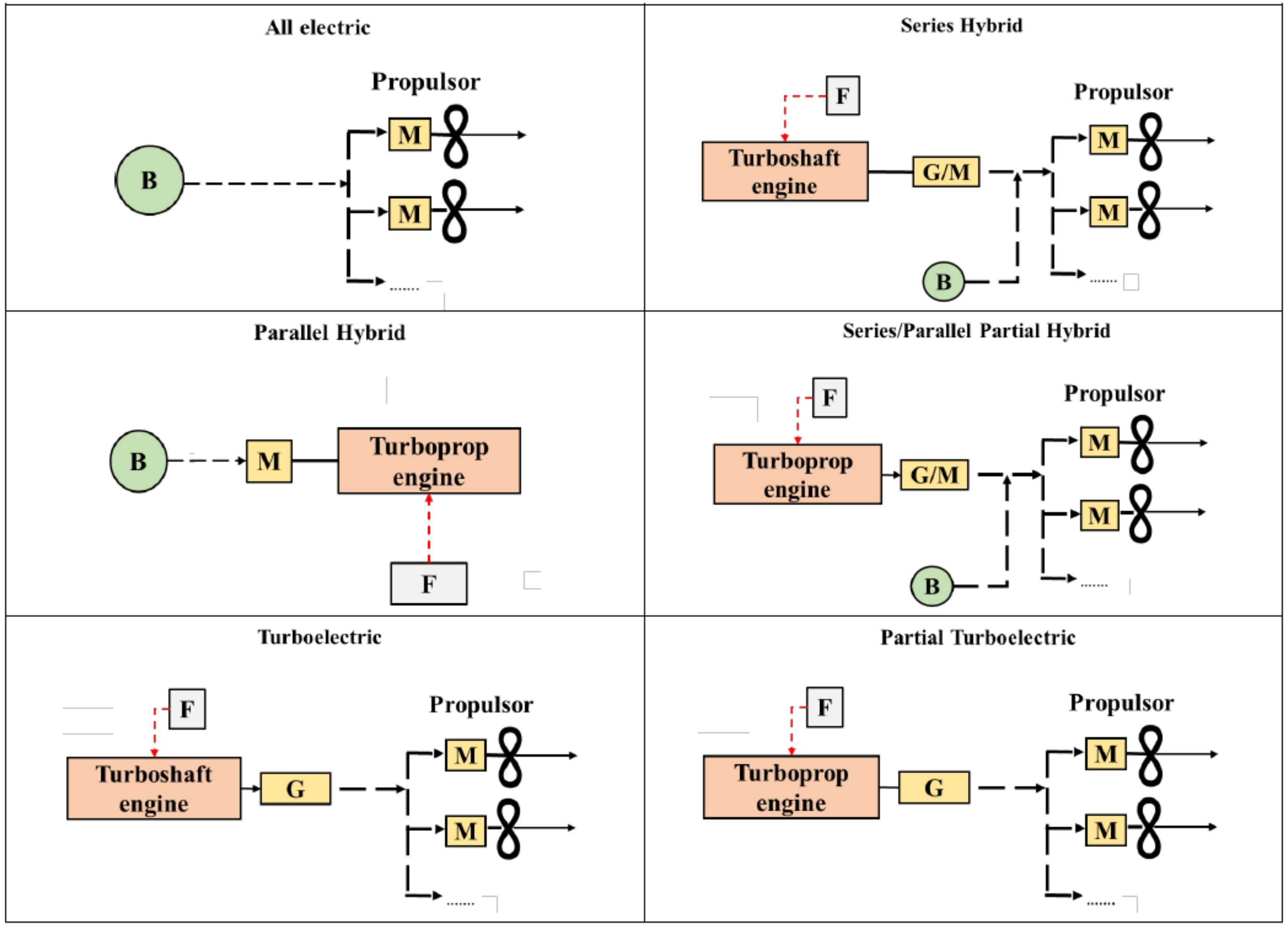


Figure 4. Electric propulsions architecture types (adapted from Felder, 2018).

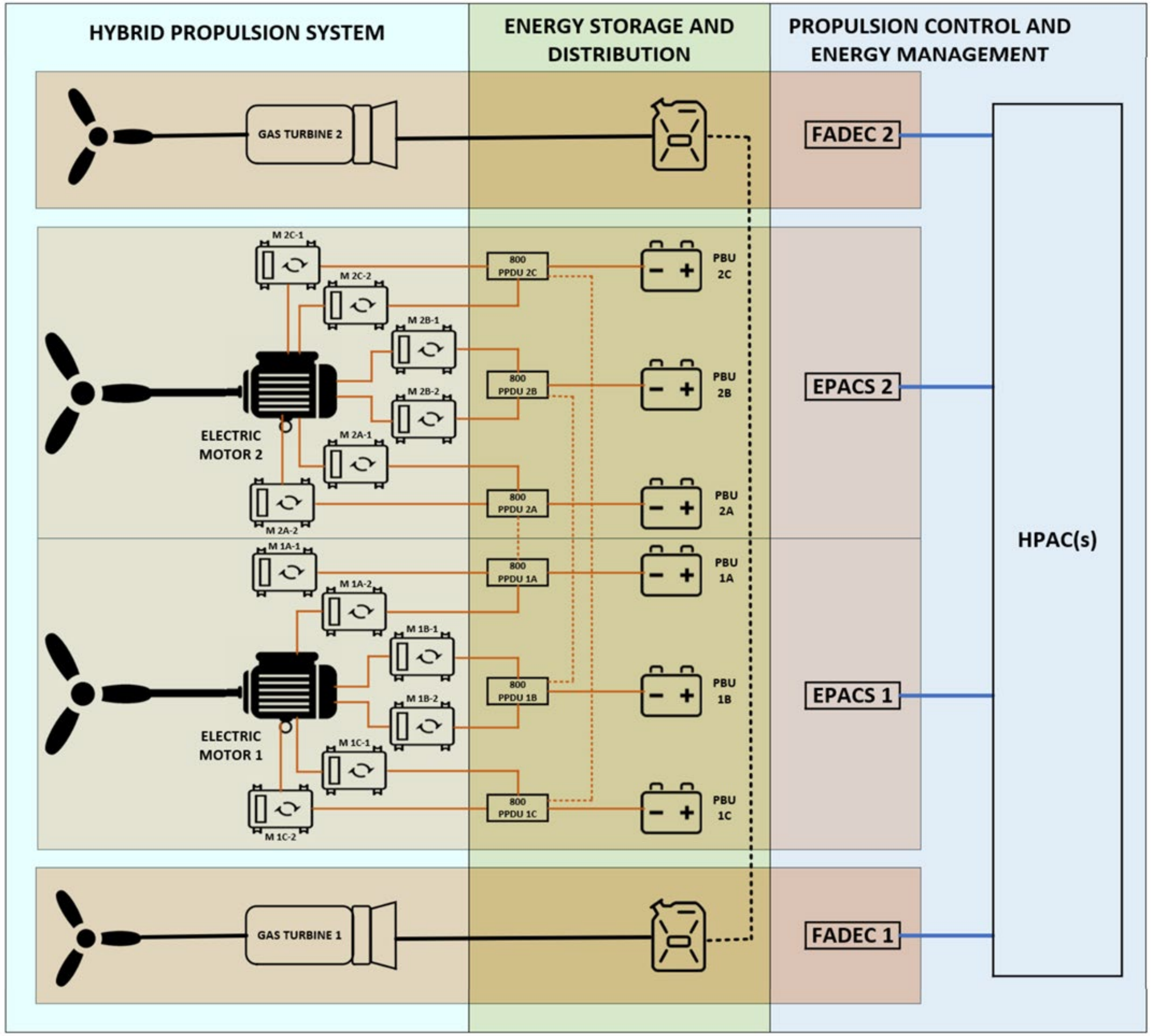
Hybrid electric architectures as suggested by the EU project HECARRUS (Horizon 2020/Clean Sky)

Heart Aerospace has previously investigated All Electric for ES-19 and Series Hybrid for ES-30

All proposed hybrid architectures have interdependencies between the fuel engine and the electric motor.
And – more importantly for Heart – they all involve costly modifications of an already certified fuel engine

Independent Hybrid Propulsion

- Our independent hybrid architecture will be implemented into the Heart X2 prototype vehicle
- This hybrid system allow full independence between the two propulsion technologies – except on the control level
- Modifications of the turboprop engines will be marginal



EPACS: Electric Propulsion Automatic Control System

HPACS: Hybrid Propulsion Automatic Control System

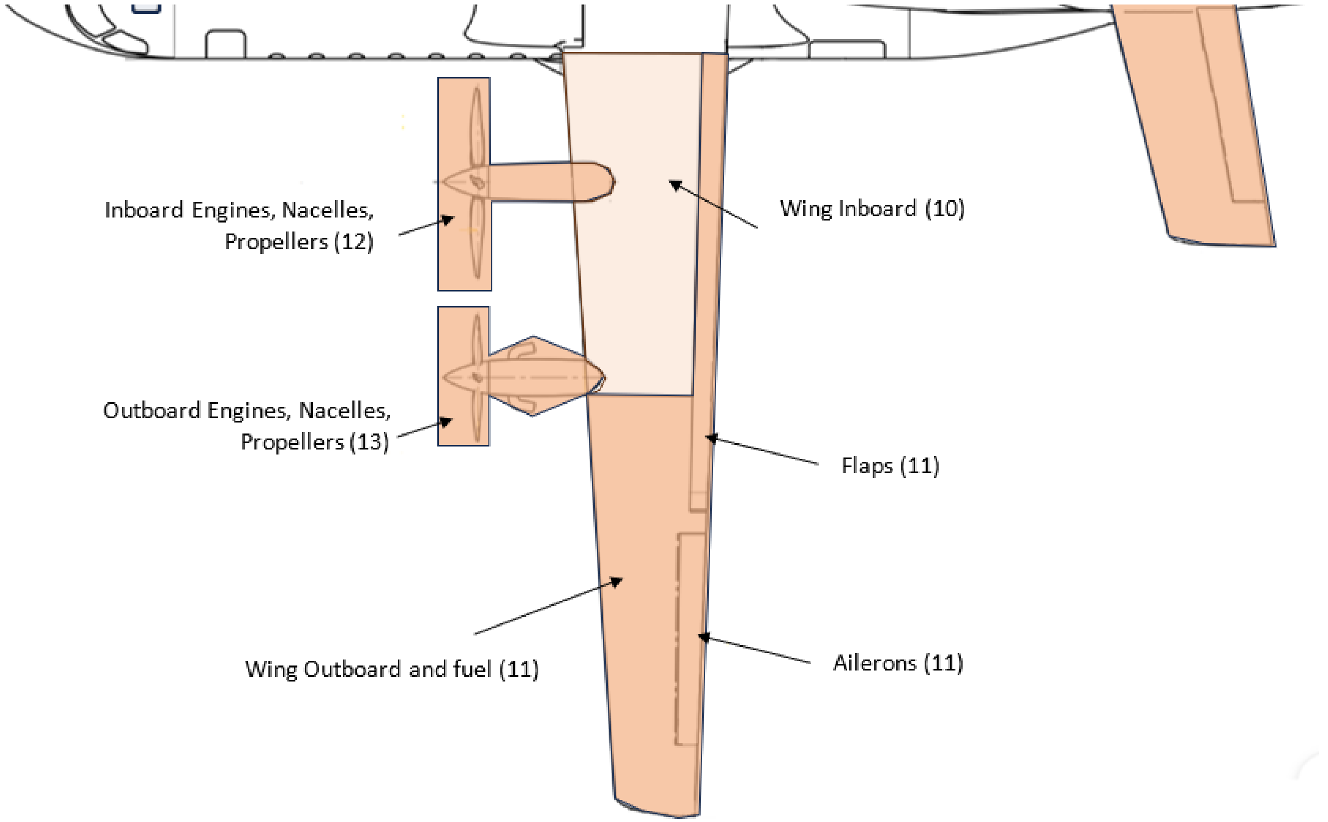
PBU: Propulsion Battery Unit

PPDU: Primary Power Distribution Unit

Independent Hybrid configuration

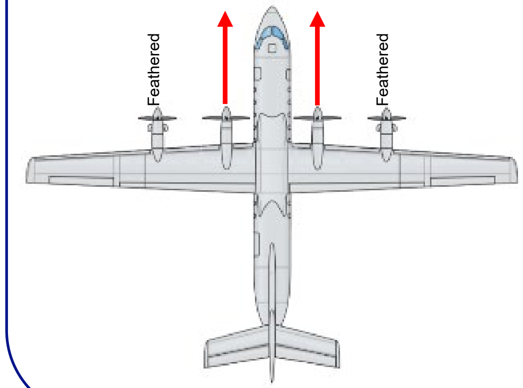
- **Electric engine propeller system**:
  - Inboard engines (2x)
  - Propeller Size: ~4 m
  - Electrical Engine 1.6 MW / 1200 rpm

- **Turbine engine propeller system:**
  - Outboard engines (2x)
  - Propeller Size: ~3 m
  - Turbine Engine 1.0 MW / 1600 rpm

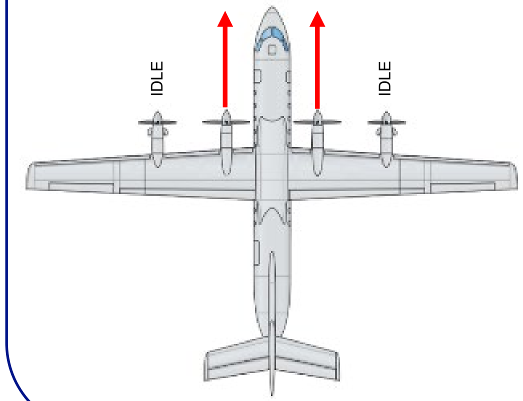


Modes of Operation

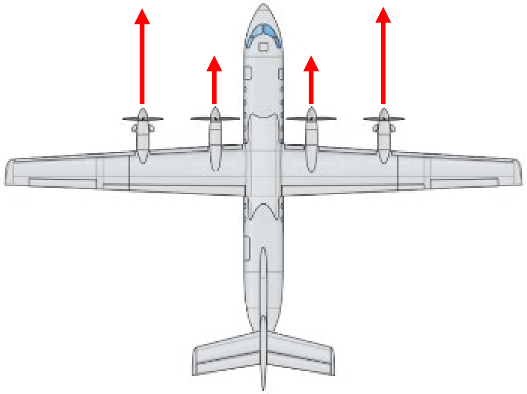
FULL ELECTRIC

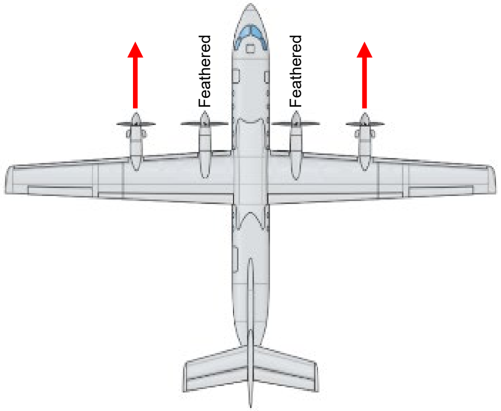


HYBRID STANDBY



HYBRID





Take-off/Go-Around

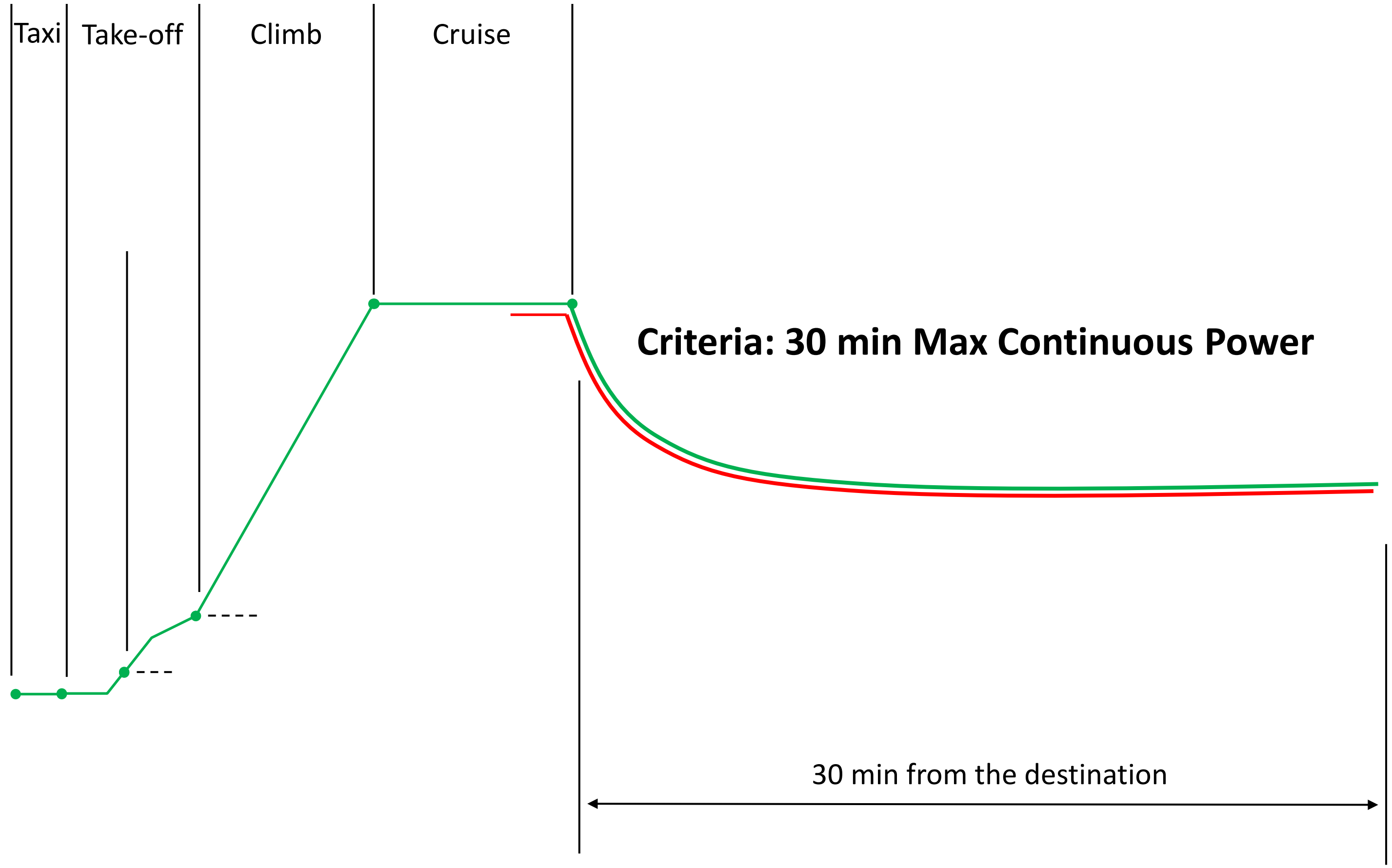
Cruise / Holding

Energy reserves

Energy reserves required for

- Failed landing attempt
  - Take-off
  - Climb
  - Go-around (cruise)
  - New landing attempt
- Alternate destination
  - Other airport

A rule-of-thumb is that energy corresponding to 30 minutes MCP is sufficient as reserves



EHPS Functions

- Provide thrust
- Provide hybrid power management according to operation modes
- Provide electrical power generation
- Provide extra drag using the propellers/engines
- Provide energy regeneration by airflow
- Provide propeller noise reduction
- Provide propeller/engine start/shutdown control
- Provide turbo engine start capability in flight (not in-flight restart)
- Provide propulsion alerting related data
- Provide propulsion displayed information related data

EHPS brings novelties to the standard functions list

Independent Hybrid design challenges

Two independent propulsion systems can absolutely improve system safety, however:

- Different propeller sizes may give acoustic and vibration effects at the aircraft
- OEI (One Engine Inoperative) performance at low battery state-of-charge
- Hybrid supervisory control - Multiple propulsion operation modes
- Cockpit controls design - Pilot involvement in hybrid operation or not?

Number of Power Levers under evaluation
- 1 lever: Highest level of automation, minimal redundancy
- 2 levers: High automation, available differential thrust, limited redundancy
- 4 levers: No automation. Same redundancy as existing aircrafts.

Independent Hybrid design challenges

Electric engine

Cooling
- Performance highly dependent on constant flow of cooling fluid

Air braking with propeller instead of flaps
- Require battery charge acceptance
- Novel function

Icing
- Anti-icing / Deicing while engine OFF

EMI/EMC
- Current ripple between battery and electric engine

Turbine engine

Starting
- On-demand
- Cold-soak
- High altitude (up to 20,000 ft)

Windmilling
- Windmill operation while engine OFF

Icing
- Anti-icing / Deicing while engine OFF

EHPS Control Systems Functions

- Provide Thrust Control
  - Provide Speed and torque control.
  - Provide propeller pitch control.
  - Provide thrust balance between engines (Trim).
  - Provide System Protection
    - Torque, Speed and Temperature Limits Protection.
    - Shutdown due to: Overspeed or Uncontrollable High Thrust/Power
- Provide electrical power generation
  - Provide turboprop electric power extraction capability.
  - Provide electrical power regeneration.
- Provide normal engine start / shutdown capability (on ground and in flight)
- Provide propeller synchronization/synchrophasing capability
- Provide hybrid power management according operation modes
- Provide propulsion system data to the aircraft systems
- Provide extra-drag
- Provide propulsion system health monitoring and diagnostics capability

EHPS Control Systems Functions

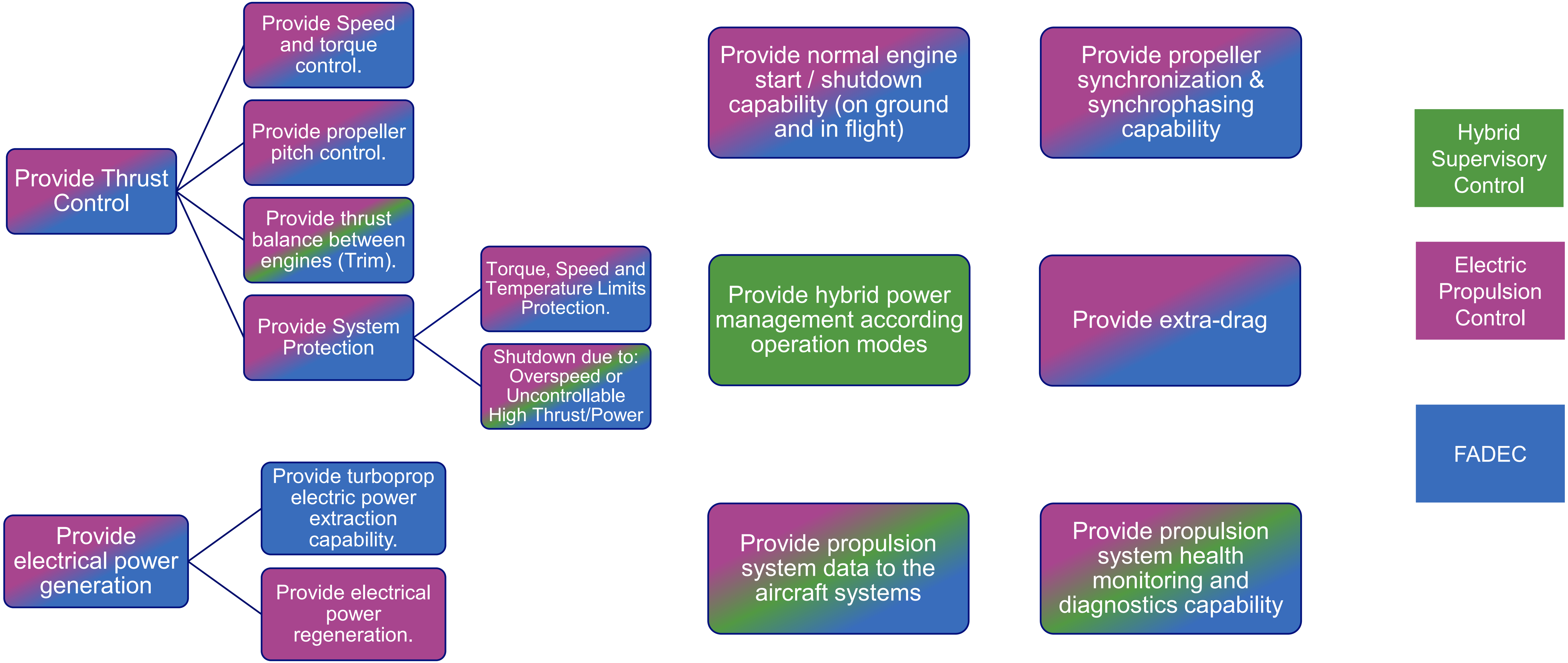


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TABLE 2 Failure Condition Classifications

		Classification of Failure Conditions				
		Negligible[A]	Minor[A]	Major[A]	Hazardous[A]	Catastrophic[A]
Classification Considerations	Effect on Aircraft	No effect on operational capabilities or safety	Slight reduction in functional capabilities or safety margins	Significant reduction in functional capabilities or safety margins	Large reduction in functional capabilities or safety margins	Normally with hull loss
	Effect on Occupants	Inconvenience for passengers	Physical discomfort for passengers	Physical distress to passengers, possibly including injuries	Serious or fatal injury to an occupant	Multiple fatalities
	Effect on Flight Crew	No effect on flight crew	Slight increase in workload or use of emergency procedures	Physical discomfort or a significant increase in workload	Physical distress or excessive workload impairs ability to perform tasks	Fatal injury or incapacitation

Faults per flight hour: 10^{-3} 10^{-5} 10^{-7} 10^{-9}

Table 4: EASA incidents - root cause identification

EASA incident data from Jan 2020 to April 2021:

	Number of incidents	Root Cause Identified: Only due to LOP	LOP + incorrect pilot action*	Unknown
HAZARDOUS: accidents with serious injuries	62	23 (4.0%)	31 (5.4%)	8 (1.4%)
HAZARDOUS: accidents with single fatality	17	1 (0.2%)	11 (1.9%)	5 (0.9%)
CATASTROPHIC: multi-fatality crashes	17	0 (0%)	13 (2.3%)	4 (0.8%)

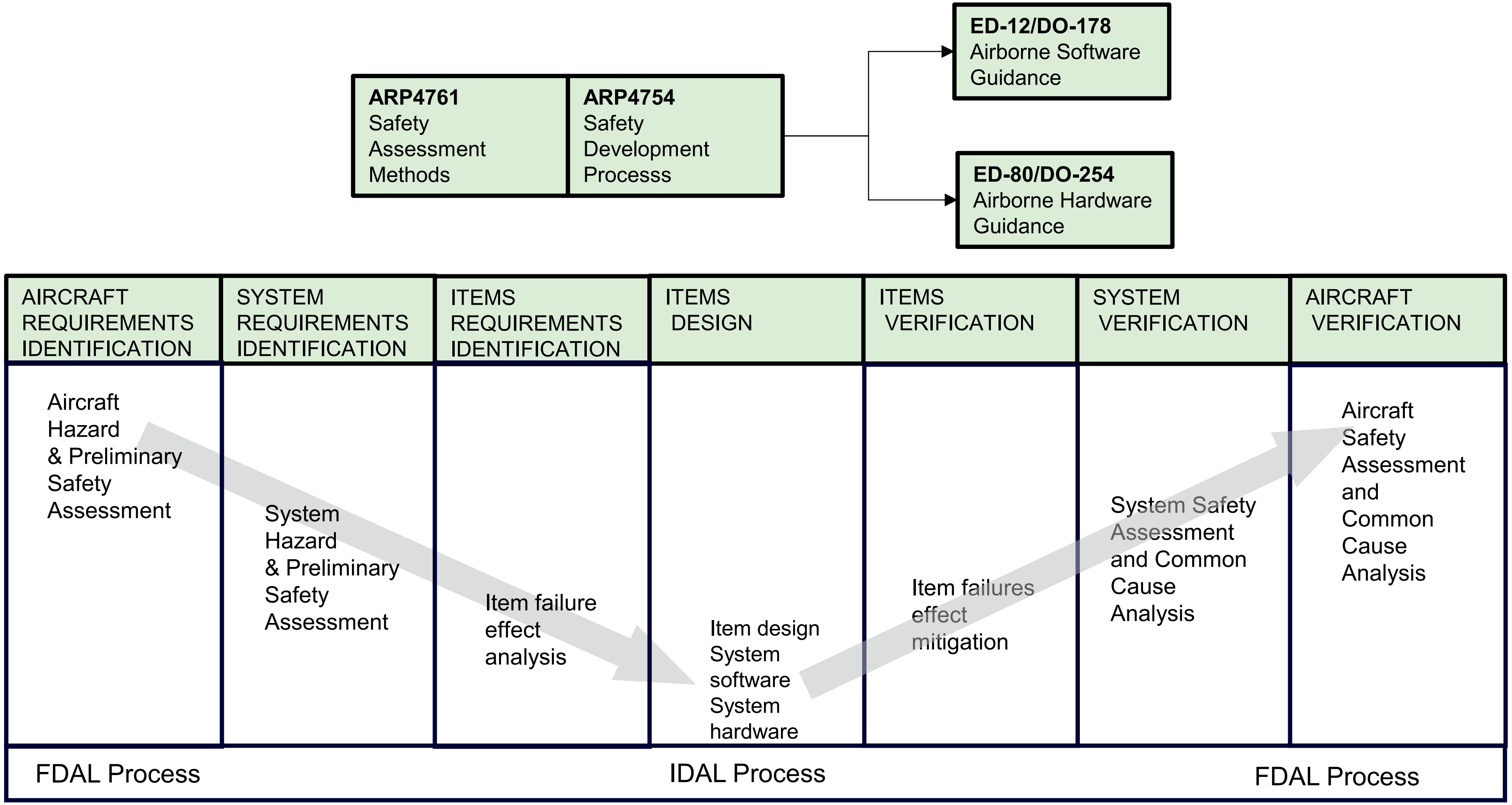
* Indicates the pilot applied the wrong emergency procedure following a LOPC event.

The EASA study highlights that emergency procedures are crucial to avoiding Hazardous and Catastrophic outcomes, as the leading cause of HAZ+ events is a combination of LOPC and incorrect pilot action.

ES-30 Robust Development Process

SAE ARP 4754 together with SAE ARP 4761 supported by ED-12/DO-178 and ED-80/DO-254

Source:
SAE ARP 4754

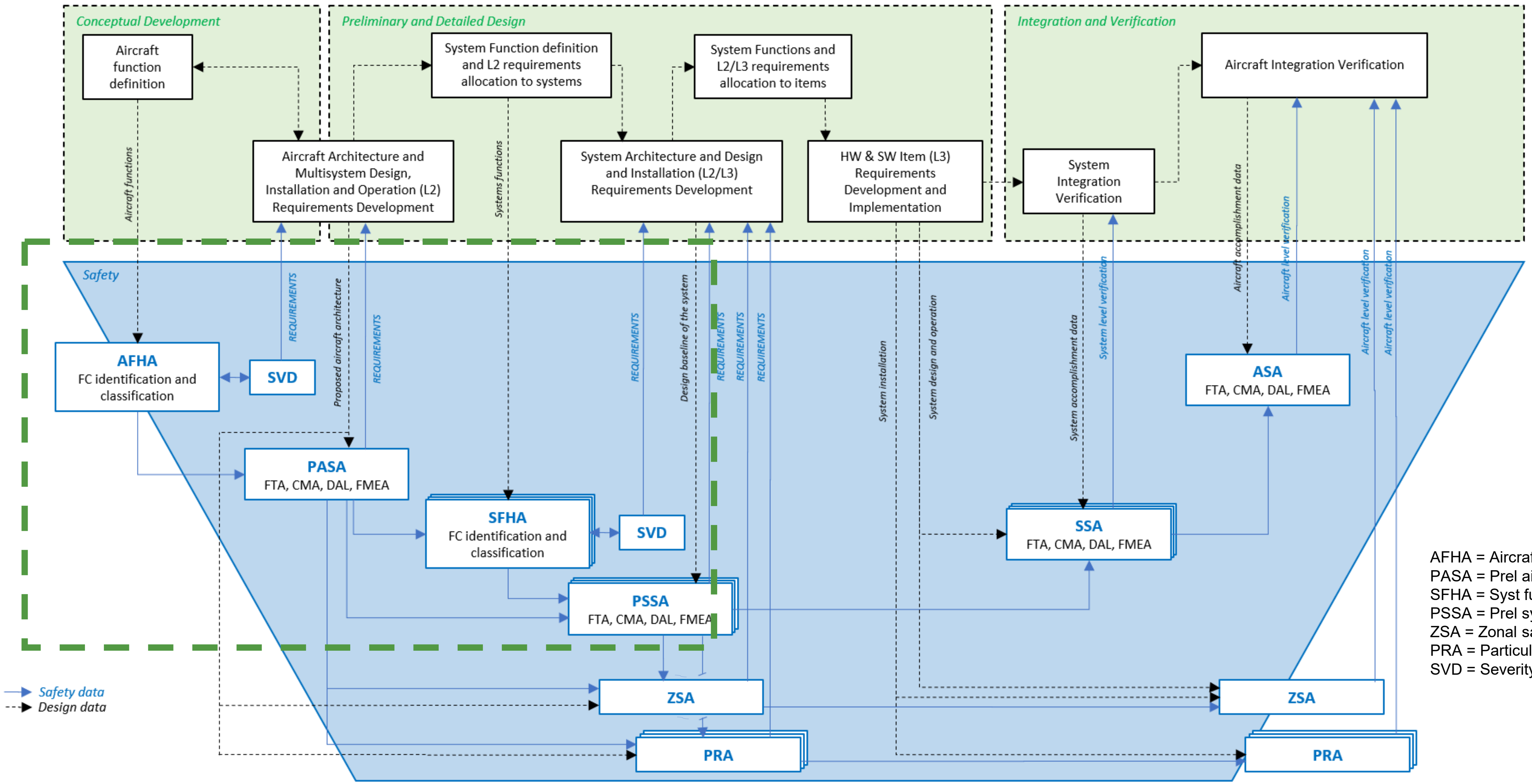


FDAL = Functional Design Assurance Level

IDAL = Item Development Assurance Level

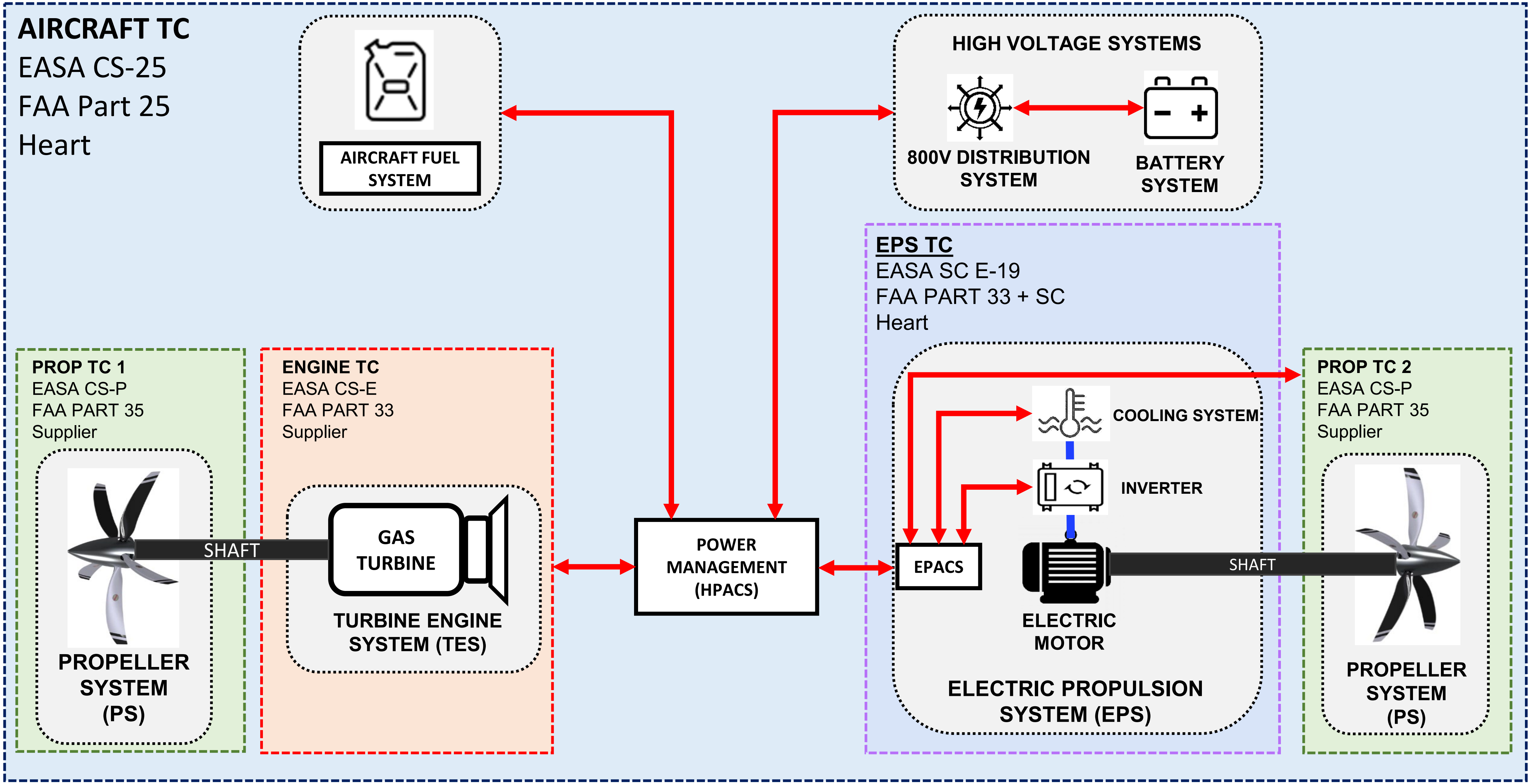
ES-30 Safety process overview

ES-30 development safety process use the SAE ARP4761 set of analyses, for both aircraft and systems levels.



AFHA = Aircraft func hazard anal.
PASA = Prel aircraft safety ass.
SFHA = Syst func hazard anal.
PSSA = Prel system safety ass.
ZSA = Zonal safety ass.
PRA = Particular risk ass.
SVD = Severity validation doc.

EHPS certification approach



Certification according to SC E-19

Certification according to SC E-19

Powerplant Failure Scenarios

- An analysis of the consequences of failures of the system on the aircraft has to be made to provide compliance with regulations, such as CS 25.901, CS 25.903 and CS 25.1309.

- Some of the most critical powerplant systems related failure conditions include the following:

  - Thrust management system
  - Propeller controls and indications
  - Powerplant ice protection
  - Fire protection system
  - Fuel system

References:

- AMC 20-1A Certification of Aircraft Propulsion Systems Equipped with Electronic Control Systems
- AMC 20-3B Certification of Engines Equipped with Electronic Engine Control Systems

AMC = Acceptable Means of Compliance

LOPC = Loss of Power Control

- This report provides guidance to assess the tolerance of an aircraft electric engine design to electrical and electronic failures leading to Loss of Power Control (LOPC) events
- Its intent is to provide a means to demonstrate compliance with certification requirements
- At issue 1, this document has been developed to address fully electric engine configurations targeting single engine aircraft applications with conventional engine installation

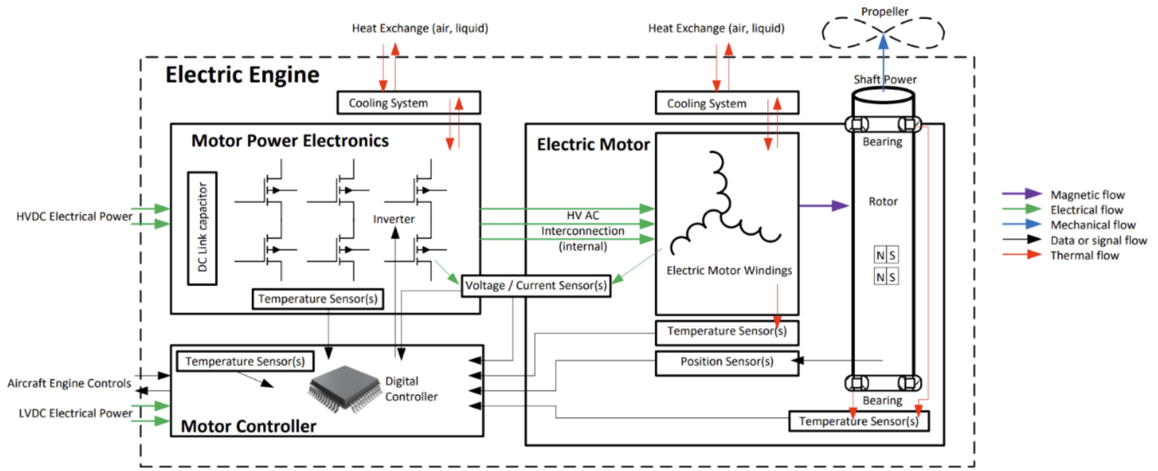
SAE INTERNATIONAL

AEROSPACE INFORMATION REPORT

AIR7130™

Issued 2024-10

Assessment of Electric Engine Failures Leading to LOPC



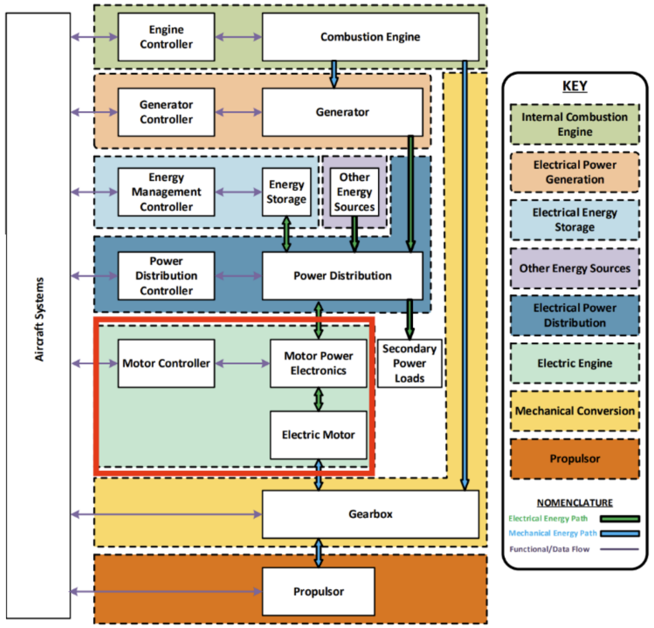


Figure 1 - Generalized functional architecture

LOPC = Loss of Power Control

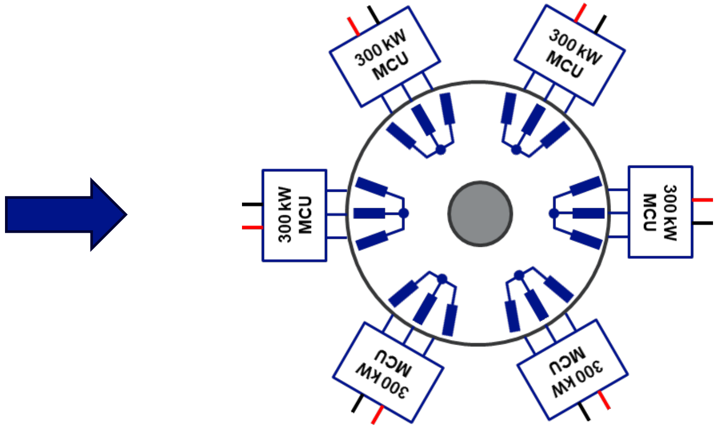
Traditionally, LOPC has been defined as an event where the Engine Control System has lost the capability to

- manage above 85% of maximum rated power
- manage unacceptable power oscillations
- govern the engine in line with operability specifications

Proposed single-fault ratings for electric engines:

Declared ratings	Duration	Power	Temperature. limitation	Maximum initial temperature
MCP	unlimited	80%	130°C	130°C
MTOP	5min	100%	130°C	70°C
ESDP	3min	80%	200°C	100°C
ECDP	unlimited	50%	200°C	200°C

MCP: Maximum Continuous Power
MTOP: Maximum Take-off Power
ESDP: Emergency Short Duration Power
ECDP: Emergency Continuous Duration Power




Thank you for your attention!

Non-CO_2 emissions

- In recent years, we have learned much more about the impact of contrails on the climate change. Contrails are formed by other emissions (soot, NOx) under certain conditions. Contrails are not water vapor.

- Probably 2 times higher impact from contrails than CO2 emissions

- Estimations made that a 60% reduction in contrails can be achieved by redirecting 2% of aircraft routes by (sideways or new altitude). Delays are counted in minutes.

- This means that electric aviation has a greater impact than just the lower CO2 emissions