PPEM014 – Very Long Endurance Propulsion Systems

SEAS DTC Conference 2009

Mark Husband

Strategic Research Centre

Rolls-Royce

Propulsion systems

- Long endurance achieved by lightweight construction, high aspect ratio wing, large fuel mass and efficient propulsion system
- As endurance increases:
  - fuel load increases
  - efficiency of propulsion becomes more important
  - power density becomes less important
- PPEM014 aims to increase endurance by increasing efficiency of propulsion system

Increasing propulsive efficiency

Increasing power density

HALE System Specification

- HALE – High Altitude Long Endurance
- Loiter for 1 week at an altitude of 20km (65000ft)
- 3500kg take-off mass and fuel mass must be limited to less than 50% of take-off mass. Payload mass of 300kg
- Wing aspect ratio of 30. L/D during loiter of 38. Cruise speed of M0.25 – M0.35
- ‘Start of cruise’ design point. 140kWe required.

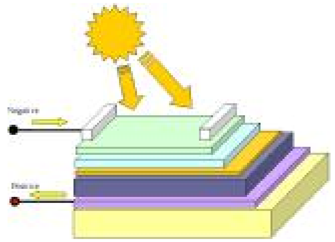
Atmospheric conditions

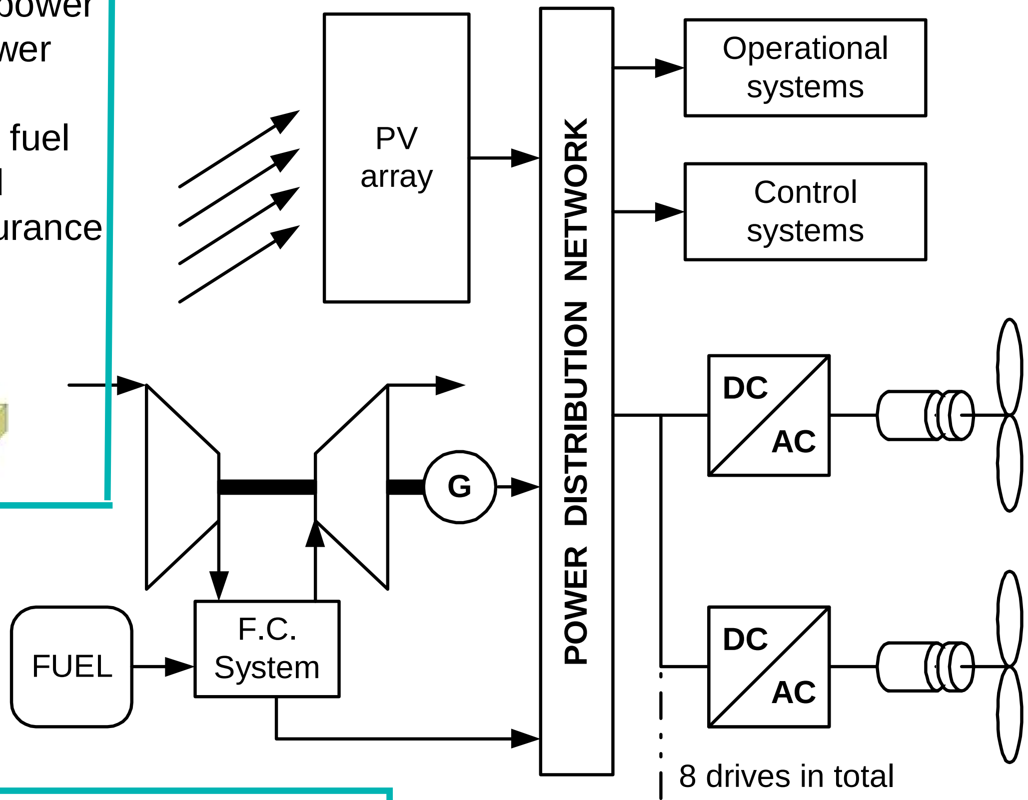
Altitude (m)	Temp (K)	Pressure (kPa)	Air Density (kgm^{-3})
0	288	101	1.23
15000	217	12.1	0.20
20000	217	5.53	0.09

PPEM002 Results

Photovoltaic Array

-Cannot meet cruise power
-Operate for max. power at all times
-No storage required, fuel consumption reduced
-10% addition to endurance





Power Distribution Network

-Minimal energy storage due to weight penalty of batteries
-Variable voltage network (200V -300V) investigated for simple, lightweight, efficient power transmission.

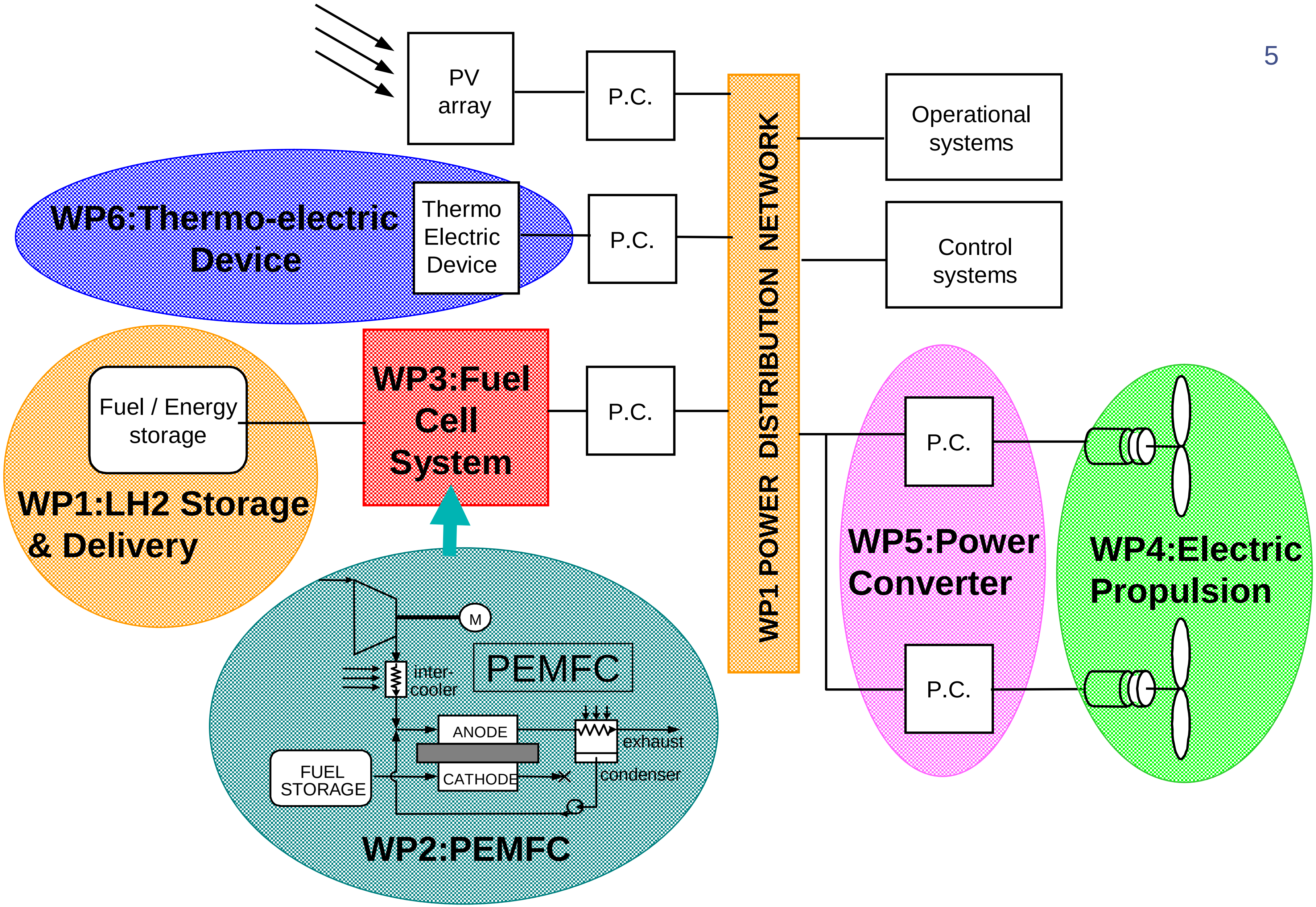
Hybrid GT/SOFC generation

-Consider fuel cell systems if LH2 fuel is used
-Air compression required for FC at altitude
-SOFC/GT hybrids modelled, low power density, high efficiency (~55%)

Propeller Drives

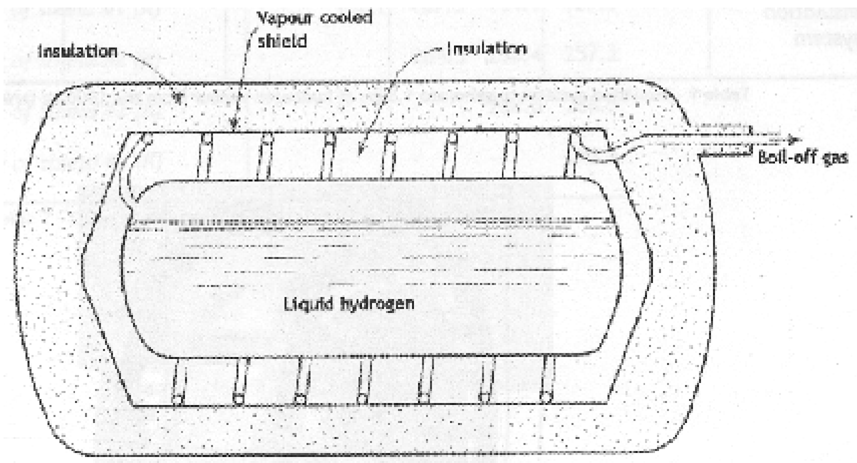
-8 prop drives: geared, air-cooled 15,000rpm PM machines driving variable pitch props.

-Design, simulation and prototype of machine at Sheffield UTC


PV array
P.C.
WP6:Thermo-electric Device
Thermo Electric Device
P.C.
WP1 POWER DISTRIBUTION NETWORK
Operational systems
Control systems
Fuel / Energy storage
WP1:LH2 Storage & Delivery
WP3:Fuel Cell System
P.C.
M
PEMFC
inter-cooler
ANODE
CATHODE
FUEL STORAGE
exhaust
condenser
WP2:PEMFC
P.C.
P.C.
WP5:Power Converter
WP4:Electric Propulsion

WP1 – LH2 Storage (PPEM014)

- Storage Methods Considered:
  - Foam insulation
  - Vacuum insulation
  - Vapour cooled systems
- Foam Insulation with a vapour barrier preferred.
  - Lightest
  - More robust
  - Higher Boil-off



WP1 – LH2 Delivery & Power Network

- **This work package will investigate hydrogen delivery along with the electrical network.**
  - Distributed hydrogen storage
  - Consideration of integration of hydrogen system within airframe

- **Power network considerations:**
  - Investigation of power cabling - at liquid hydrogen temperatures the weight of a power conductor is reduced by 100.
    - A 1mm diameter Al wire at 20K can operate at over 700A.
    - A 20mm diameter Al wire is rated at 540A.
  - Investigation of natural fault current limitation potential.

WP2 - Fuel Cells for Long Endurance UAVs

- Many types of fuel cell available.
- PEMFC widely considered for transportation applications due to
  - Power density, start up time, transient response, mechanical robustness
- SOFC generally considered for static power generation due to
  - efficiency, high grade heat output
- Traditional drawbacks of SOFC for transport applications are less relevant for long endurance UAV

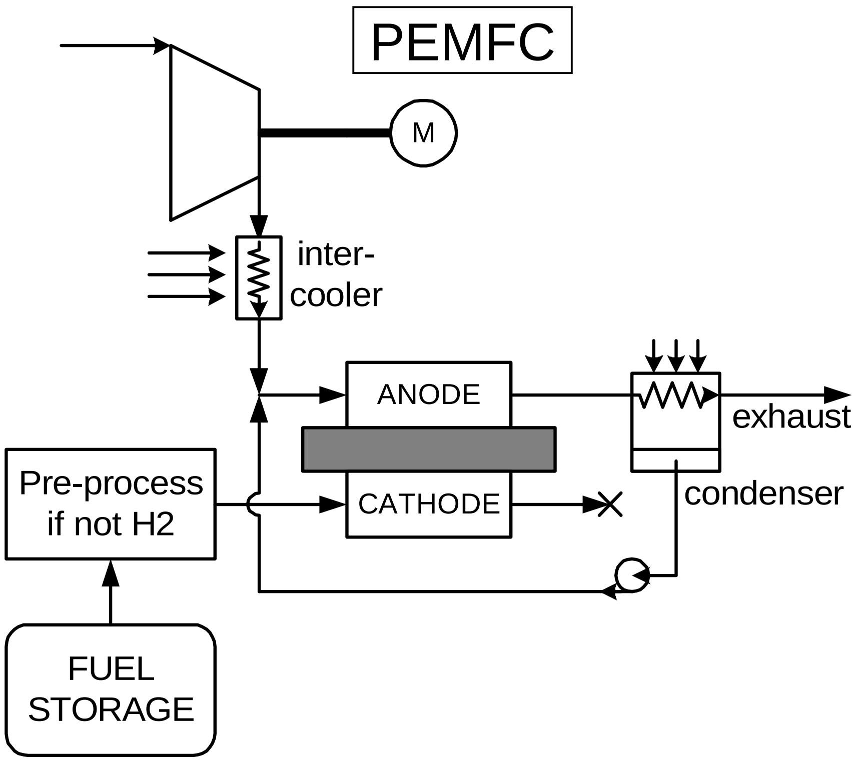
WP2 – PEMFC (PPEM014)

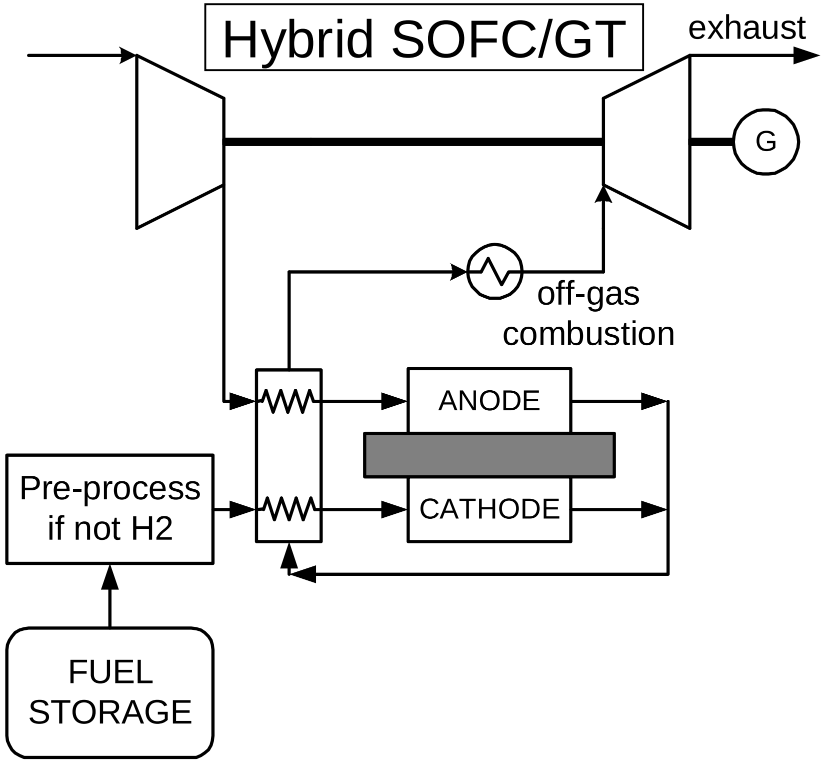
- **PPEM002 highlighted that given the air density at altitude, the compression requirements for a HALE UAV, resulted in SOFC technology being favoured. PPEM 014 will revisit this assumption at lower altitudes.**

- **Intelligent Energy as part of a £5million DTI funded project achieved significant power density improvements by using pressed plate technology.**
  - This achieved 1kW/kg (current best around 0.5kW/kg).
  - A 70kW prototype built and tested.
  - Though the demonstrator was successful some manufacturing issues were identified.

- **Based on the intelligent energy design an updated PEMFC model is being generated.**

WP3 - Possible FC system cycles

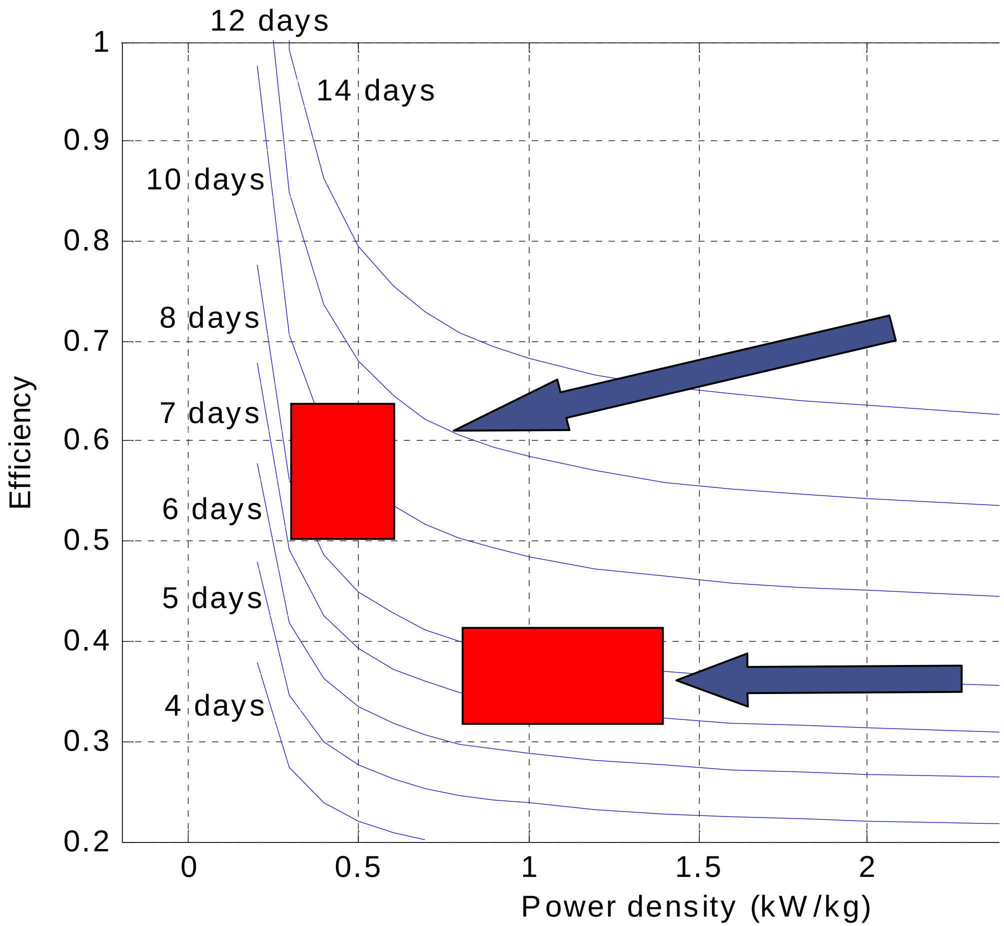




- Comp. Ratio 12 (0.7 bar abs.)
- 350K stack
- Electrically driven compressor
- Water cooled stack
- Complete fuel utilization

- Comp. Ratio 12 (0.7 bar abs.)
- 850K – 1150K stack
- Hybrid GT/FC cycle
- Air cooled stack
- Off gas combustion

WP3 - Fuel Cell Comparison (PPEM002)



- Hybrid SOFC
  - 850-1150K Stack
  - Hybrid GT/ FC cycle
  - Comp Ratio 12 (0.7bar)
  - Air Cooled stack
- PEMFC
  - 350K Stack
  - Electric Compressor
  - Comp Ratio 12 (0.7bar)
  - Evaporative cooled

UAV endurance model to trade FC power density and system efficiency

WP3 – Fuel Cell System (PPEM014)

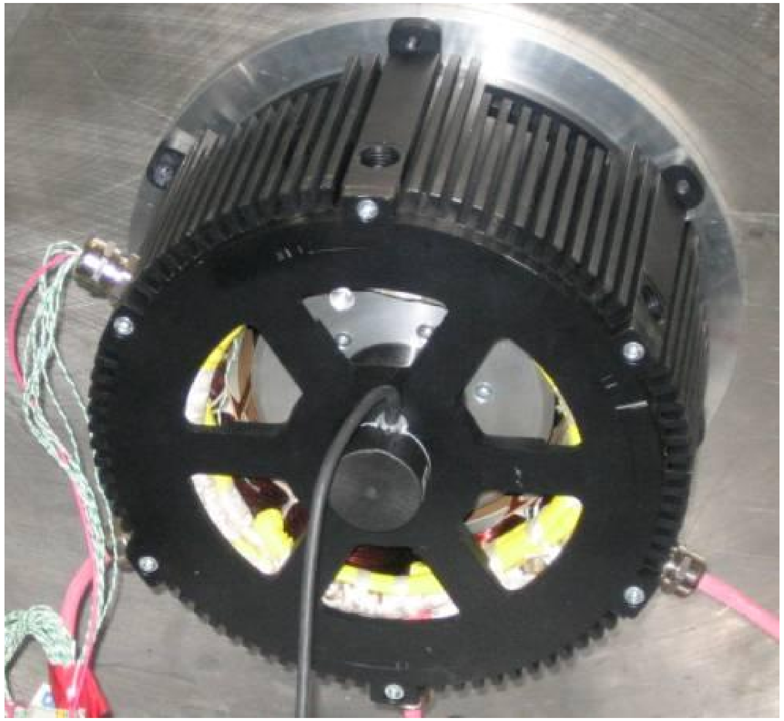
- The preliminary design models completed in PPEM002 for a HALE SOFC GT hybrid system are being developed further to ensure that the design is applicable to the off-design performance required.

- Updated preliminary designs and models of both the SOFC GT hybrid and PEMFC systems are being developed for us at lower altitudes to understand potential power sources for a range of UAV applications.

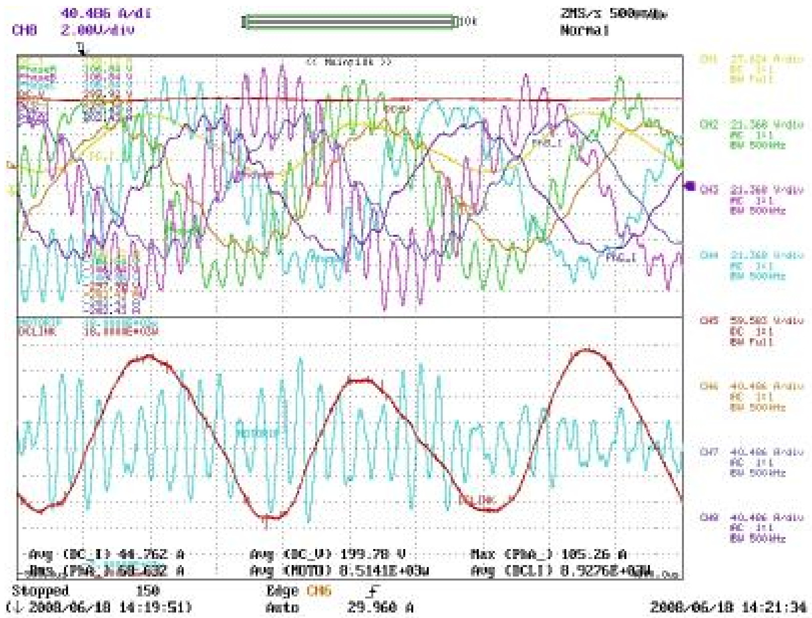
WP4 – Air-cooled Motor (PPEM002)

- PM002 - Machine built and dyno tested at Sheffield
- Inverter built for testing

PM Rotor



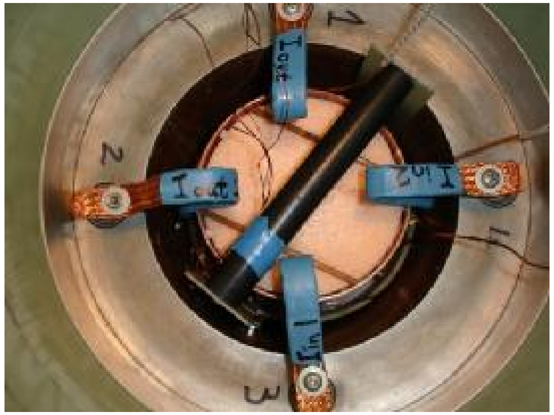
Prototype Machine



Dyno measurements

WP4 – Fuel-Cooled Motor (PPEM014)

- The University of Manchester is considering the potential benefits provided by LH2 fuel-cooled electrical machines.



Conventional machine Stator within Cryostat

- This work package is considering low temperature conventional and superconducting technology

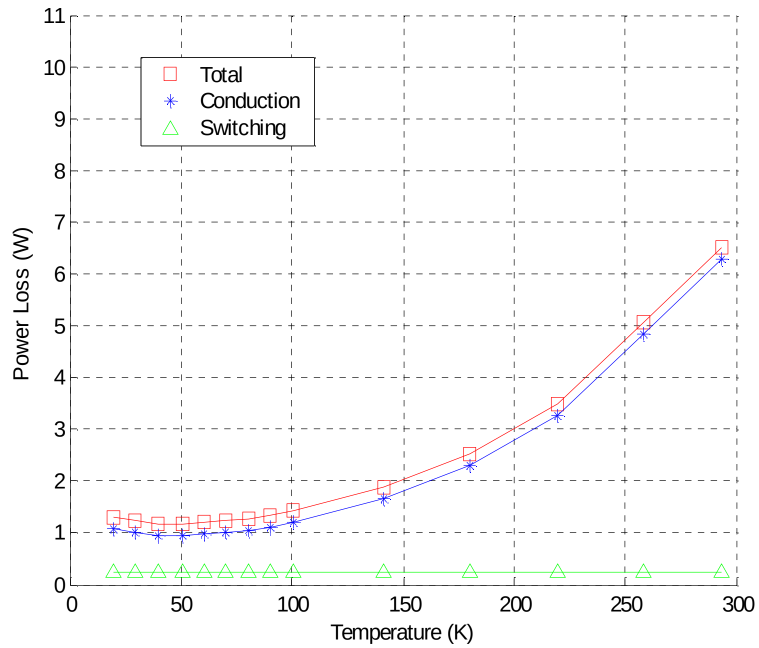
WP5 – Air-cooled Power Converter

- The University of Sheffield will complete the PPEM002 baseline design by initially undertaking an air-cooled converter design using the latest power components.

- The University of Sheffield will then consider potential benefits provided by novel power electronic devices such as SiC and GaN.

WP5 – Fuel-Cooled Power Converter

- The University of Manchester will investigate fuel-cooled converters that lead to improved power densities:
  - Reduced heat sink:
    - Reduced losses in power devices
    - Increased switching speeds
  - Reduced passive components:
    - Lower conduction losses in passive components

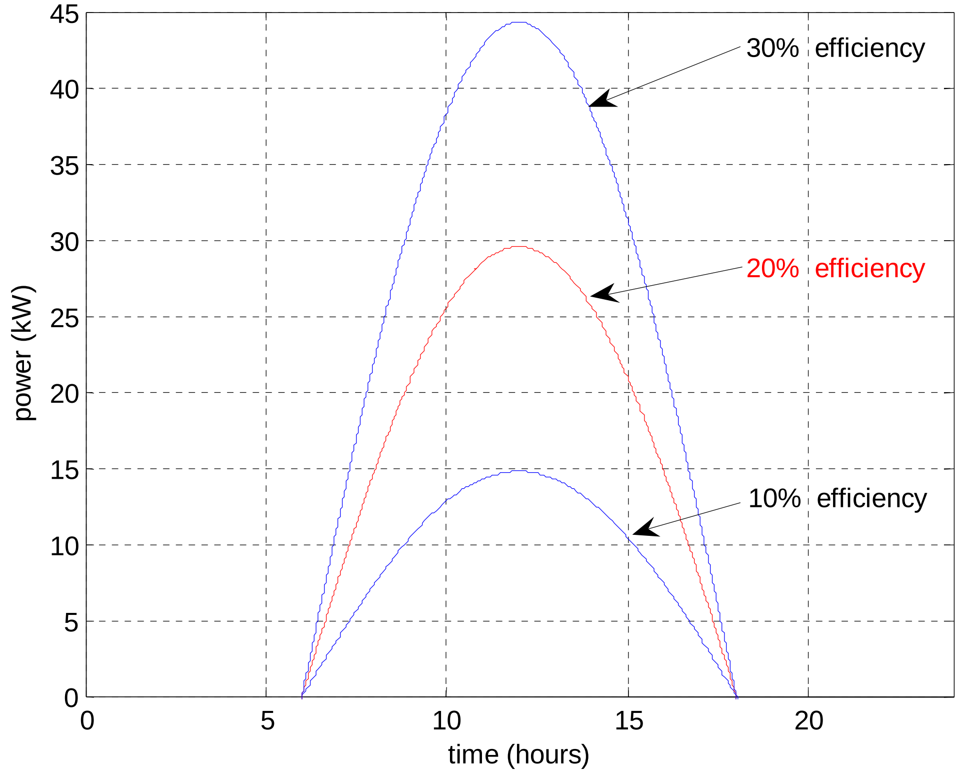


Semiconductor Losses in 500W DC-DC Converter

Rolls-Royce

WP6 - Thin film PV wing surface (PPEM014)

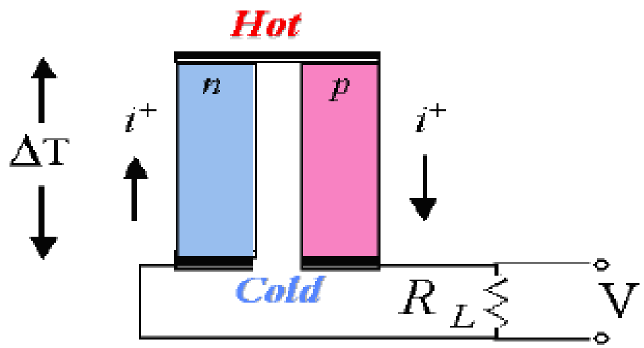
- A 12 hour day model was used to estimate PV power available
- At 20% conversion efficiency:
  - Peak power - 27kW
  - Average power - 9.4kW
- Peak power cannot meet total demand at any point during cruise
- No requirement for PV energy storage – leads to simple hardware and control strategy:



- PV array operates for maximum power at all times, primary source of generation varies output accordingly
- Primary source must be rated for total power demand, PV extends endurance but is not essential

WP6 – Thermo-Electric Device

- The Peltier-Seebeck effect defines that in the presence of a temperature difference a voltage is generated between two different semiconductors.



Schematic of a Thermo-Electric Device

- By using fuel cooling a temperature difference could be established that would enable continuous power to be generated reducing the required fuel cell power rating.

End of Presentation

- Thank you for your attention

Mark Husband
Strategic Research Centre (SINA-28)
Rolls-Royce plc
PO Box 31
Derby
DE24 8BJ