ROYAL AERONAUTICAL SOCIETY
GREENER BY DESIGN GROUP

AIR TRAVEL - GREENER BY DESIGN

ANNUAL REPORT 2023/2024

Greener by DESIGN

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The Royal Aeronautical Society ('the Society') is the world's only professional body and learned society dedicated to the entire aerospace community. Established in 1866 to further the art, science and engineering of aeronautics, the Society has been at the forefront of developments in aerospace ever since.

The Society seeks to (i) promote the highest possible standards in aerospace disciplines; (ii) provide specialist information and act as a central forum for the exchange of ideas; and (iii) play a leading role in influencing opinion on aerospace matters.

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INTRODUCTION

Greener by Design will celebrate its 25th birthday at the end of this year. It is salutary to look back and see how things have changed. 25 years ago most people did not believe in global warming and GBD spent much of its time trying to convince them that global warming was actually happening! No one will take action to rectify a problem that does not appear to exist. Even when I first started lecturing on the subject some 17 years ago, half the MSc aviation students on the course did not believe in global warming. However, this was before global warming was added to the GCSE Geography syllabus. This has precipitated a major change in public attitudes – today even six year olds know lots about it! So now most people believe in global warming and many think it is an emergency!

Also gone is the idea that all those who believe in global warming are somehow 'anti-aviation'. Just because we need to adjust what we do and how we do it (such as the switch to SAF and managing contrails) does not mean it will damage aviation – any more than other changes to reduce climate impact will damage our way of life.

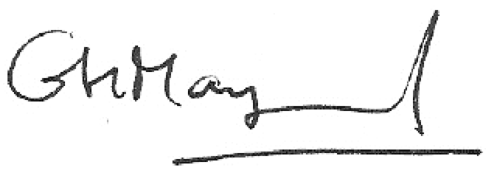
The change in public opinion has gone hand in hand with an acceptance that changes should be made for environmental reasons. Initially, this was principally focused on noise but then the pressure moved on to CO_2 emissions and latterly to the question of NO_x and contrails. Significant improvements have been made in the efficiency of aircraft and GBD was at the forefront of advocating these improvements. Work was done on flight profiles and an early win was the introduction of continuous descent approaches to runways. These minimise ground noise and reduce fuel consumption. GBD also pressed at successive conferences for improvements to ATM to allow more fuel efficient flight paths ('perfect flight'), engine improvements and air frame changes, such as retro fitting winglets. Attention was also drawn to fuel savings that could be made on the ground, through using ground fixed power supplies rather than APUs, and possibilities for moving aircraft around with electric tugs.

More recently, we, have turned our attention to the question of contrails, the need to quantify their effects on global warming and the need for action to reduce this effect. 25 years ago no one knew that contrails contributed every bit as much to global warming as aviation CO_2 does – indeed considerably more if you consider a 20 year time horizon rather than the classic 100 year horizon. We were also early advocates of the use of SAF, although it is fair to say we underestimated the problems in getting SAF production under way. Now all this is changing with incentives and mandates being put in place to encourage investment in new SAF plants, with many under construction now. Further details are on page 24 of this report.

Our industry has also doubled in size in the last 25 years, and is making a rapid – in many areas a complete – recovery from the effects of the pandemic.

However, the same cannot be said of our climate. On a visit last year to Switzerland I looked down on a glacier I had climbed up some 40 years earlier. Now the glacier has largely melted- just a few ribbons of ice left among a lot of moraines. The mountain hut where I stayed was only 50 metres or so above the glacier: now it is several hundred metres above what little bits of it remain.

The message is clear: our tardiness in tackling all causes of global warming has already caused irreparable damage. We must redouble our efforts to halt global warming so that further damage is avoided. We must also realise that Net Zero by 2050 is probably too late.



Geoff Maynard **Chair, Greener by Design**


SAF

TECHNOLOGY REVIEW

The last year (23-24) saw an apparent crystallisation of different future propulsion options in different market segments. However, these will likely change as the experience and technology associated with all options grow.

For now, sub-regional (9-seat and less) aircraft concepts favour battery-electric applications. Substantial battery technology improvements from current levels are critical to longer-range (larger aircraft) operations.

Many regional to short-haul (<150 seats) aircraft concepts are increasingly exploring 'Series Hybrid-Electric' propulsion options, ie a gas turbine or fuel cell converting a hydrocarbon or hydrogen fuel to electrical power that drives propellers via an electric motor. Some concepts also include electrical battery energy storage.

Conventional gas turbines burning kerosene/SAF (possibly hydrogen) seem most likely for future aircraft with more than about 180 seats.

All pathways have substantial technology, operational, certification and industrial challenges, which may alter the above mentioned preferences.

CONVENTIONAL DEVELOPMENT PATH

Perhaps the most notable observation concerning the conventional development path is the almost 3,800 gross aircraft sales achieved by Airbus and Boeing alone during 2023, which is more than double their 2023 deliveries (their backlog is growing).

These aircraft typically introduce a 10-20% fuel efficiency improvement if replacing older aircraft directly. However, many of these aircraft will grow the global fleet, leaving only SAF, seat densification and operational enhancements capable of directly addressing emissions from these aircraft through to 2050, when many should still be in service. Offsets address them indirectly.

There are little apparent near-mid-term efficiency improvements expected in the widebody market due to inadequate incentive to develop new aircraft types. There are also commercial constraints on large-scale investments in the post-lockdown environment, where airframe and engine companies focus on near-term delivery challenges related to their considerable and growing backlogs and rebuilding their balance sheets.

Current engine enhancement programmes might improve various in-service types by up to 1%. However, many prioritise improved maintenance costs to balance better the penalising effects of high gas-path pressures and temperatures needed to deliver high propulsive efficiencies (low fuel burn and emissions) and low community noise.

Embraer plans to improve the EJet 2 family's fuel efficiency by 2.5% in 2025 through a combination of minor airframe 'improvements' (probably aerodynamic) and reduced engine bleed air (improved engine efficiency).

The early/mid 2030s represent the earliest opportunity for new or significantly upgraded Boeing 787 engines, with A350 engines becoming upgrade candidates later in the decade. However, there are no public announcements related to such activity at the time of writing.

The Rolls-Royce Ultrafan test campaign successfully concluded, reaching its intended thrust capability. Further work will only occur when a suitable application appears. However, various elements will likely appear in the previously mentioned engine upgrade programmes.

The much-delayed Boeing 777-9 certification programme continues with its EIS currently planned for 2025 but, again, fuel efficiency probably matches its competitor rather than offering a significant improvement.

The only currently active widebody programme involving an all-new airframe is the COMAC C929, a potential 787 and A330neo competitor. Following the Russian aviation industry's withdrawal, the programme is now exclusively Chinese. However, the aircraft is unlikely to offer a step-change in efficiency beyond the 787 and A330neo, primarily because of a lack of propulsion system technology beyond the 787 engine technology.

The much-delayed Boeing 777-9 certification programme continues with its EIS currently planned for 2025 but, again, fuel efficiency probably matches its competitor rather than offering a significant improvement.

The 150-200 seat single-aisle market is the most likely focus for upgrades in the mid-2030s as Boeing and Airbus seek to replace their ageing, although heavily upgraded, models. The 737 first flew in the 1960s and is now on its 4th generation of upgrades (with about 50% less fuel per passenger mile than its earliest variants), while the 1980s' A320 airframe is on its third major upgrade. Both have publicly discussed a mid-2030s Entry-Into-Service.

Airbus and Boeing appear to favour kerosene/SAF-fuelled propulsion systems for these programmes, with Airbus' stated focus on the larger A321, ie ~200-seat, airframes, possibly pushing a little bigger, as this seems to be where the market is increasingly interested.

The original A320 family sales initially focused on the smaller A319 and A320 before shifting up to the A320 and A321. The A321 eventually just outsold the A319 (both achieving a ~20% share of the total family sales). Conversely, by February 2024, the A321neo received over 60% of the 10,000+ neo orders, with most other sales selecting the A320neo and little market interest in the A319neo.

The extended range (XLR) A321neo variant received its EASA certification in mid-2024, delayed due to required changes to its unique integral fuel tank. It offers potential fuel efficiency improvements on 'thin' (relatively low traffic) medium-range routes without significant freight requirements.

The Boeing trends are less clear due to the MCAS-related production and delivery interruptions and the resulting certification delays for the larger 737Max 10 and smaller MAX 7. However, Boeing's intent on developing the 737Max 10, the longest-ever 737 variant, indicates its recognition of this market segment's importance.

In itself, this interest in the larger variants represents improved fleet efficiency, ie lower carbon intensity per passenger mile/kilometre. However, it also increases total emissions for a constant number of aircraft movements.

Airbus' significant market success in the A321neo market against the 737 Max 9 and 10 could cause Boeing to move first, addressing the imbalance even though the 737 Max 10 is not yet in service.

A decision will be informed by Boeing/NASA's formal launch of the X-66A Transonic Truss-Braced Wing (TTBW) demonstrator in June 2023. It will provide full-scale testing of a very high aspect ratio truss-braced wing to deliver up to 10% improved fuel burn. It should guide Boeing's decision-making regarding any 737 successor. The concept includes an MD-90 fuselage and Pratt & Whitney GTF engines to reduce programme risk and timescales. The flight testing will clearly address the wing's flying qualities and response to atmospheric disturbances while confirming its aerodynamic and weight attributes and suitability for future production concepts.

Other potential improvements in this market sector aircraft involve structural weight savings due to composite or aluminium-lithium primary wing and fuselage structures. The engine manufacturers will likely receive requests for 10+% efficiency improvements relative to the CFM Leap and PW 1100G engines. The CFM Rise engine with a single-stage open rotor and a static second stage received considerable coverage over the last year. The need for a large blade diameter (similar to a modern widebody engine nacelle) delivering a much lower specific thrust is an integration challenge.

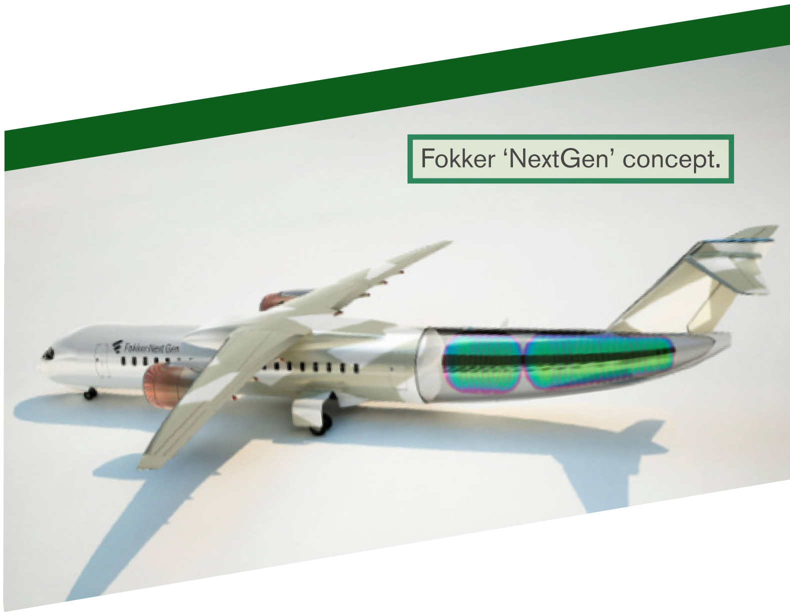
High aspect ratio wings, such as those planned for the X-66A TTBW demonstrator, are a likely source for improved aerodynamic efficiency. The potentially considerable, ie up to about 10%, improved aerodynamic efficiency, benefits of active or passive laminar flow might finally justify the additional production and maintenance costs of the related systems.

Dassault's technology roadmap discussed their intent to introduce a laminar flow wing to their large, long-range Falcon 10X business jet in the mid-2030s. The wing's sweep indicates an active laminar flow system, ie involving through surface suction, around the wing's leading edge.

The 120-150-seat Fokker NextGen concept targets a mid-2030s Entry-Into-Service using liquid hydrogen fuel burned in relatively conventional gas turbines. The high-wing architecture provides adequate ground clearance for its high-bypass ratio gas turbines.

The two-tank arrangement in the rear fuselage appears similar to that used by the ATI FlyZero single-aisle concept, which also targeted hydrogen combustion. Fokker initially reported a planned flight demonstrator programme based on a Fokker 100 airframe in 2028. However, it subsequently dropped this element of the programme.

The Chinese aerospace industry also announced plans for a 2035 Green Aviation 'Ecosystem', which includes their conventional aircraft being SAF-compatible. The programme also plans to address the commercialisation of electric aircraft (eCTOL) and the exploration of hydrogen-fuelled aircraft discussed in the following sections.



Fokker 'NextGen' concept.

NOVEL AIRFRAME CONFIGURATIONS

Last year's most noteworthy development in this field was the USAF Defense Innovation Unit's funding of a Blended Wing-Body demonstrator by JetZero. The programme targets a 767-size aircraft, ie a small widebody, and is described as a 'commercial aircraft demonstration programme' by JetZero.

These configurations typically offer significant aerodynamic efficiency and possibly weight improvements relative to conventional airframe architectures, but they generally impose stability and control, propulsion integration and cabin evacuation challenges. The effect on weight is uncertain due to non-circular pressure vessels and the propulsion integration challenges mentioned previously.

NASA X-66A Transonic Truss-Braced Wing (TTBW) demonstrator.

A 12.5% subscale demonstrator received certification to fly in late March 2024, with an expected first flight soon after. This model will test an articulating nose gear that substantially increases in length for the take-off roll to improve the high-lift performance. A full-scale demonstrator is planned for 2027 using PW GTF engines.

Bombardier also flight-tested a less-conventional configuration with a broader lifting fuselage and a 'U-Tail' empennage to shield the exhaust noise from the engine exhausts (mounted above the rear fuselage).

In March 2024, Embraer announced its near-term priority to improve its financial position by exploiting its current products, with a stated aim to be in a position to launch a new executive or commercial aircraft in about 2026. How their 'Energia' programme (reported in previous Greener by Design reports) will influence is unclear.

ELECTRIC AVIATION

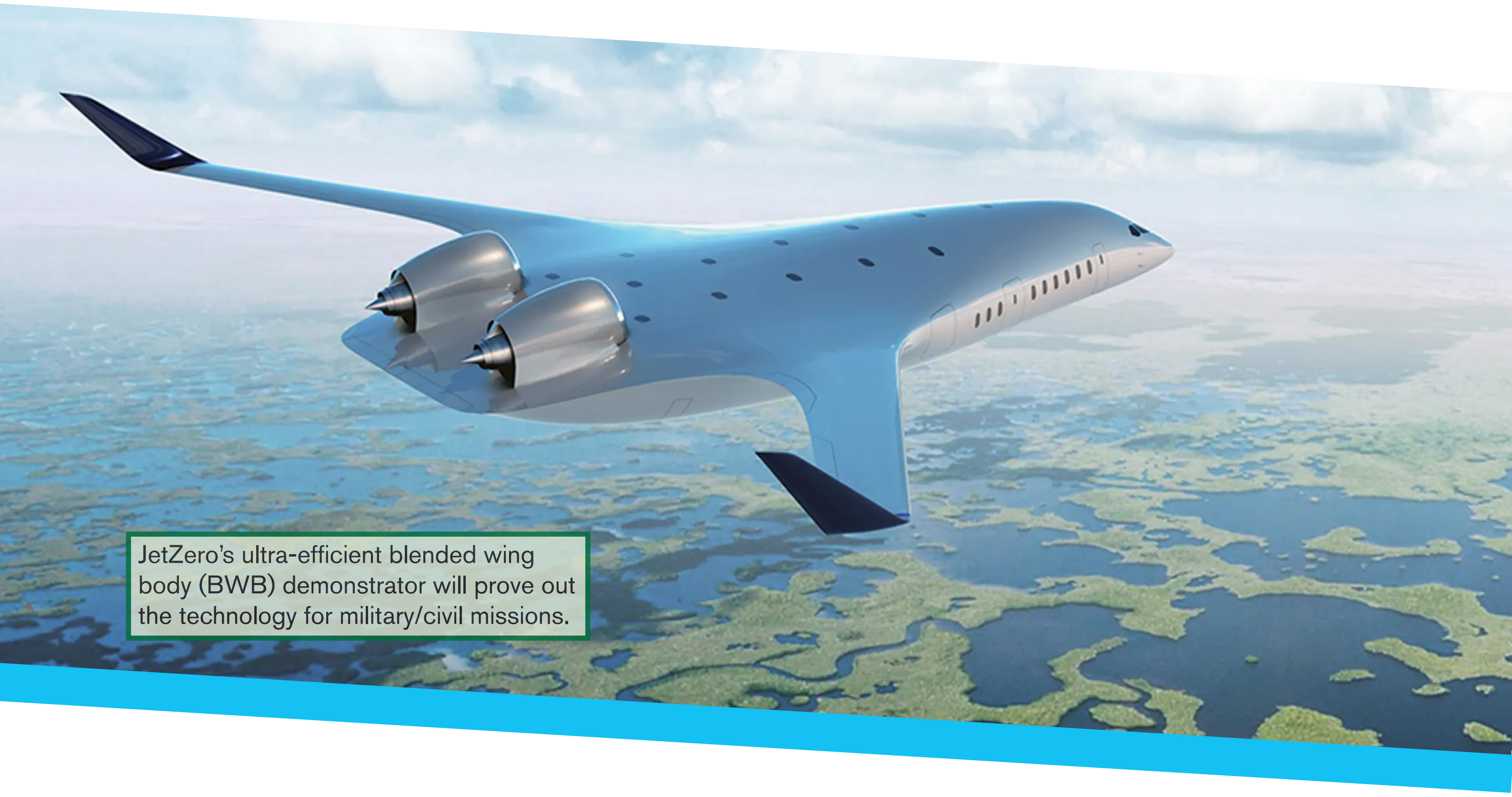
The underlying attractions of battery-electric aircraft propulsion are apparent. Zero tailpipe emissions are good for air quality and deliver zero operational carbon dioxide. It does require a plentiful, low-carbon electrical energy supply to deliver a global benefit relative to kerosene, but that is an industrial and governmental issue rather than an aerospace one. The same constraint applies to 'green' hydrogen and many Sustainable/ Synthetic Aviation Fuels (SAFs)

Battery-electric solutions work on cars/ automobiles for three prime reasons.

Firstly, a car's ratio of stored energy (fossil fuels) mass to the total vehicle mass ('energy mass fraction') values is less than 2-3% and delivers enough range such that consuming a full tank of petrol or diesel in a single day is rare. A 10,000-12,000 mile annual usage equals <32 miles per day and requires about 20-30 refills per year (once every 12-18 days).

Secondly, electric cars can easily refuel (petrol or electricity) at any convenient point along a longer journey with minor increases to overall travel time, especially if stopping for a 'comfort break' or meal, necessitated by the relatively slow speeds on long trips. Running the car until its battery is almost exhausted is possible and acceptable.

Finally, suppose a battery's cyclic life is 1,000 full charge/discharge cycles. An electric car should only need one battery pack during its lifetime. A 1,000 full-charging cycles should provide a lifetime mileage greatly exceeding the lifetime value of most petrol or diesel cars.



JetZero's ultra-efficient blended wing body (BWB) demonstrator will prove out the technology for military/civil missions.

Most trips involve short journeys or longer trips split into numerous shorter legs (typically 2-3 hours) and 150-200 miles (240-320km), ie well below half a tank.

Consequently, batteries that double the energy mass fraction while halving the range capability, ie a 6% energy mass fraction and 250-300 mile range, still work for many customers, permitting most charging at home or the workplace.

Electric aircraft impose additional fundamental challenges on the same basic power architecture.

Conventional aircraft fuel-mass fractions for the smallest, short-range aircraft are more than double those of cars (6-10% depending on range) and increase with longer-range aircraft. It is due to a combination of these short-range aircraft routinely flying hundreds, even thousands of miles each day and higher drag.

The aircraft's higher drag force is due to its higher profile drag (due to higher speeds) and its lift-dependent drag (minimal on a car as it does not generate any significant lift).

Doubling the energy mass ratio from around 10% (kerosene on a small aircraft) to 20% for a full battery-electric aircraft has a much more significant effect on the aircraft's weight, drag and configuration compared to the same effects on a ground vehicle.

The aircraft's reserve energy requirements further accentuate aircraft fuel/energy fraction requirements. The 'reserves' ensure the aircraft does not exhaust its energy supply due to unforeseen circumstances delaying or preventing landing at the planned destination airport at the intended time. The reserve energy requirements for short mission lengths can get close to the main mission fuel, often exceeding it in the real world, depending on the fuel/energy policy in use.

A car can top up its energy just before it depletes its battery with an accidental exhaustion being an inconvenience to its occupants. Battery exhaustion on an electric aircraft is an existential threat for those on board.

Visual Flight Rules (VFR), used for small personal or training aircraft, require modest reserve fuel/energy reserves. However, the challenge increases substantially for commercial transport aircraft that must flight plan to land with considerable unused energy (reserve fuel/energy) still on board the aircraft.

Battery life – each flight is a substantial battery charge /discharge cycle, suggesting the aircraft reaches a nominal 1,000 cycles (assumed previously) in <4-6 months, based on 6-10 flights per day.

Does this require two expensive battery changes each year, or are battery cyclic lives greatly exceeding the nominal 1,000 cycles assumed? Will the high reserve energy fraction extend battery life, as the battery status rarely gets below 50%? Whatever the answer to these questions, the battery replacement costs attributed to each flight's costs need consideration, but not for cars.

Bombardier's blended wing EcoJet sub-scale demonstrator.

BATTERY-ELECTRIC PROGRAMME RESPONSES

The last few years saw an apparent realisation of the above challenges. Some programmes with full battery-electric propulsion systems switched to hybrid-electric solutions. The 30-seat Heart ES-30 and 80-seat Maeve M80 programmes added gas turbines as turbogenerators to supplement the battery storage. Their previous 19-seat Heart ES-19 and 44-seat Maeve-01 concepts were full battery-electric aircraft.

The Maeve M80 propulsion system appears capable of using battery and turbogenerators supplied electrical energy at any time, delivering up to 800nm range. This approach may permit the inclusion of smaller gas turbines but does generate tailpipe emissions on all flights. However, the battery energy should substantially reduce the mission emissions compared to conventional turboprop aircraft.

A July 2024 announcement identified Pratt & Whitney Canada as the propulsion partner for current studies.

The ES-30 battery sizing enables a short 200km flight on battery energy alone, with the turbogenerators consuming kerosene or SAF for the reserve fuel requirement, ie it is not routinely consumed. The mass of the turbogenerators, ancillary systems and fuel (tank and kerosene/SAF) weighs considerably less than the batteries needed to provide the same reserve energy.

Longer flights (up to 400km) use the turbogenerators, consuming the kerosene/SAF as 'range-extenders' while still supplying the reserve energy requirements.

Heart Aerospace's ES-30.

May 2024 saw a further reconfiguration with the outboard electrically driven propellers replaced by conventional turboprop engines. Increased diameter inboard propellers driven by larger electric motors provide all propulsive power in full battery-electric mode. This architecture frees up the rear fuselage space previously used to accommodate the gas turbine turbogenerators for battery accommodation, thus greatly reducing the battery storage compartments below the fuselage.

The increased diameter inboard propellers and the elimination of the prominent under-fuselage battery compartment (evident in the image above) are clear in the images at the bottom of this page.

The new configuration should reduce the aircraft drag due to the battery compartments and remove the proximity of noisy turbomachinery to the passenger cabin. It also greatly reduces the fire risk in the fuselage.

The aircraft feathers the turboprop propellers when operating in all-electric mode to minimise their drag, running the engines as range extenders. Performing a pure turboprop take-off is probably impossible due to the substantial asymmetry following an engine failure, thus requiring some thrust from the inboard engines. The latter could involve battery or some level of electrical power offtake from the turboprops, ie they are still acting as turbogenerators.

Presumably, replacing the turbogenerators and powering the electric motors with turboprop engines also delivers more efficient thrust generation as it avoids any losses from the electric power train.

The Dutch 90-seat Elysian E9X concept uses the same approach as the earlier Heart ES-30 configuration with distributed propulsion using motor-driven propellers. The concept stores some of its batteries inside the wing profile.

Maeve is developing an 80-seat hybrid-electric regional airliner.

One certification question: how are the flight crew certain the turbogenerators will start until they try to start them, possibly after a decision to abort a landing? A problem already faced by glider pilots flying aircraft with sustainer motors. They often test their motors before leaving the vicinity of their departure airfield. Despite this, the gliders still sometimes make field landings when the engines fail to start when needed.

A solution to this might require at least one of the gas turbines to be running continuously, with questions over whether it should run at idle or at a higher power. The idle option consumes minimal fuel, ie emissions, but provides no gain or benefit to the aircraft, thus increasing the flight's energy costs. Increasing its throttle provides some thrust or secondary power to augment the battery power but increases the flight's emissions. The situation is complicated by gas turbines' highest efficiency typically occurring at relatively high powers.

These changes follow Cranfield Aerospace's Project Fresson 2021 switch from an initial battery-electric propulsion system to hybrid electric using hydrogen fuel cells to deliver zero tailpipe emissions. Both activities included retrofitting the systems to a Britten-Norman BN-2 Islander aircraft.

Wright-Electric (working with easyJet) originally (2017) planned a 150-seat all-electric A320 replacement with a 2027 entry into service (EIS). In late 2021, their plans switched to using a fuel cell-based hybrid-electric system powering four of their 1.5-2MW electric motors to a BAe-146 aircraft, with a planned 2024 first flight and 2027 'Entry-Into-Service' (EIS). Both hydrogen and aluminium fuel cells are under consideration.

Recent news releases suggest continued motor testing, but there is no update on the first flight date.

Elysian Aircraft's E9X.

Following the Eviation Alice's first and only test flight in 2022, there are no reports of further flights or an updated expectation of its EIS, last reported as 2027. The latter probably requires production aircraft flight testing to start before the end of 2025.

Eviation released a rendering of the production aircraft in April 2024 following the completion of its Conceptual Design Review. While it retains the prototype's basic architecture, its tubular fuselage cross-section and blunter nose profile are now more conventional compared to the prototype's more triangular and constantly varying cross-section and elongated nose. These changes probably result from manufacturing costs and possibly weight (cross-section) and certification requirements (nose profile).

There are also no public updates during the 2023-24 period from the Harbour Air programme eBeaver programme. The most recent update involving the de Havilland DHC-2 Beaver aircraft retrofitted with electric batteries and motor was its summer 2022 45-minute demonstration flight from Vancouver to Victoria, British Columbia. It is reportedly awaiting updated batteries, which are better suited for a payload operation.

Some of these programme decisions highlight the considerable challenges of deploying full battery-electric propulsion to aircraft of increasing size and range. The battery's poor specific energy compared to kerosene creates a 'vicious circle' in the aircraft design. The resulting heavy batteries limit the energy available on board the aircraft, which reduces their maximum range.

Whisper Aero released details of its 'Jetliner' 100-seat battery-electric concept in early 2024, following a 2023 unveiling of the 9-seat Whisper Jet in mid-2023. The Jetliner includes a distributed propulsion system claiming a 5-10% improved propulsive efficiency, with the exhaust blowing over the upper surface to improve lift and increase its aerodynamic efficiency.

The concept targets a 0.78 Mach number and a 770-mile range (unsure if statute or nautical miles). However, it is a 2050 concept, enabled by >640Wh/kg battery technology at pack level (>800Wh/kg cells).

Its resulting >23t battery mass is more than double the payload mass and represents a 32% energy mass fraction, which is triple the equivalent value for a modern 2015 EIS regional jet's equivalent value at the same mission length. The A220-100 value increases to about 22% at its 2,200nm design range.

Data sources: Whisper Jetliner – Aviation Week 4th March 2024: A220-100 – RAWAvCon performance data.

The aircraft's glide performance with some or all of the electric motors inoperative is unclear, but the lack of overwing blowing will reduce lift, and the ducting and stationary blades should increase drag and possibly further degrade lift.

The Whisper Jetliner concurs with various other reports (and the writer's analysis) that identify 700-800Wh/kg battery pack specific energy as the required threshold for battery electric aircraft of significant size and range, ie impact on global aviation emissions.

At this level, the battery breaks free from a large proportion of the stored energy transporting the battery itself rather than the payload.

HYBRID-ELECTRIC PROPULSION

The battery challenges and expected continued focus on improved kerosene/SAF aircraft with nominal seat counts exceeding 180-200 seats create a potential market segment below 180 seats. It could be filled by the various forms of hybrid-electric propulsion systems, although kerosene/SAF options and hydrogen combustion will likely challenge in this space.

Many of the larger hybrid-electric options consider using fuel cells to convert stored energy into electricity to power motor-driven propellers. The Wright-Electric BAe-146 is mentioned previously with possibly a hydrogen-fuelled or aluminium fuel cell. Like many other fuel cell systems, this is a


The Eviation Alice.

Whisper Aero has unveiled a concept for a 100-seat electric airliner.

Universal Hydrogen's flight test demonstrator.

series hybrid-electric solution, ie all electrical energy generated by a gas turbine or fuel cell with no battery energy storage.

After 5-years of activity, the RTX Hybrid-Electric Propulsion Flight Demonstrator programme (presumably a renaming of the original Project 804 branding) is testing some propulsion components but with no first flight date published. However, the consortium reported the first full-power runs of the 2MW propulsion system in July 2024. The propulsion system comprises a 2MW gas turbine and a 1MW electric motor.

Work continues on hydrogen fuel cell propulsion systems at Airbus, ZeroAvia, Universal Hydrogen, Cranfield Aerospace, DLR, GKN and Intelligent Energy. The various projects mainly target electric motor-driven propeller aircraft in the <100-seat market segment.

However, Universal Hydrogen ceased trading in June 2024, having flown a DHC-8-300 aircraft in 2023 with a hydrogen-powered fuel cell replacing one of the original turboprop engines. Their website included a stated intent to enter passenger service in 2025.

The reserve energy mass represents a small fraction of the mission landing weight at these short ranges. It is a result of hydrogen's high specific energy. The additional tank mass and volume introduce a penalty, but the net comparison with kerosene/SAF is minor. It eliminates one of the battery's primary challenges.

However, hydrogen fuel cell-based aircraft propulsion is also not straightforward. The cooling systems required to extract the fuel cell's waste heat and exhaust it into the atmosphere cause potential weight and drag challenges. Note the large air inlets/radiators on either side of the starboard (right) powerplant installation of Universal Hydrogen's flight test demonstrator. The latest renderings of Cranfield Aerospace 'Solution's Project Fresson Britten-Norman Islander also show a substantial cooling system installed beneath the fuel cell installation.

The placement behind the propeller disc increases the flow velocity into the radiators, possibly reducing the thrust produced, which requires significantly higher fuel cell power output (with even greater cooling requirements). It is possible that some of the radiator technology lessons and designs for World War 2 aircraft are applicable. The de Havilland Mosquito's radiators were positioned inside the wing leading edges with exhausts on the lower wing surfaces to reduce blockage behind the engine, ie drag.

In 2021, ZeroAvia targeted 2024 revenue flights with passengers across the North Sea between London and Rotterdam. No further press releases suggest this will happen in the coming months, although they announced a partnership with the Dutch KLM airline in July 2024. It targets a 2026 demonstration flight between two airports with a large turboprop airframe equipped with a fuel cell propulsion system.

Other major ZeroAvia highlights included Airbus becoming ZeroAvia's lead investor in late 2023, with Alaska Airlines also investing. The latter includes a donated de Havilland Canada DHC-8-400 turboprop aircraft for test bed purposes.

ZeroAvia also announced a partnership with JEKTA to investigate a fuel cell-powered version of their 19-seat amphibious aircraft (the baseline is battery-electric). It targets an increased range of

Jekta and ZeroAvia will develop and certify an integrated fuel cell power generation system, including inverters, other electronic components, a hydrogen tank and fuel system.

about 500-600km, compared to the approximately 100nm range of the baseline battery-electric aircraft.

The progress over the next few years will be interesting, including ZeroAvia's possible use of Cryo-compressed hydrogen (CcH2). It increases hydrogen's volumetric specific energy (kg/litre or Wh/litre), reducing the tank volume, although the 240-bar storage pressure presumably increases the tank mass. This solution, a hybrid of liquid hydrogen's cryogenic storage and 700-bar gaseous tanks, also removes the boil-off considerations for conventional cryogenic tanks.

Various fuel cell companies, including ZeroAvia are also exploring 'High Temperature' fuel cells as a means to improve overall system efficiency, including the previously mentioned large, draggy cooling systems. However, their characteristics might impose other operational challenges.

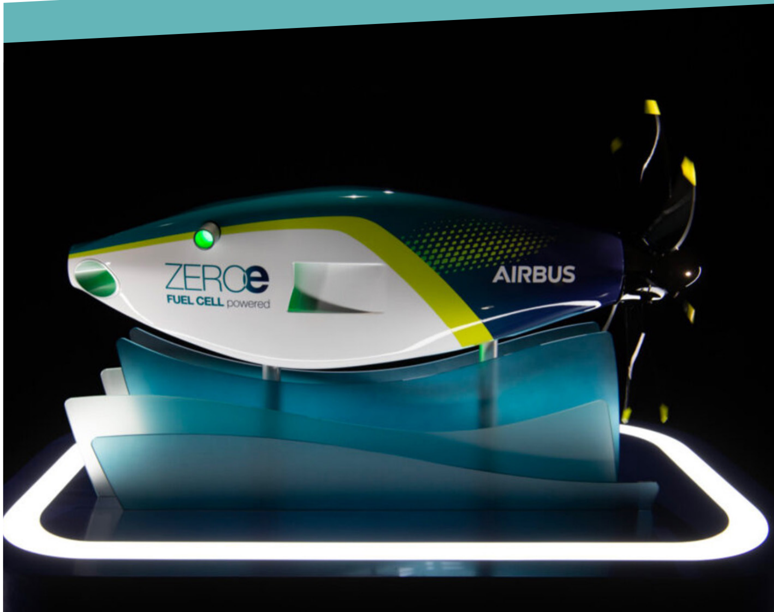
March 2024 also saw the formation of the 'Hydrogen in Aviation' partnership involving easyJet, Rolls-Royce, Airbus, Orsted, Bristol Airport, GKN Aerospace and ZeroAvia. The partners possess the breadth of skillsets to explore and address the various multi-disciplinary challenges of designing and operating hydrogen-fuelled aviation in the UK. In April 2024, the consortium conducted the first airside trial of hydrogen refuelling. It involves refuelling baggage tractors but involves similar risk management and challenges of the corresponding actions for an aircraft.

Airbus reported the successful ground tests of a 1.2 MW hydrogen fuel cell in mid-2023 as part of their 'Aerostack' collaborative project (with ElringKlinger). Subsequent successful testing of the electric power train (motors to power a propeller) and fuel cell's ancillary system train in Autumn 2023 enabled 'iron pod' testing, combining the two elements connected in early 2024.

Airbus also discussed how their increased focus on the 180-200+ seat with a SAF/Kerosene replacement might also represent an opportunity for a hydrogen-fuelled propulsion system on smaller aircraft. Airbus discussed a likely 100-seat regional aircraft using hydrogen fuel combusted in modified gas turbines (probably larger turbofans) or fuel cells (likely propeller-driven aircraft). Decisions on the route forward are reported likely in 2025-26, which supports a potential mid-2030s Entry-Into-Service.

The larger variants' dominance of the mid-2020s single-aisle market might indicate the hydrogen 'options' potentially addressing less than half of that market.

Airbus reported the successful ground tests of a 1.2 MW hydrogen fuel cell.



Boeing released a 'Hydrogen and 'Sustainability' Factsheet in March 2024. They view hydrogen fuel cells (and Battery-Electric) propulsion systems slowly penetrating into Advanced Airborne Mobility and < 20-seat sub-regional markets until beyond 2040, when they might grow into <80-seat regional markets.

They view SAF as the only option for larger, > 20-seat aircraft until '2040 and 'beyond' when hydrogen combustion becomes a possibility, driven by the production of clean hydrogen for various synthetic SAFs.

The French Beyond Aero company revealed details of its 'Beyond Aero 'One', an 8-10 seat business jet, at the EBACE 2024 show in May 2024. The aircraft uses a 1.3-1.4MW fuel cell hybrid-electric propulsion system driving a pair of ducted fans, with a planned 2030 Entry-Into-Service and an 800nm range capability. The cylindrical, gaseous hydrogen fuel tanks apparently fill the lower fuselage below the cabin with the fuel cell system in the rear fuselage between the engines.

The certification of the 700 bar hydrogen tanks under survivable emergency landing loads will be critical, given their location close to the passenger cabin.

SUPERSONIC

Expected 2023 first flights of the Boom XB-1 demonstrator and NASA X-59 QUESST did not occur, with targets slipping into 2024. The XB-1 made its maiden flight in late March 2024.

Beyond Aero hydrogen-powered business aircraft.

The Boom XB-1 demonstrator.

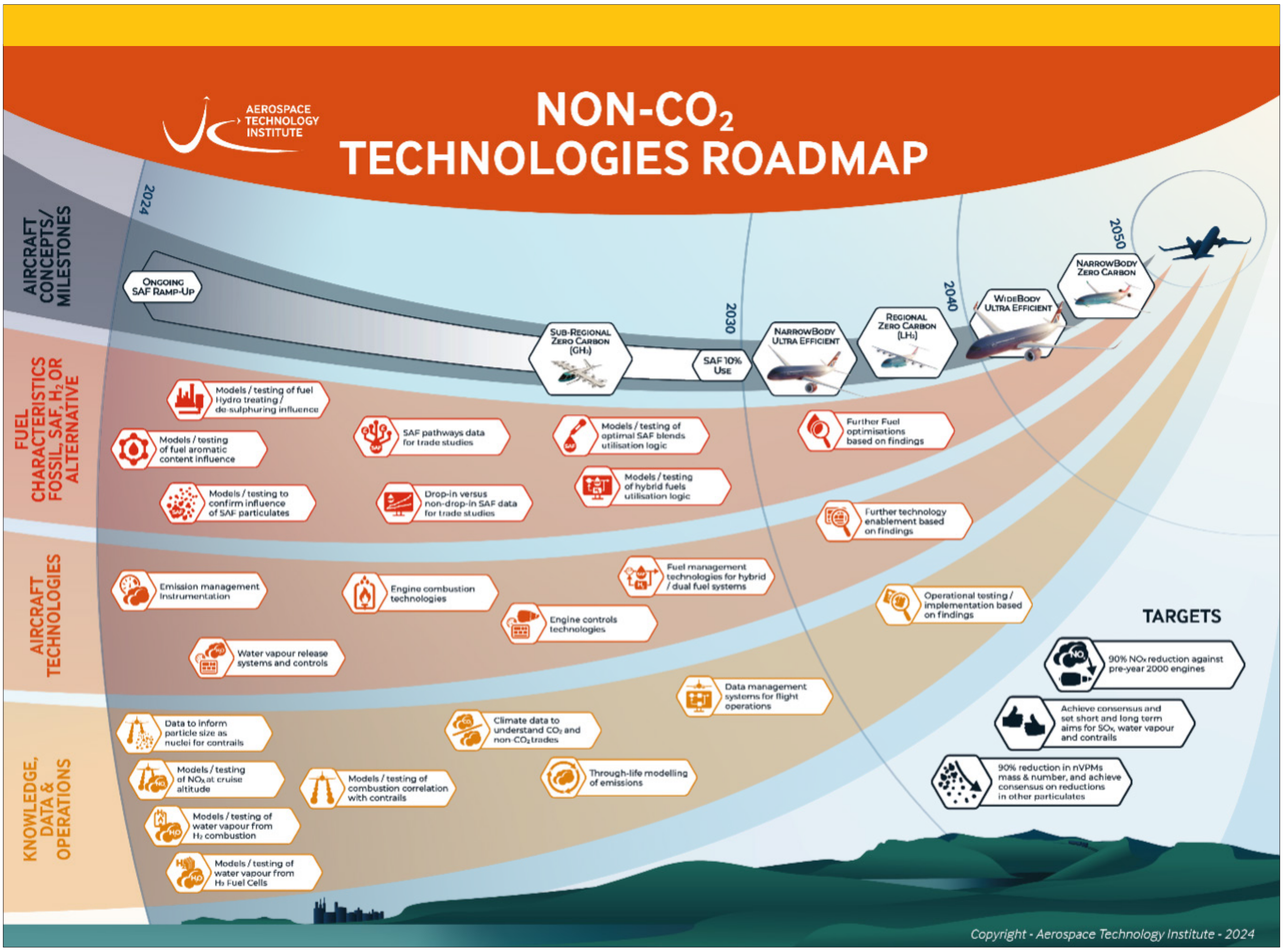
However, their only route for supersonic net zero flight is the diversion of limited SAF supplies from other classes of more fuel-efficient commercial air transportation, capable of delivering much greater revenue tonne-kilometres per tonne of SAF.

EU CLEAN AVIATION AND UK AEROSPACE TECHNOLOGY INSTITUTE (ATI) ACTIVITIES

The various EU's Clean Aviation flight demonstrator projects are in their early stages, with few headlines from the last year. Major milestones/headlines for flight demonstrators should occur in the coming years.

However, the UK rejoined the EU Horizon research and innovation funding programme, which supports the Clean Aviation programme, in September 2023 and should be of interest to UK-based readers.

The UK ATI continued its ongoing programme supporting the UK aerospace industry. In March 2024, it released a 'Non-CO_2 Technology Roadmap' with £17m initially assigned to projects addressing the subject.



NEXT STEPS...

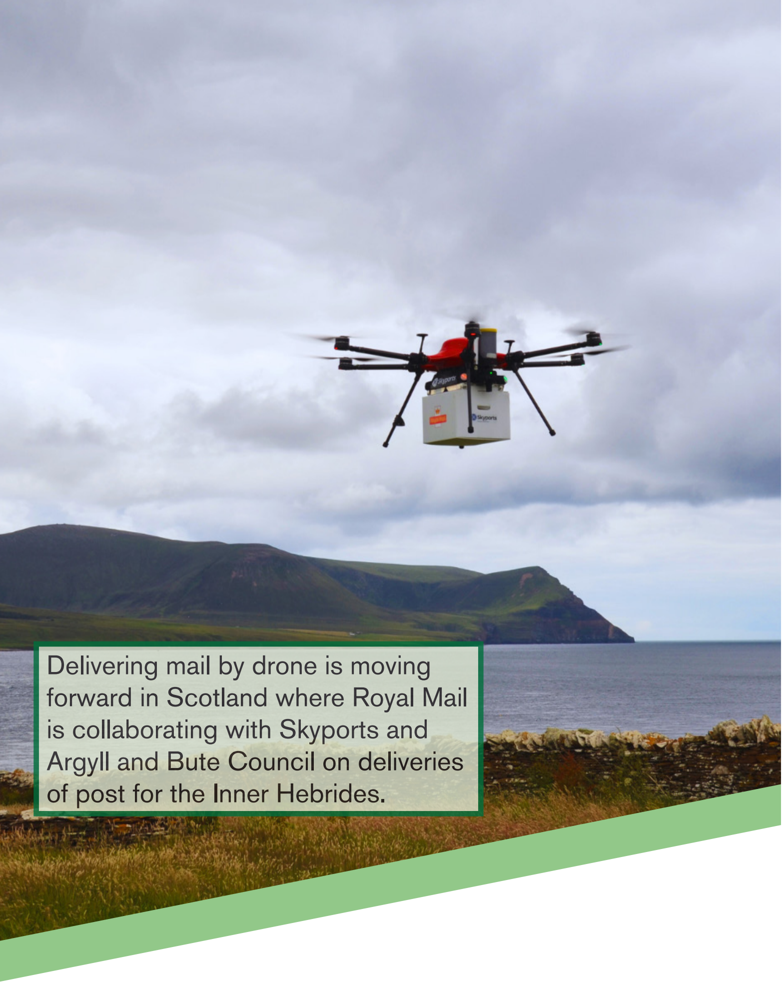
If the various novel propulsion systems are to meet their targets for commencing commercial operation in late-mid 2020s, the coming year (2024-2025) should start to see the increasing emergence of prototype aircraft and flight-test/production configurations firming up before their ultimate assembly.

Any special certification conditions or novel acceptable means of compliance also need defining. An example of battery-electric aircraft includes whether the battery output must remain capable of performing a missed approach at the end of the diversion mission. It is not specified or necessary for a gas turbine-powered aircraft, whose gas turbines define the maximum propulsive power output rather than its energy supply (fuel feed).

Potentially exciting times

This first round of novel propulsion system concepts, whether successful or not, will guide subsequent concepts targeting Entry-Into-Service (EIS) during the 2030s. It continues the process already evident in the various and fundamental recent changes to the concepts targeting novel propulsion systems.

Developments in the planning and expectations for future 100-250-seat aircraft by Airbus and Boeing are also keenly awaited. However, their activities are likely to focus on narrowing down alternatives rather than launching any firm programmes.



Delivering mail by drone is moving forward in Scotland where Royal Mail is collaborating with Skyports and Argyll and Bute Council on deliveries of post for the Inner Hebrides.

OPERATIONS REPORT

ICAO'S LONG-TERM ASPIRATIONAL GOAL (LTAG) AND GLOBAL FRAMEWORK FOR SAF, LCAF AND OTHER AVIATION CLEANER FUELS

At the last ICAO assembly it was resolved that "ICAO and its member States are encouraged to work together to strive to achieve a collective long-term global aspirational goal for international aviation (LTAG) of net zero carbon emissions by 2050 in support of the Paris Agreement's temperature goal ..." . To achieve this long-term goal, a Global Framework is being developed to accelerate the development and deployment of SAF, LCAF and other clean aviation fuels, and predictability to all stakeholders and is critical if aviation is to be Net Zero by 2050. This will provide greater clarity, consistency and predictability to all stakeholders. This global framework has four building blocks: policy and planning, regulatory frameworks, implementation support and financing. The building blocks are interconnected and to achieve their intended purpose they need to work together. They will achieve international uniformity in the production and savings claimed for the use of these fuels.

As a result at the CAAF/3 meeting in November last year it was agreed to work towards a vision of implementing the Global Framework. This is based on dividing the work into the four 'building blocks' identified above. The vision is to reduce worldwide aviation emissions by 5% by 2030 through using SAF and LCAF. It also encourages States to work with ICAO to work out how this is to be done. Critical to this is increasing the production of these fuels and facilitating financing and the technology transfer required. There are several criteria listed which States should follow, including not negatively impacting the growth of air transport and contributing to a level playing field among all States. No fuel should be excluded if it meets the CORSIA sustainability criteria. It is also recognised that, to achieve the vision, a collaborative effort is required, and States are encouraged to include other aviation stakeholders, such as aircraft operators, airports, aircraft and engine manufacturers, fuel producers and fuel standard bodies in developing their action plans.

The second building block is the regulatory framework. To ensure regulatory transparency, the CORSIA sustainability and certification criteria and the associated methodology laid down for CORSIA eligible fuels should be used. States are encouraged to accelerate the certification of additional fuel production pathways to help maximise the production of SAF and LCAF. Also listed here are a number of accounting methodologies designed to ensure the environmental integrity of the system by avoiding double counting and using verified emissions information. As far as possible the CORSIA methodologies and procedures are to be used.

Building block 3 is associated with implementation support. Basically this is about encouraging the need for partnership and alliances between States and stakeholders, facilitating exchanging information and developing national and regional policies that can be applied across all stages of the fuel supply chain. It should cover items, like government incentives, grants, tax credits, etc, for research and development into the sourcing of potential feedstocks and increasing their supply. Knowledge needs to be shared between States because otherwise some countries are likely to be left behind. This would be contrary to ICAO's NCLB policy (no country left behind).

Building block 4 is about financing. The LTAG report suggests that fuel suppliers will need to

invest up to 3.2tn US dollars to produce sufficient cleaner fuels through to 2050. This excludes investment for other CO_2 reduction methods, including operational improvements and aircraft technologies. A number of suggestions are made about how additional finance might be achieved, including mention of public private partnerships and considering potential investment opportunities and returns. States are encouraged to talk to other financial organisations and stakeholders to draw on a wider range of finance. States also welcome the establishment of the 'ICAO Finvest Hub'. This has been set up to improve the aviation industry's access to public and private investment and funding from financial institutions. ICAO is encouraged to speed up its work on this so that it can complement the other opportunities in decarbonisation.

While one may be critical of the speed and bureaucracy of ICAO, there is no doubt it is headed in the right direction, and it is well placed to encourage all States to address reducing aviation's carbon footprint. It will achieve little if only some States reduce carbon emissions, while others continue to increase. The section on SAF on page 24 explains in more detail what the UK and Europe are doing.

CONTRAILS

Since our very successful conference on Contrail Management last year (details can be found starting on page 28), an interesting research paper has been published. The study is entitled 'Feasibility of contrail avoidance in a commercial flight planning system: an operational analysis' by A. Martin Frias *et al* and it was published in Environmental Research: Infrastructure and Sustainability, 4(2024) 015013, published on 19 March 2024.

This study has used a commercial flight planning system used by airlines to calculate the optimum route for their flights, considering all the variables.

The study then considers what alternative route should be flown on a particular day to avoid predicted contrails, and what the implications on cost and fuel consumption would be. Their conclusion is that additional cost would be very small (+0.08%), and that the increase in fuel consumption would also be very small (+0.11%). They would have made a very substantial and significant decrease in contrail climate forcing (–73.0%). The authors note that "this simulation provides evidence that contrail mitigation entails very low operational risks even regarding fuel. This study aims to serve as an incentive for operators and air traffic controllers to initiate contrail mitigation testing as soon as possible and begin reducing aviation's non CO_2 emissions."

This mirrors the message that our conference last year gave: contrail management needs to be introduced now to significantly reduce the very significant global warming effect of contrails. The cost is insignificant.

SUSTAINABLE AVIATION FUELS

WHAT ARE THEY?

One of the ways aviation can reduce its impact on global warming is by moving away from burning kerosene (Jet A) and switching to sustainable aviation fuels. These are non-fossil based fuels which generate lower life cycle carbon dioxide emissions than conventional jet fuel. SAF is designed to be burnt in ordinary jet engines, and is currently certified to be used in a blend with kerosene of up to 50%. Various trials have been undertaken successfully with higher percentage blends up to 100% and it is widely expected that the maximum percentage blend will be raised in the near future.

SAFs are divided into 'generations', depending on the type of feedstock used to make them.

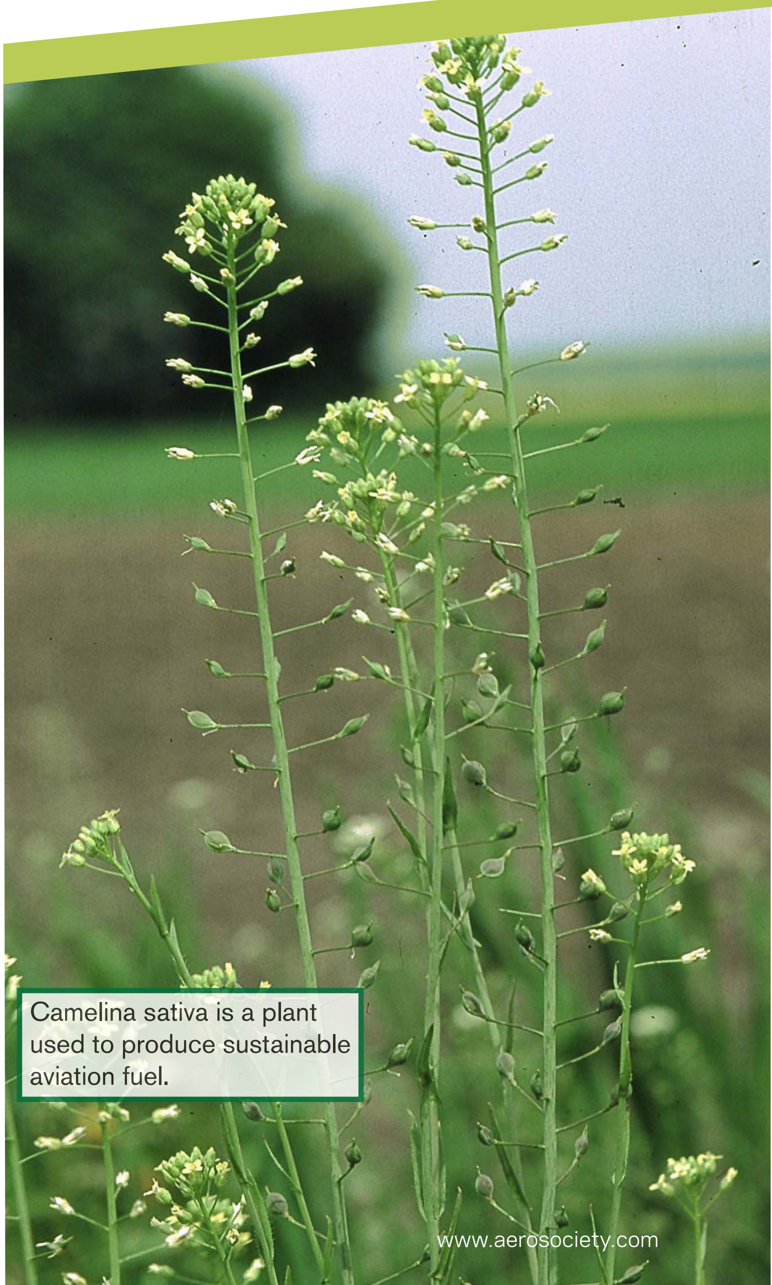
1g fuels were the first to be developed, being made from HEFA (hydrogenated esters and fatty acids). This is the main route for the production of SAF commercially today. Around 300m litres were produced worldwide in 2022, estimated to rise to 5bn litres by 2025 (IATA forecast).

2g fuels are currently under development, with several ready to enter full scale production in the very near future. They are produced from other sustainable feedstocks, either from plants (grown specially or waste plant material from existing processing) or from other carbon containing waste (including gases). Various methods are approved, including conversion of waste first into a synthetic gas, and then its conversion into a fuel using catalysts. Another method is to convert flue gases or biomass waste into ethanol and convert that into SAF.

3g fuels are often referred to as 'e-fuels' or PtL (power to liquids). Instead of letting plants capture the carbon dioxide from the atmosphere, it is taken directly from the atmosphere by chemical means (or from an industry source) and combined with green hydrogen to make SAF. This process requires a lot of energy (more than is released when the SAF is burnt), so a plentiful green electricity supply is essential for this process to be carbon-neutral. Although the process is well understood, further development is required, along with a demonstrable practical capability to achieve large-scale direct air capture. Governments have recognised the importance of supporting the development of PTL fuels, for example in the EU and the UK where they have set PTL sub-targets as part of the SAF mandate. In addition to this, there will need to be access to key enabling factors, such as cost effective renewable energy and green hydrogen.

THE NET ZERO CHALLENGE

The UK government was the first government to publicly announce that it would reduce emissions to net zero by 2050. It followed this up with legislation so it became a binding legal commitment and it also proceeded to draw up a plan as to how the target was to be achieved.



Camelina sativa is a plant used to produce sustainable aviation fuel.

The government's plan to achieve net zero by 2050 (now incorporated into law) examined various ways that aviation could achieve net zero. It concluded that, while battery power and hydrogen propulsion may become practical before 2050, their effect on the need for Jet A fuel would be negligible. This is partly because battery operation is only likely to be practical with small aircraft travelling shorter distances, and introducing hydrogen extensively as an aviation fuel cannot be achieved before 2050 as no aircraft of this type are currently in production. The government, therefore, decided to make SAF the key component of achieving net zero in the aviation sector. The plan assumes that SAF will be produced in sufficient quantities to reduce net CO_2 emissions by approaching 50% compared with today, including allowing for some expansion of the aviation industry. The balance will be removed by carbon capture and storage, and various other means.

Depending on the production methods, 1g SAF is likely to have around a 70%- 90% reduction in carbon intensity, rising potentially to 100% for 2g and 3g SAF. Generally, this will require some associated Greenhouse Gas Removal technology (with associated storage capability) to remove the CO_2 produced during the SAF production, Note that, while SAF can be carbon-neutral in respect of CO_2, it does not follow that they are neutral so far as their effect on global warming is concerned. Contrails and the effect of other substances present in aviation exhaust (such as NO_x) are not necessarily addressed by the switch to SAF and need to be considered separately. Further research is being undertaken to better understand the potential benefits of SAF in reducing the incidence of contrails.

Costs are the big unknown. It is widely accepted that SAF costs will exceed those of fossil-based fuels by at least 100%, and that 2g and 3g produced fuels will be even more expensive. Because the rules on the provenance of feedstocks for SAF fuels are tight (and rightly so to avoid food suitable for human consumption been diverted into producing SAF), the availability of suitable feedstocks worldwide will be insufficient to meet the demand for SAF using solely 1g SAF. Hence, the need for 2g and 3g fuels produced chemically, at initially significantly higher cost.

So the challenge is how to accelerate the production of 2 and 3g SAF so that the cost differential with fossil fuel can be reduced.

SWITCHING AWAY FROM FOSSIL FUELS

As SAF is considerably more expensive, why would airlines want to use it? There is a limited case on financial grounds at today's level of carbon prices and incentives. However, the world is very rapidly getting warmer. The World Meteorological Organization reported in its 'State of the Global Climate' report in March 2024, that the global mean near surface temperature in 2023 was 1.45 degree (+/–0.12 deg) C above the 1850-1900 average. This is very close to the 1.5 degree target (the Paris target). Aviation is a consumer industry, and needs to reflect public opinion if it is to continue to prosper. Concern about global warming is now widespread and 'flight shaming' movements could easily increase. The airlines are, therefore, keen to reduce their carbon footprint by using SAF, provided it does not disturb competition.

Such altruistic sentiments are, however, insufficient to persuade investors to build lots of new SAF plants. Something stronger is needed. The UK government, along with the EU, are introducing laws requiring (initially small) defined amounts of SAF to be blended into all aviation fuel from January 2025. In the case of the UK, a 10% SAF blend will be required by 2030 and in the case of the EU 6% by the same date. The UK will, therefore, require around 1.5bn litres of SAF by 2030. This will require very dramatic expansion of SAF production in Western Europe before 2030 but it does provide the assurance to investors that there will be a significant demand for their product.

The government has provided funds (£180m) to facilitate early stage development of eight UK SAF plants through the green fuels green skies (GFGS) competition. The government has also set up an advanced fuels fund (AFF) (£165m) which has provided funds to support thirteen plants through to financial investment. Many of the plants are on Teesside, with others on the Solent and at Sheffield, Immingham, Ellesmere, Port Talbot and Orkney.

All the fund awards can be seen at this link:

https://www.gov.uk/government/publications/advanced-fuels-fund-competition-winners/advanced-fuels-fund-

NEXT STEPS

There are still a number of issues on which the government has to make a final decision. They issued a consultation document last year entitled 'Pathway to net zero aviation: Developing the UK sustainable aviation fuel mandate'. In this document they asked for comments from interested parties on several key details of the proposed fuel mandate. These issues included the proposed increase in the compulsory SAF component of aviation fuel mandate beyond 2030; the percentage that can be met by PtL (3g) fuels and also a maximum level for the input from HEFA – the HEFA cap. Views were also sought on how the scheme provides price support, the level

of the buyout price which determines the maximum potential financial incentive for supplying SAF; exactly which feedstocks are eligible to be made into SAF, together with the eligible sustainability criteria. There are issues surrounding the certificate system and how the certificates can be issued and traded and used for compliance, together with who will be the ultimate administrator of the scheme and how the proposals will be enforced. There will also be definitions relating to the exact extent and coverage of the obligation and how the proposals interact with domestic and international policy.

The consultation is now closed and at the time of writing further details from the government as to how they intend to proceed on these items are awaited. They have already indicated that they will make a decision so that the final design of the mandate can be incorporated into legislation in time for introduction next year (2025).

It is essential that the mandate specifies specific percentages of SAF are included in Jet A fuel from 1.1.2025 so industry is left in no doubt SAF will be needed, and in an increasing % as the decade goes by. The second key requirement is that a certain (rising) % must come from non HEFA sources. This is critical for the UK, as UK supplies of HEFA sources are limited, and to meet the requirements into the 2030s, non HEFA production needs to be ramping up quickly.

CONCLUSION

The scene will be then set for the legal introduction of a minimum % of SAF to be incorporated into Jet A, gradually increasing so that the carbon intensity gradually falls as we approach 2050.

In addition to reducing its in-sector emissions, mention has already been made to the fact that the sector will need to invest in greenhouse gas removal technology (GGRs) to enable it to produce 0% CO_2 SAF.

GGR technology will also be needed to remove the CO_2 produced by continuing burning of fossil fuels in 2050. Depending on the size of the industry, and its ability to reduce energy consumption, there will still be a significant component (up to 47%) of fossil fuel powered flight. So expanding GGR capability is essential to reach net zero emissions by 2050 – the first important step to achieve this is for GGRs to be eligible within the UK Emissions trading Scheme which the previous UK government had indicated will be a priority.

The introduction of SAF, coupled with other initiatives, such as more direct routing, greater fuel efficiency of new aircraft and greater use of small battery electric planes, shows that the UK is now firmly headed towards achieving aviation net zero by 2050.

It must, however, be borne in mind that underlying aviation's – and all other sectors – transition away from fossil fuels, is a reliance on a steadily increasing supply of green electricity, with the associated national grid infrastructure to convey it to where it is needed. To get anywhere near the UK's national net zero target by 2050, the supply of green electricity must be expanded rapidly.

CONFERENCE REPORT

CONTRAIL MANAGEMENT: TIME FOR ACTION

There was a call for urgent action to slash aviation's climate impact at the recent Greener by Design conference held on 21 November at RAeS HQ.

Leaving criss-crossed skies typical of crisp mornings, the wider perception of contrails is of a benign, photogenic phenomenon. However, the last few years have prompted an increasingly revealing study of a nuanced sting in the tail.

Formed from emitted water vapour and particulates bonding and freezing aloft, contrails swiftly dissipate in drier air. However, increasing humidity and particularly, the relatively thin but extensive ice super-saturated regions (ISSR) overlapping with cruise altitudes cause their persistence and spread into contrail cirrus.

By day, this reflects incoming solar and outgoing Earth radiation, potentially offering net cooling. Critically, the nocturnal effect reverses to one of global warming through trapping Earth's heat. This balance of heat energy entering and leaving our atmosphere, radiative forcing, is exacerbated by persistent nocturnal contrails.

Within the declared uncertainty range, an increasing number of studies are consistent: contrail cirrus radiative forcing is between at least comparable and more significant than CO_2 emissions. Most of this effect could be neutralised by targeting a small proportion of flights.

Often described as 'low hanging fruit', their identification and mitigation has become key, hence the Greener by Design Contrail Management: Time for Action symposium at the Royal Aeronautical Society Headquarters in London in late November. Here follows a summary of the presentations by various players across sectors and nations.

Opening remarks

Society Past-President Kerissa Khan made a punchy introduction, outlining the climate challenge facing aviation. Ten days prior to COP28, Khan spoke of "not just ambition, a litany of pledges, but aligned action," noting today's "vociferous green generation" and of her connections to one of those nations for whom a 2C rise would be a "death sentence." She exhorted the audience to find ways to help the global aviation sector to better understand how we can try harder with contrail management and recommend concrete pragmatic solutions that we can pursue with immediate action.

RAeS President 2023-24, Kerissa Khan FRAeS opens the Greener by Design Contrail Management: Time for Action symposium.

In his keynote, Cranfield University Professor Sir Iain Gray noted that since he chaired the closing session of Greener by Design's 2020 Conference on non-CO_2, and personally committed to engage with the topic, there had been a flurry of initiatives. He described the establishment of the Jet Zero Council strategy in July 2021, leading to an initial DfT funded literature review on non-CO_2, a four-year non-CO_2 research programme, a commitment to explore inclusion of non-CO_2 in the UK ETS and the establishment of a Task and Finish Group which he chairs. The purpose of this group, established in mid 2023, is to identify, develop and implement the identified solutions to the non-CO_2 impacts – while not duplicating other initiatives. The group supports the recommendation of both the IPCC and CCC that there should be separate targets for CO_2 and non-CO_2, with a UK-led MRV framework to enable policy development to be evidence led. The group is also considering a contrail free trial in a reasonably sized UK controlled area – or a combination of making contrails and avoiding them, following discussions with Prof. Ian Poll.

Dr Marc Stettler, Imperial College, London.

Ian Poll FRAeS, Emeritus Professor, of Cranfield University.

He welcomed the provocation of the day's title, and the role that Greener by Design plays in creating awareness of the need to address non-CO_2 impacts and in particular, contrails. Now is the time, he concluded, to take some considered action around contrail management. There is a sense of urgency and he suggested we should proceed at pace with rigorous research on trials and increasing our fundamental knowledge. He believed that "now is the time for the UK to put in place a demonstrable flight trial evaluation" and that "there is an opportunity for the UK to develop a regional contrail mitigation scheme."

Atmospheric Science

Dr Marc Stettler of Imperial College introduced global contrail impact using humidity modelling validated by in-flight measurement in 2019-2021. The problem is highly disproportionate: 5% of flight distance forming persistent contrails and 2.7% of flights (1.1m of those studied) through trigger areas accounting for 80% of the contrail forcing effect. Globally mapping this data showed prevalence over the north-western USA, central Russia and particularly, the North Atlantic. The effect is the opposite in subtropical latitudes, and particularly China due to lower average cruise levels. Peak cooling and heating times were considered 0730 and 1800 local time respectively.

Professor Nicolas Bellouin of Climaviation explained mitigation metrics. Using 2019 data on 260,000 contrail-producing North Atlantic crossings, the conclusion was that uncertainty in contrail energy forcing is very large, but graphing results identifies best rerouting candidates. (As an observation, the non-pilot community often referred to rerouting as diversion when they mean deviation.) Flight selection and climate outcome are metric-dependent, with nine separate measures available (AGWP, AGTP and ATR models per 20, 50 and 100 years – how to express temperature delta and over what timescale). A revelation was that contrail heating is largely stored in oceans; initially dominant over the CO_2 effect, achieving parity towards 20 years and dissipated after 50, while CO_2 keeps working.

Imperial College's Dr Edward Gryspeerdt described using satellite data to link contrail formation with flights. Challenges included the pause since aircraft passage (contrails becoming visible after ten minutes but potentially much later), downwind movement and becoming harder to identify as they evolve into cirrus. Modelling across aircraft types suggested that, while newer generation aircraft are more fuel efficient, they may be more contrail-producing: flying higher forms colder contrails with more, smaller ice crystals remaining suspended longer.

Professor Christiane Voigt of the German Aerospace Centre (DLR) discussed the extent of uncertainties, including the contrail effect of SAF blends (a joint project with Boeing under way). Declared was the need to improve measurement and forecasting of atmospheric humidity by accelerating rollout of lower-cost aircraft sensors, a commonly recurring theme. The amount of water produced by hydrogen-powered aircraft cannot yet be assessed to test for any trade-off in CO_2 reduction but contrail increase.

TOOLS

Met Office Science Manager, Dr Piers Buchanan described contrails as an increasingly important priority, but more data and validation was required to improve their products. He expanded on the field of cloud microphysics and gave an example of GOES (Geostationary Operational Environmental Satellite) use for contrail detection. The lack of airborne humidity measurement is currently receiving attention. Its effect on contrail formation is nuanced: high atmospheric saturation typical over Greenland causes larger ice crystals, settling from the atmosphere sooner. Current humidity models have been validated by IAGOS (In-Service Aircraft for Global Observing System) data: though not conventionally fitted, nine A330s of various airlines carry humidity probes as part of an atmospheric sampling suite. A Water Vapour Sensing System (WVSS) will increase numbers, including a partnership with Loganair due in 2024. An observation made among the pilot community was that the coverage of a small Embraer fleet is limited.

Eurocontrol representatives, Philippe Very and Dr Gabriel Jarry explained their use of AI and imagery in the Maastricht trial (covered later) to create a common, contrail observation dataset. Matching contrails to offending aircraft was described as an order of magnitude harder than pure observation.

Boeing and NASA have been investigating SAF and Non-SAF contrails with its ecoDemonstrator initiative.

In a coverage-versus-detail trade-off, they used geostationary Meteosat (MTG-I1) data and a network of fish-eye ground cameras in the visible and IR bands, AI-corrected for sunlight and temperature.

Dr Klaus Gierens of DLR outlined some of the challenges in forecasting ice supersaturation and persistent contrails. While fully acknowledging the potential for contrail management, he stressed the need for improved representations of ice-clouds and their supersaturated environment in NWP models, for many more good humidity measurements at cruise level for data assimilation and for better detection of contrails in satellite data for validation.

The morning ended with questions, one asking what single item each speaker wished for? There was consensus on two: an inevitable assent for further study, but also majority agreement we had advanced enough to make a confident start somewhere. Ongoing analysis and discussion of metrics should not be a bar to commencing trials because we stand to learn just as much by practice, in parallel with science. One speaker summarised this: “the value of data is that it is usable – and used.”

This was echoed in the day’s dominant headlines of the Covid Inquiry confession the ex-PM was “bamboozled” by lockdown data. Discussion prompted the frank explanation: “For any minister to be bamboozled by science is unforgivable and represents failure on the part of the advisers. The reason we are having trouble getting action is that the government relies solely on advice from a small number of people who do not understand airline operational issues, but think they do. There is no one in their room to set them straight.”

TRIALS

Leigh Hudson from IAG kicked off the afternoon session with a description of the six studies relating to non-CO_2 that companies from the group are participating in. She also made the point that by January 1st 2025 all carriers departing Europe must start EU-ETS Monitoring, Reporting and Verification. IAG are working on targeted flight trials though they are still awaiting further consensus regarding how to mitigate non-CO_2.

Eurocontrol's Chris Jeeves described Maastricht's breakthrough experiences as the first air traffic region to perform anti-contrail trials in 2021. Their study revealed that avoiding damaging, overnight contrails was possible, but also that ISSR forecasting was more complex and geostationary satellite verification harder, than expected. Avoidance is best planned pre-flight as controllers dealing with short-notice, tactical requests reduced airspace capacity by around 20%. Complexity increased exponentially with the number of flight levels blocked.

Post-Covid air traffic controller numbers, qualification lead-in times and traffic concentration over the Balkans since Ukrainian airspace closures are recent additions to the challenge of slot-constrained European airspace. Jeeves was candid about conflicting airspace pressures: environmental benefit added to maximising capacity and reducing cost. "The temperature is rising in the political sphere, which is just what we need," he opined. "This starts and finishes at the policy level."

On incentivising responsible airline behaviour, CEO, Dr Adam Durant of climate-optimised flight planning software creators, SATAVIA gave the key statistic that the bulk of warming occurs from 5-10% of flights in certain regions. This cohort is identified with a global, cloud microphysics model at 5km resolution across flight levels, producing a contrail-optimised flight plan before departure. Trialled throughout 2022 with Etihad, a profile of one flight was shown, its vertical amendments calculating significant benefit. Crucially, SATAVIA's model suggests a tradeable unit of positive and negative airline impact. Airlines have always planned with a variable 'Cost Index' of fuel versus time and 'Climate Index' could become another.

In less restricted US airspace, flight-planning provider, Raimund Zopp and Alejandra Frias from Flightkeys described how, after running 49,000+ American Airlines flights through their climate simulation, 19.9% of flights were considered to have produced persistent contrails with 12% producing net warming ones; of those 98% could be re-optimised. Lateral and vertical amendments were visualised by their Loretta app for in-flight replanning.

American efforts with AI were explained by the team of Frank Opel, PACE, Marc Schapiro, Breakthrough Energy, Carl Elkin, Google Research (the latter triggering inevitable interest) and Mark Galyen, American Airlines. A small subset of pilots on US continental flights sought to create contrails on one leg and avoid on the return. Applying wind data to 2-3km resolution satellite imagery enabled contrail detection after 20 minutes. This held up in winter months, though the shoulder seasons were more challenging. The team stated theirs was not a commercial product, but has room for improvement and shows promise.

Edward Kay from Airbus outlined the different deliverables of the CICONIA programme, due for completion by mid 2026, including defining the level of forecast service achievable to support operational climate effective decisions, examining the accuracy of assessing the climate impact of contrails from individual flights, choosing a metric that addresses both CO_2 and non-CO_2 climate effects and measuring the efficiency of various operational mitigation options.

James van der Hoorn spoke on behalf of the British Airline Pilot's Association. Airway structure permits multiple routes between city pairs, varying according to winds, weather, airways charges, time and fuel cost. With airlines choosing their preferred metric(s), contrails should be added to that mix. A potentially longer route raises the issue of small margins of increased fuel burn (data suggests +0.1% on the 5-10% flight cohort targeted) but avoiding contrails has a net positive climate effect.

The 'piece of string' analogy reflects the fact that routes are rarely if ever straight. Any planned deviation one side for conventional reasons would be no different from the same the other for contrail avoidance. This counters a common argument that deviations automatically increase fuel burn, suggesting a non-CO_2 market-based measure and variable airway charging for responsible flight planning.

CONCLUSION

Afternoon questions commented that scaling SAF will take years we do not have, but to be able to make a swift impact now with an alternative mitigation without costly investment was amazing. It was agreed that science can confuse the consumer so simple messaging is needed, though unlike CO_2, contrails are at least always visible.

A divergence of view emerged over the time horizon to be used for any comparison between CO_2 and contrails. Adam Durant put the case for 100 years, being the period commonly used by scientists.

A packed panel for the Contrail Management conference debate.

Raimund Zopp put the case for 20 years, reflecting the urgency of short-term action to address the 1.5 degree temperature ceiling.

A question about the need for cost-neutral, positive regulation received more questions than answers. For some it was necessary – but it may be that only the threat of regulation is sufficient. Adam Durant suggested it would require accurate data on which to base the regulation. An independent, consumer rating to recognise responsible airlines was suggested and Carl Elkin asked what level of accuracy is necessary before airlines could be rated in this way. A further question noted that all presentations were about single point results with no indication of uncertainty. This may need to be amended before it goes before the public.

These questions will need answering soon.

Concluding, Professor Ian Poll was positive: "I for one am very encouraged by what I've heard today, after plugging away for so long it finally seems something is happening." He emphasised that while the science should be finessed, we knew enough to begin.

He then opened a candid, peer debate, matching gravitas with an impish drive for action emphasising 'why not?' over 'why?' With Maastricht's head start tempered by airspace intensity, it was agreed the contrail-prone North Atlantic was the most promising target. With dominion over half, this also represents a potential opportunity for the UK.

Against a backdrop of regulatory ideas and options, he floated two ideas. First, what if the flight plan was constrained to exclude any increase in fuel burn? Then if a warming contrail could be avoided without an increase in fuel burn, it would be a clear win-win. Who could argue with that? Secondly, he noted that 10 BA aircraft have an IAGOS pack fitted. What if all new aircraft had to have humidity measurement equipment fitted and all existing aircraft were required to be fitted during a C check? The Schmidt Appleman test could be applied, an ISSR test made and a message sent to the cockpit, to ATC and weather forecasters. The aircraft fleet would become analogous to a fleet of weather ships – but we need research on better instrumentation.

With CO_2 and SAF claiming primacy, it is time to advance in parallel and introduce non-CO_2 and contrails into wider policy, practice and awareness. Put simply: beyond cutting traffic, the industry has no other way to make a significant impact on its global warming contribution in the next decade.

Geoff Maynard, GBD chair, concluded with the assessment that sufficient scientific certainty exists to support starting contrail management now. As the level of certainty increases, the amount of contrail management action can be increased – but we should start now, and definitely before the next conference.

From an original submission in RAeS Aerospace by commercial pilot, writer and former environmental consultant Robin Evans.

Greener by DESIGN

The 25th anniversary conference of the Greener by Design group will be held in Spring 2025. This coincides with the anniversary of the first meeting of the Greener by Design group. In order to celebrate this we are arranging a special conference programme reflecting the diverse topics that this group is involved in. This will also include an Anniversary Dinner.

Further details will be published on the Royal Aeronautical Society/ Greener by Design website as soon as they are available.

ROYAL AERONAUTICAL SOCIETY
GREENER BY DESIGN GROUP

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The Greener by Design Group

Greener by Design was formed in 1999 by the Royal Aeronautical Society and bodies representing airports, UK airlines and the aerospace industry, bringing together experts from every part of the aviation industry with government bodies and research institutions. The initiative is supported by the Department for Business, Energy and Industrial Strategy and other bodies in the aviation sector but it is non-aligned, researching and advising independently of any interest.

Greener by Design

Researches, assesses and advises government and industry on operational, technological, economic and regulatory options for limiting aviation's environmental impact.

Promotes best practice across the aviation and aerospace sectors.

Promotes a balanced understanding of aviation's true environmental impact and its environmental programmes, in liaison with other groups with similar objectives.

Issues an annual report and holds an annual conference and workshops on sustainable aviation.

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