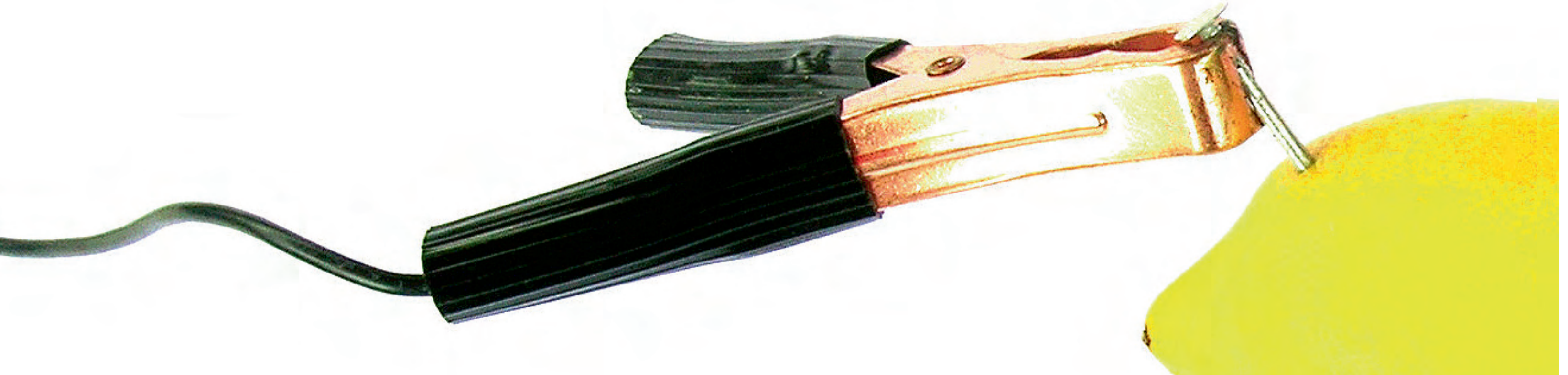
Electric aircraft:

In this first article on electric aircraft, Ian Tadd takes a realistic look at what is possible for them within the constraints of current technology



History is littered with those who have attempted to predict the future. Call me foolish, but I'm now going to do just that. Great expectations were placed on diesel engines, and while progress has been made, it has not yet resulted in serious competition for the petrol engine. Just because a technology becomes possible, it does not automatically lead to its widespread adoption.

As the diesel engine has shown, the GA business as a single entity is not large enough to attract not only the level of investment, but investors comfortable with 10-20-year paybacks. My contention would be that if electric aircraft are to become viable, GA has to look at adapting technology from other uses.

Throughout these articles, I will apply that principle. However promising on paper, I will avoid technology that does not have the driving force of large-scale use outside of light aviation.

I will also be avoiding the trap of claiming electric power is going to be some kind of magic solution that will transform light aviation and dramatically reduce costs. For example, I will not be looking at (free-power) solar panels – not because of cost, but because of clouds and surface contamination. While they do continue to work in low light levels and may be useful in providing a supplement to recharging even possibly while airborne, what we need is a full and predictable 'energy' tank before we take off.

This and future articles will look at a number of areas:

» What's been achieved so far

» A specification for an electric power system derived from asking the question, "What would it take to replace the Rotax 912 in a standard Permit airframe with an electric motor and electric 'fuel tank' giving the same performance?"

» Compare a number of technologies, motors, batteries, capacitors and fuel cells with our hypothetical specification

» Look at research that may make the difference between what's currently available and what is needed

» And finally, look at how our hypothetical electric power system may influence aircraft design

SO, WHAT'S GOOD ABOUT ELECTRIC?

Here are ten great advantages

1 Much lower parts count and very low operating temperatures combine to give reliability far in excess of the petrol engine.

2 No complex cooling issues.

3 No carburettor icing problem.

4 No altitude effect on power – a non-turbo combustion engine will lose around 40% of its power by 8000ft.

5 Depending on the particular design, maximum torque can be available down to zero rpm. Modern petrol engines produce their maximum torque usually in the range 4000-7000rpm, well above the ideal for the propeller.

6 Weight. The hi-pa drive (a wheel hub motor designed and built for cars) produces 160hp for a weight of 25kg. This weight includes all the control electronics, DC to AC conversion, regeneration and braking.

7 Price: Producing a comparable power electric motor is a fraction of the cost of a combustion engine, 50kW motors optimised for car use can be purchased for under $1000.

8 As has been well demonstrated by the Antares 20E, the potential exists to incorporate the motor with the propeller and spinner. It does not take a great leap of imagination to see the potential to incorporate a variable-pitch mechanism. This should be a straightforward development, as it is relatively easy to arrange both DC and AC motors to spin around a fixed shaft.

9 There are also advantages to AC motor design and efficiency if the motor can be run at a constant frequency, which could be designed to be directly proportional to the ideal constant speed for a variable-pitch propeller.

10 Power pulses, which put considerable stresses on propellers, can almost completely be eliminated using particular motor designs.

ROTAX REPLACEMENT

What would be the spec for a hypothetical electric power system to replace the 80hp Rotax 912?

Just a quick reminder that horsepower and Watts measure the same thing, power, and that 1hp is 746 Watts. 80hp is thus approximately 60kW. For simplicity, I have assumed that

Maximum power is only required for 10 minutes (take-off and climb), with a further 10 minutes of maximum power every hour for manoeuvring/climbing;

Cruise requires 40kW (53hp). It is important to remember that the engine supplies all the power for everything. As much as 15hp is currently used to power parasitic requirements, alternator, cooling system, oil and fuel pumps and so on, so you don't need to consider such things as radios as their consumption is already accounted for in with the 60kW;

Electric motors can be made very efficient – over 90% is common. This results in minimal cooling requirements and nearly all the power potential can be assumed to be available to the drive shaft. It is rare that petrol engines actually produce their full quoted power. I have, therefore, assumed those loses are comparable to the efficiencies of an electric motor;

Take-off and climb requires 60kW for 10 minutes = 60 x 10/60 kilowatt hours = 10kWh;

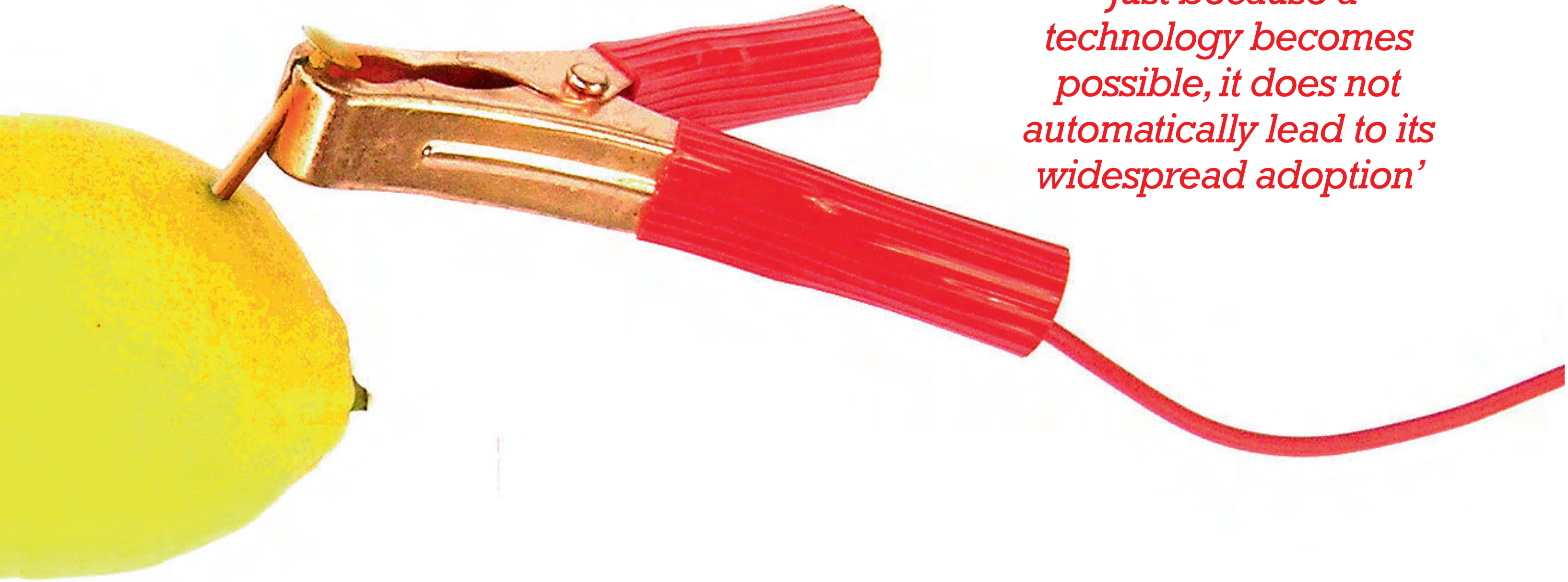
Cruise for 50 minutes requires 40kW for 50 minutes = 40 x 50/60 kWh = 33kWh.

So, for my hypothetical Permit aircraft, the power requirements are 43kW per hour (kWh). Therefore, a typical three-hour flight with one-hour reserve requires a total power 172kW. For simplicity, I will use 170kW for the rest of this article. I believe this reasonably reflects the power profile of a 912 in a typical Permit aircraft.

WEIGHT

Breaking down the various components that make up a typical UK 450kg Permit aircraft, around 150kg is taken up with engine, propeller, fuel and fuel system, water and

lemon or reality?



‘Just because a technology becomes possible, it does not automatically lead to its widespread adoption’

cooling system etc. It is within this 150kg that we have to get a viable three-hour capacity electric propulsion system.

It should be noted that many designs limited to 450kg in the UK are commonly approved at greater MTOW under other authorities, and under these authorities we could possibly have up to 200kg available for the propulsion system. However, I will stick to the limits imposed by our UK 450kg limit, as this represents a significant and growing proportion of the UK Permit fleet.

MOTOR CHOICE

A typical DC motor produces at best around 2hp per kilo, but iron-less DC motors have been demonstrated that produce 7hp per kilo. Certain types of AC motors can produce as much as 10hp per kilo.

Batteries, capacitors, fuel cells and solar panels produce direct current (DC), so at first glance it seems the DC motor is the simpler and obvious choice. However, not only are available DC motors heavier than AC, they are usually more expensive to make and there are greater losses controlling and transmitting high current DC than AC. I’ll explain.

A circuit that is handling AC gets the chance to ‘cool’ during the off periods and does not build up heat in the same way as a DC circuit. The cheapest way to control a DC current (with minimum losses) is to convert it to AC by rapidly switching it off and on. Transistors that are partially on get very hot very quickly and they need to be half on to directly control DC. By varying the on-off periods the average current can be accurately controlled, and the transistors doing the switching are either fully on or fully off, minimising heat generation and, therefore, losses. This technique is refereed to as Pulse Width Modulation (PWM) and is commonly used in computer power supplies. I’ll go into PWM controller techniques in a later article and how PWM can benefit efficient motor design.

As with anything in life, the choice is a compromise between effects. So in the interests of balance, in favour of DC is the lack of ‘skin effect’. In a wire carrying DC, the current is evenly distributed; in a wire carrying AC, the current is not evenly spread across the wire, being concentrated towards the outer edges. In effect, this means little current is flowing through the centre of the wire. This is not a minor effect; on high-power transmission systems the skin effect justifies the costly production of hollow wires. The hollow is often taken up with steel or fibre wire for strength.

There is a point worth underlining. As has been clearly shown by the attempts to produce a successful small aviation diesel engine, the aviation market is not big enough to attract the same level of development investment as the car industry. Considerable investment in research has been done by all the major car manufacturers and they have all concluded the AC motor is the best option. However, a major factor in this choice has been the regeneration of electricity when braking, ie the motor changes function to a generator and recharges the battery. There is little opportunity in an aircraft to use this functionality, although even if a DC motor was the better choice for a replacement, who is going to put up the money to develop a suitable motor? I would contend that with AC motors such as the Hi-pa already available, it would be best to ‘go with’ what’s already developed and available.

The Hi-pa is available in 40, 80 and 120kW versions giving very high torque at low rpm, and weighing 18kg, 21kg, 25kg respectively. The weight includes the control circuits and DC to AC conversion. All that is necessary is to connect the DC direct from the source and a control signal.

I am not claiming it would be a simple case of just bolting a Hi-pa drive into an aircraft, but that a version could be developed biased towards aviation use.

Again in the interests of balance, the iron-less DC motor developed as part of NASA General Aviation Propulsion program (GAP) resulted in a DC motor that showed the potential to generate 7hp per kilo. However, as far as I am aware, development for aviation purposes by NASA has gone no further.

On balance, I favour the AC motor, although the success of the Antares E20 DC motor system cannot be ignored.

HYPOTHETICALLY SPEAKING

Using existing technology, I believe it would be reasonable to assume motor, spinner, propeller, controller and cabling etc would be less than 50kg, leaving 100kg for the power source. Taking our power requirement of 170kW, this implies we need an electric store or generation system capable of 1.7kWh/kg. It’s worth making a comparison with petrol, which has a potential (depending on octane rating) of 13kWh/kg. At first glance, it appears something is wrong with our comparison. However, the combustion engine is inefficient and has a theoretical best thermodynamic efficiency of 37%.

In practice, this is impossible to achieve and the car industry usually quotes an efficiency of around 15-20%. I could not find a comparably figure for aircraft engines, but if we use the manufacturer’s quoted 15 litres an hour for 75% power, it suggests the 912 is achieving around 3kWh/kg. It initially appears that 1.72kWh/kg is still not generous enough, but when we factor

CURRENTLY FLYING

Antares' propeller turns at a maximum of 1700rpm, with implications for both noise and efficiency.

Boeing's Dimona uses a fuel cell hybrid.

Electraflyer Trike can stay airborne for two hours.

These four designs represent current 'commercial' achievements, though there are a number of small companies and individuals around the world experimenting.

ELECTRAFLYER TRIKE

The Electric Aircraft Corporation claims up to two hours' duration from its Electraflyer Trike, but that will be achievable only in ideal conditions ie lightest pilot, favourable flying conditions etc. They market the complete aircraft from around $18K, or a complete powerplant conversion kit from between $9K and $14K, depending on battery capacity and choice of reduction unit propeller etc. www.electraflyer.com/trike.php

YUNEEC E430

With a glide ratio of 25:1 the E430 is really a motor glider requiring relatively little power to take off and very low power to maintain level cruise. Rumours have it that a quick-build kit will cost $100,000. The manufacturer is reported as saying that is very telling on the existing capability and cost of available technology, stating, "It is hoped that by the time the batteries have to be changed, far cheaper and lighter batteries will be available."

Manufacturer's specification:
Wingspan: 13.8m (45.2ft)
Fuselage length: 6.68m (21.9ft)
Empty weight: 178kg (392lb without battery)
Maximum take-off weight: 430kg (946lb)
Motor output: 40kW (54hp) @ 2,450rpm
Battery type: lithium polymer
Battery weight (6 packs): 72kg (158.5lb)
Flight times of between 1.5 and 3hr

BOEING DIMONA

The Boeing Fuel Cell Demonstrator uses a Diamond Super Dimona HK-36 motor glider as a test bed for a fuel cell-powered light aeroplane research project. This is not a pure fuel cell-powered aircraft, it is (as with most vehicle applications) a fuel cell hybrid using, in this case, a lithium-ion battery. In fairness to Boeing, this was not an attempt to make a practical fuel cell-powered aircraft, but a test bed for fuel cells.

ANTARES 20E

The beautiful Antares 20E motorglider has a combined Lange Aviation electric motor and propeller and is currently the only EASA-certified electric engine.

Yuneec E430 needs very little power to stay up.

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back in the relative light weight of the electric motor and, therefore, the twice-as-heavy (compared to petrol) allowance for its 'fuel', a target figure of 1.72kWh/kg is confirmed as a reasonable benchmark for a three-hour flight with one-hour reserve.

POWER SOURCES 1: BATTERIES

Currently rechargeable battery technology can just about achieve 300-400Watt hours per kilo(0.3-0.4kWh), so in theory, using the best available technology, a 172kWh battery pack would weigh 600-800kg. In practice, this is not achievable as many other factors effect choice of battery type including efficiency, life, max number of charging cycles, density of cell packing and, not least, safety.

While lithium polymer batteries are starting to become available, they only offer a 25% improvement over the best commonly available battery, the lithium ion (Li-ion), at up to 0.2kWh per kg. After some notable failures, the Li-ion cell type has proved to be capable of close mounting in packs without overheating, each pack having its own charger and monitoring and control circuits.

At present, Li-ion has a life of around 1000 times before capacity degrades by more than 10%, so a 172kW pack would give 3000 hours of flying before needing replacement. Weight, however, would be well over 1000kg.

Cell packs are available to order over the internet, so, leaving the weight issue to one side, is this economic compared to 3000 hours of fuel? Taking a quote from http://liionbms.com/php/about_packs.php, a 170kWh battery pack is £81,000, weight 1350kg with 17,000 cells and a volume of 23cu ft.

3000 hours of fuel (mogas) @ 15 litres per hour and £1.10 per litre = £45,000.

From the perspective of both cost per hour and weight, batteries in their current state of development are nowhere near practical and, worse still, many Li-ion batteries that can achieve over 0.2kWh/kg have a life of only two to four years. So, for a Permit aircraft only flying 200 hours a year, the batteries would have to be replaced after only 400-800 hours use, a cost of around £100 to £200 per hour.

Re-charging is, of course, a major issue, and estimates vary. However, an overnight (12-hour) charge would probably require a minimum 60amp supply to fully charge a 170kWh pack. What is often not understood is that batteries do not charge at a fixed rate – the charge cycle varies greatly between even closely related battery types and the complexity of the charger for multiple cells.

However, a typical charge cycle means that to get the last 20% into the battery takes 50% of the charge time. You may have experienced this yourself. While it may take a charger 6-12 hours to fully recharge a car battery, it's possible to get enough charge in 30-60 minutes to start the engine. However, with many battery types, partial charging risks the battery acquiring a memory, which can significantly degrade available capacity.

To give a better idea of the scale of these various battery specifications, a typical car battery (lead-acid) is a useful comparison. It will provide 0.03kWh/kg in theory, but usually only 0.02wh/kg in practice, 500-2000 recharges and up to 20 years' shelf life.

What batteries are the electric aircraft mentioned earlier using?

The Electraflyer Trike, as far as I can tell, is using battery packs very similar to those available on-line from Eithion. I would suggest they are achieving around 0.13-0.15kWh/kg.

The E430 is harder to establish as they quote the weight of the battery packs, but not their capacity. It is worth noting that the parent company is a major battery manufacturer and unlike everyone else, they are using lithium polymer. With little to go on, I would suggest they may be achieving something in the region of 0.2kWh/kg.

The Antarres E20 is using a standard production cell (for which specifications are easily obtained), and assembling them in their own packs. I would suggest they are achieving around 0.12kWh/kg.

The first and obvious issue is charging. Even if a limitless source is available, batteries have a finite max rate of charge. In practice, using our hypothetical model means an aircraft is only going to have a practical range of three hours, after which it will require an overnight (12-16 hours on charge) and will require far more than a 13amp socket.

The other significant issue with batteries is temperature. Most high-efficiency types degrade in performance below 5°C.

To sum up batteries, we need to see a factor of 10 times in cell energy density (both mass and volume) before practical battery packs can emerge that give our hypothetical requirement of 1.7kWh/kg, as well as significant improvements in shelf life, safe operating temperature range and number of recharges.

POWER SOURCES 2: CAPACITORS

More accurately, ultra capacitors. The best available ultra capacitors are now achieving the same weight energy density as lead acid batteries at around 0.03kWh/kg.

Rather bizarrely, the humble coconut is responsible for this. All the major manufacturers of ultra capacitors use 'powdered activated carbon' refined from coconuts. This is particularly fortuitous for me as my wife's family has a coconut farm – though I'm not sure what LAA Engineering's reaction would be when presented with, "It's powered by coconuts!" Various alternatives to the coconut are available, but are considerably more expensive. An 'aerogel carbon' is being used for ultra capacitors of up to 0.09kWh/kg, and various car manufacturers are already using samples in parallel with batteries for experimental electric/hybrid vehicles.

It's worth at this stage having a closer look at energy density. For our purposes, we need to not only consider the weight (or more accurately the mass) energy density, but also the volume. Ultra capacitors at the moment are around twice as bulky as batteries.

Advantages of the capacitor over the battery are

» Very rapid charging. Measured in seconds, charging is in practice mainly limited by the size of the termination and the available supply;

» No overcharging risk; capacitors inherently self-limit;

» Very high discharge rates without risk of overheating;

» Shelf life in terms of tens of years;

» Re-charges in the millions compared to a thousand for the best batteries;

» Unaffected by temperatures down to -30°C

» Far lower safe disposal considerations;

» Fewer problems with high numbers in parallel.

The disadvantages are:

» As already mentioned, poorer volume energy density compared to batteries;

» As capacitors discharge, the voltage drops in proportion to the energy stored; batteries maintain their voltage within 10% of maximum when discharged. That means that far more complex control circuitry is required to maintain voltage to the load, in our case the motor. In practice, something around 25% of the stored energy is probably unusable for our purpose;

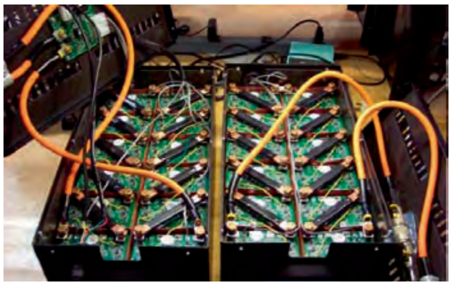
» Voltage balancing is required for capacitors connected in series. This probably equates with the complications of balancing the charging of batteries in parallel;

» Self-discharge is significantly higher than

WARNING
Maxwell
BOOSTCAP
ULTRACAPACITORS
3000 Farads | 2.7 VDC
BALANCE

Currently available ultra capacitors from Maxwell Industries range from 0.005kWh/kg to 0.03kWh/kg.

Close-up of Antare's 20E electric motor.

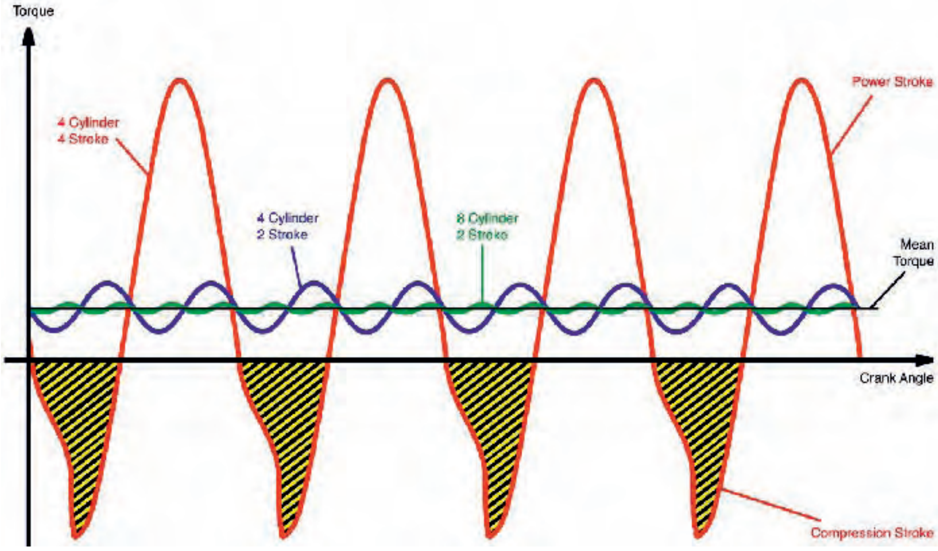


Li-ion battery pack

Intelligent Energy fuel cell.

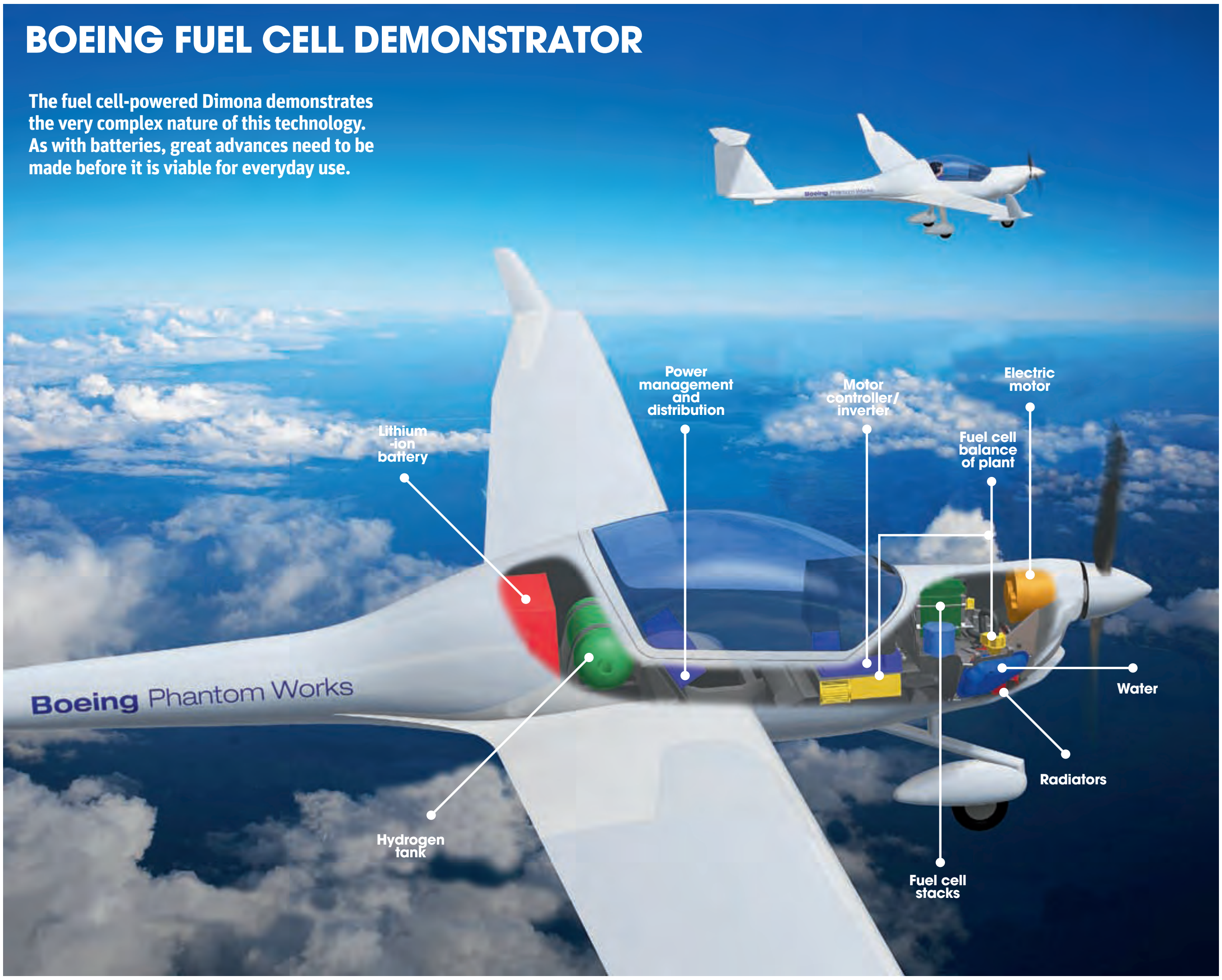
ELIMINATE POWER PULSES

Power pulses, which put considerable stresses on propellers, can be almost completely eliminated using particular motor designs. A four-stroke, four-cylinder engine actually produces a negative effect on the propeller at certain stages of the power cycle as the graph below shows.



BOEING FUEL CELL DEMONSTRATOR

The fuel cell-powered Dimona demonstrates the very complex nature of this technology. As with batteries, great advances need to be made before it is viable for everyday use.



batteries, but probably not high enough to cause significant loss during a three-hour flight.

To sum up ultra capacitors, we would need to see a 50 times improvement in energy density, but life, the number of recharging cycles and other specifications including self-discharge, are already satisfactory.

POWER SOURCES 3: FUEL CELLS

I think the first thing to comment on is complexity – the internal drawing of the Boeing demonstrator shows this all too clearly. Also, the fuel cell only provides enough power for level cruise (at 3000ft) for 20 minutes at 54kt, while the battery provides the take-off and climb boost. Even if all the limitations can be sorted out, the hydrogen fuel cells for transport will almost certainly be a hybrid. If the fuel cell and associated components were replaced by an equivalent weight of currently available batteries, it would probably have flown higher, longer and faster.

A fuel cell is an electrochemical cell that converts a source fuel into an electrical current and water. It generates electricity inside a cell through reactions between a fuel and an oxidant, triggered in the presence of an electrolyte. The reactants flow into the cell, and the reaction products flow out of it, while the electrolyte remains within it. Fuel cells can operate virtually continuously as long as the necessary flows are maintained (I took that from Wikipedia as I could not come up with a better one explanation!)

Fuels cells can be considered chemically rechargeable batteries, rather than reversing a chemical process as in rechargeable batteries, one or more chemicals being replaced in a continuous process. This leaves a number of problems, the principal one being that fuel cells don't accelerate rapidly and in practice require a store (battery or capacitor) to provide short-term power.

One of my hopes for electric-powered aircraft is simplicity, not only from the perspective of reliability, but also building and maintenance. As can be seen, fuel cells start at a disadvantage over batteries and capacitors for the homebuilder. Substantial cooling systems are required, as fuel cells get hot and are typically 50% efficient, which while better than combustion engines, leaves a significant amount of heat to be removed.

The difficulties don't end there, because while hydrogen has a potential to deliver a higher energy density than petrol, it is far less dense unless in liquid form or stored under pressure. These issues carry significant issues for the strength and weight of the hydrogen fuel tank and the system to feed the hydrogen to the cell stack.

There is an option to produce the hydrogen on demand rather than storing it. Nissan produced a car demonstrator using sodium borohydride fuel mixed with borax to produce hydrogen on demand, which was fed to a hydrogen fuel cell-battery hybrid. While it had a range of 300 miles at 60mph, it was over twice the weight of the petrol car, and passenger space had to be reduced to accommodate the systems. The complexity and weight almost certainly rules out this approach as a viable one in a light aircraft.

While fuel cells are able to compete with batteries as far as the main fuel stack is concerned (figures as high as 0.6kWh/kg having been achieved), once storage of the hydrogen and other ancillary requirements are taken into account, it is doubtful if much more 0.1-0.2kWh/kg can currently be achieved.

There are many other chemicals that can be used in fuel cells and hydrogen is simply currently the lead contender. The sceptics among us may think the reason why governments have funded hydrogen research so heavily is because it would be relatively easy to tax compared to an electric recharge system like batteries.

CONCLUSION

At the present time, there is no system that can replace our trusty 912s. However, next time we will take a look at research programmes and laboratory demonstrations that give some hope that a practical and lightweight system of electricity storage may be possible.