ACCIDENT

Aircraft Type and Registration:	Piper PA-46-350P (Modified), G-HYZA	
No & Type of Engines:	2 YASA electric motors (common shaft)	
Year of Manufacture:	1997 (Serial no: 4636130)	
Date & Time (UTC):	29 April 2021 at 1425 hrs	
Location:	Near Cranfield Airport, Bedfordshire	
Type of Flight:	Other	
Persons on Board:	Crew - 2	Passengers - None
Injuries:	Crew - None	Passengers - N/A
Nature of Damage:	Left wing detached, landing gear collapsed and nose cowl distortion	
Commander's Licence:	Airline Transport Pilot's Licence	
Commander's Age:	63 years	
Commander's Flying Experience:	34,620 hours (of which 1,588 were on the basic type, 12 were on the modified electric variant) Last 90 days - 59 hours Last 28 days - 19 hours	
Information Source:	AAIB Field Investigation	

Synopsis

The electrically powered aircraft was undertaking experimental flight tests, under E Conditions[1], when power to the electrical motors was lost. A forced landing was carried out close to Cranfield airfield during which the aircraft was severely damaged.

The loss of power occurred during an interruption of the power supply when, as part of the test procedure, the battery was selected OFF with the intention of leaving the electrical motors solely powered by the hydrogen fuel cell. During this interruption the windmilling propeller generated a voltage high enough to operate the inverter protection system, which locked out the power to the motors. The pilot and observer were unable to reset the system and restore electrical power.

Five Safety Recommendations were made regarding Civil Aviation Publication (CAP) 1220, *'Operation of experimental aircraft under E Conditions'*. The operator has also taken Safety Action to address a number of findings from this accident.

Footnote

[1] Annex A in this report provides an overview of E Conditions.

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Introduction

G-HYZA was being operated as part of an experimental and development programme to provide aircraft propulsion systems with zero emissions and lower noise. This was to be achieved using electric motors supplied with electrical power from hydrogen fuel cells. Much of the technology used in the programme had been transferred from other transport modes and industrial applications. The company behind the project was founded in the USA in 2017 and, at the time of the accident, the experimental flight testing was being carried out at Cranfield Airport by the European division.

The piston engine on G-HYZA had been replaced with two electrical motors suppled with electrical power from a high voltage lithium (HV) battery and a hydrogen fuel cell (HFC). The aircraft was operated by a crew consisting of a pilot and a flight test observer. The accident occurred during Phase 3 of the programme which was establishing the optimal conditions for flight with the electrical propulsion system powered only by the HFC. As part of the risk mitigation, G-HYZA was restricted to operating within a 2 nm test area centred on Cranfield Airport and was not permitted to fly when other aircraft were flying in this area.

History of the flight

On the morning of the accident flight, G-HYZA was flown for approximately 16 minutes on test flight 85. The flight test team debriefed the results and prepared the aircraft for flight 86. The plan for this flight was for the HV battery to be switched off at the end of the downwind leg then, if able, to fly three or more circuits at 1,000 ft aal using the HFC only to provide electrical power. The flight test team discussed experimenting with combinations of higher airspeeds and propeller rpm that would reduce the aircraft angle of attack and improve the mass flow of air through the radiator which provided cooling for the HFC. This was considered as a potential strategy to manage a slow rise in temperature in the HFC which they had observed in previous flights when flying on that power source alone. The test card for flight 86 was not amended to reflect this intention.

At 1406 hrs, following a normal start using both the HV battery and HFC to provide electrical power, the HV was switched off to preserve its electrical capacity. The aircraft taxied to the holding point and was cleared to line up on Runway 03. The weather was fair with good visibility and light winds from 010°. The aircraft entered the runway and backtracked to the threshold where the pilot commenced a run-up of the propulsion system to ensure the HFC could achieve thermal stability within the flight test parameters. Once the temperatures in the HFC were stable, the pilot switched on the HV battery to bring both power sources online and commenced the takeoff run. As the aircraft accelerated and the power lever was advanced, the observer operated the high temperature override switch[2] to maintain the temperature of the HFC within the operating limits.

Footnote

[2] The high temperature override switch manually overrides the automatic temperature regulation valve in the HFC, which was found to be slow to react to power demands.

After takeoff, the pilot turned onto the crosswind leg and climbed to the circuit height of 1,000 ft agl. During the downwind leg of the right-hand circuit, the pilot stated the power was set to 95 kW, the propeller to 2,500 rpm and the airspeed to 100 kt. Once stabilised at these parameters, which were at variance with the flight test card conditions, the observer confirmed that the HFC operating temperatures were within limits. He then instructed the pilot to reduce power to 90 kW to assess the effect on the airspeed, which reduced to approximately 95 kt. The pilot increased the power to 95 kW to regain the target speed. The pilot set the power by reference to his display unit which was located below the throttle quadrant. When he looked up from this task, he recognised that the aircraft was in a late downwind position. He turned onto base leg and commented that they were losing speed in the turn. The observer suggested that they could increase power to 120 kW to regain the lost airspeed, then reduce power before turning off the HV battery to re-establish the test conditions. He also suggested a reduction in propeller rpm. The pilot increased power to 120 kW but did not reduce the propeller rpm. As he started to turn onto final, the pilot briefed that once he had established straight and level flight he would reduce the power slightly and turn off the HV battery leaving the electrical motors powered by the HFC. He called final on the radio and was cleared by ATC to fly through at circuit height (Figure 1).

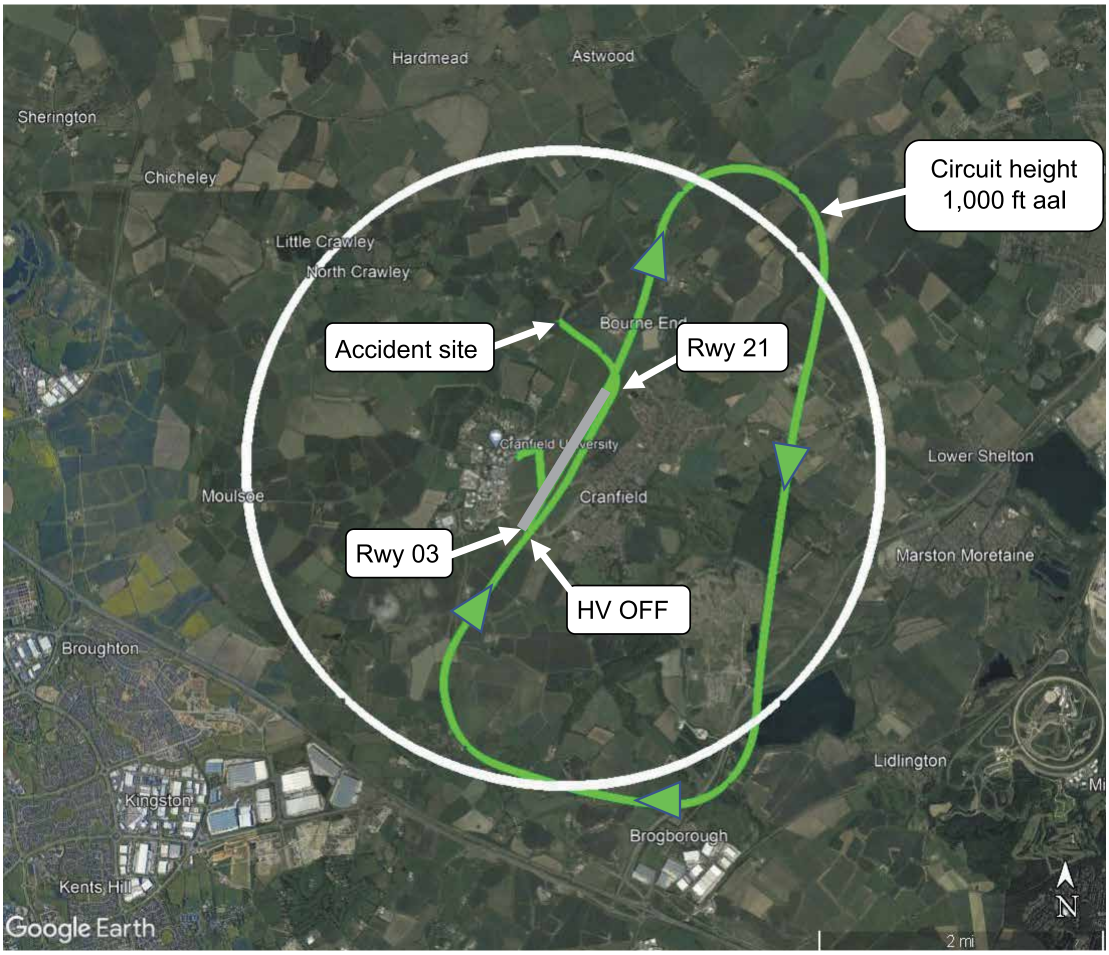

Figure 1

G-HYZA track overview (green).
White circle depicts 2 nm boundary of the flight test area

Approaching the runway threshold at approximately 940 ft agl, the pilot reduced power to 90 kW, set the airspeed to 90 kt then selected the HV battery to OFF. Immediately, all electrical drive to the propeller was lost. The pilot and observer made several unsuccessful attempts to reset the system to restore power from the HFC with the observer stating the action to be taken and the pilot making the switch selection. The observer instructed the pilot to select the HV battery to ON to reconnect the alternative power source. HV power was not restored so the observer instructed the pilot to attempt a system reset with the HFC in the OFF position. Electrical power was still not restored and at 440 ft agl the observer declared "THE VOLTAGE IS TOO HIGH", to which the pilot replied, "WE'VE GOT TO DO SOMETHING QUICK". The observer called for a further reset attempt and adjusted the power lever. The aircraft had now travelled the length of the runway and was at approximately 320 ft aal when the observer reported that power could not be restored.

The pilot transmitted a MAYDAY call and initiated a turn to the left to position for a landing on Runway 21. Almost immediately he recognised that he did not have sufficient height to complete the manoeuvre so lowered the landing gear and selected full flap for a forced landing in a field that was now directly ahead on a north-westerly heading. The aircraft touched down at approximately 87 kt ground speed on a level grass field. The pilot applied the brakes, and the aircraft continued its movement until it struck, and passed through, a hedge during which the left wing broke away. The nosewheel and left main wheel entered a ditch and the aircraft came to an abrupt stop. The pilot and observer were uninjured and exited the aircraft through the upper half of the cabin door.

The airport fire service arrived quickly at the scene. The observer returned to the aircraft and vented the hydrogen tank to atmosphere and disconnected the HV battery to make the aircraft safe.

Aircraft information

General

G-HYZA was a modified Piper PA-46-350P, Malibu Mirage, built in 1997. The aircraft was previously registered as N866LP and was modified with a HV battery supplying power to two electric motors. After the modification it was flown in the UK on a FAA experimental permit. Once the HV battery trials were complete, the aircraft was re-registered as G-HYZA and fitted with a single HFC, in addition to the HV battery, and flown under CAA Civil Aviation Publication (CAP)1220, E Conditions[3].

The original piston engine had been replaced with two Yokeless and Segmented Armature (YASA) electric motors on a common shaft driving an electrically actuated variable pitch propeller. As is common on single engine aircraft, the variable pitch propeller did not have a feathering capability. The electric motors were cooled by a circulatory sealed liquid cooling system.

Footnote

[3] Civil Aviation Authority (2019). CAP1220 *Operation of experimental aircraft under E Conditions.* http://publicapps.caa.co.uk/docs/33/CAP1220EConditions_Edition2_Nov2019.pdf [Accessed November 2021]

The aircraft flying controls and landing gear were unchanged. The cabin pressurisation system components were not required and had been removed. The emergency exit on the right side of the cabin was not accessible due to the location of the hydrogen storage tanks. The fuel tanks remained within the wings but were empty and inert.

The cockpit instruments included a moving map display, that showed the boundary of the Cranfield Aerodrome Traffic Zone, which was also the boundary of the flight test safety area. Blanking plates were fitted to the instrument panel where the engine instruments had been fitted. Two display screens were fitted to show the power plant and motor parameters, one was located on the cockpit centre console next to the pilot, and the other on the right side of the cockpit next to the observer's seat.

A 24 V aircraft battery and dual alternators, driven by a power take-off from the electric motor drive shaft, was used to provide electrical power to the avionic equipment.

Powertrain

The electrical power could be configured in one of three modes:

- Combined (Hybrid) mode. HV battery and HFC selected ON to give a combined maximum nominal power of 200 kW
- HV battery only. HV battery selected ON and HFC OFF to give approximately 50% power of 100 kW
- HFC only. HFC selected ON and HV battery OFF to give approximately 50% power of 100 kW

The power demand from the motors was set by the power lever[4]. The propeller speed was controlled by an electric governor with the desired rpm selected using a rotatory control fitted to the side of the power lever quadrant.

High Voltage battery

The HV battery consisted of one battery pack comprising Li-NMC 'pouch' cells, which provided 368 V, 50 Amp hour and 16.25 kWh. This had been demonstrated as being capable of powering the electric motors, without the HFC, in-flight for approximately 20 minutes at predicted loads.

The HV battery was mounted in a shock proof carrier attached to the hydrogen storage tank mounting framework.

Footnote

[4] The power lever was the repurposed throttle lever located on the centre console.

Hydrogen Fuel Cell

The HFC used hydrogen from the storage tanks and oxygen from the air to generate electricity.

The HFC consists of a negative anode and a positive cathode separated by a polymer electrolytic membrane. Air is passed over the cathode and hydrogen (H_2) is channelled across the surface of the anode where it splits into positive ions (H+) and negative electrons (e-). The positively charged ions pass through the membrane to the cathode; however, the negatively charged electrons are unable to pass through the membrane and instead travel through an electrical circuit, to the cathode, where they produce an electrical current to power an electrical load shown as a motor (M) in Figure 2. The positive ions and negative electrons then combine with the oxygen (O_2) in the air at the cathode to produce heat and water (H_2O) as by-products of the process. The water and any unused hydrogen exit through the exhaust.

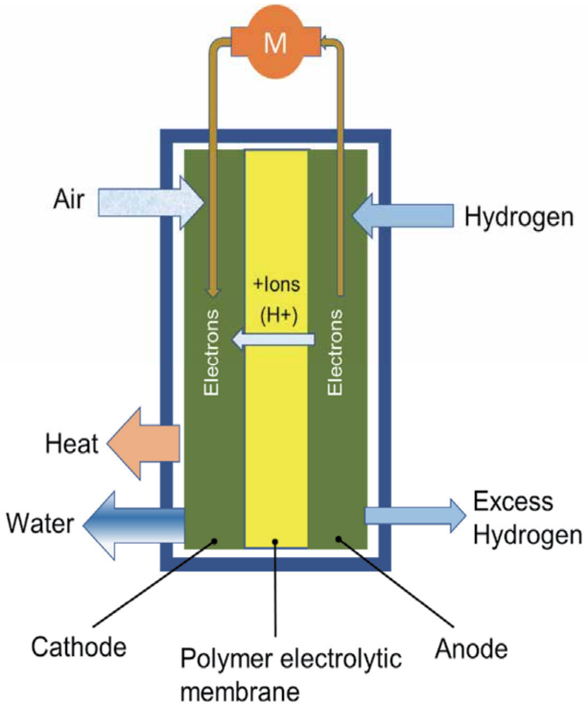

Figure 2

Operation of the hydrogen fuel cell

The temperature of the HFC must be maintained within an optimal range to ensure efficient generation of electricity. This was achieved by use of a coolant which was circulated through air cooled radiators mounted behind the propeller and controlled by an automatic HFC temperature management system. A high temperature override switch mounted on the instrument panel allowed the crew to override the automatic control of the temperature regulation valve. The flow of the hydrogen and air (oxygen) were precisely controlled to enable the HFC voltage output to build up and stabilise as a rapid or sudden load could cause an undervoltage.

Hydrogen storage

The aircraft carried sufficient hydrogen for approximately one hour of circuit flying. The hydrogen was stored in three high pressure gas cylinders connected to a manifold pressure regulator and shutoff valve. The cylinders were mounted in a frame attached to the seat mounting points on the cabin floor.

The cabin was fitted with a hydrogen detection and warning system. Electrically driven ventilation fans were also fitted in the bulkhead at the rear of the cabin to ensure fresh air constantly passed through the cabin to remove any hydrogen that had leaked out. A manually operated dump valve allowed for the rapid venting of the hydrogen to atmosphere.

Inverters

Two inverters, wired in parallel, converted the 300 to 400 V DC output from the HV battery and HFC to the AC input required by the electrical motors. The electrical power was applied to the inverters by DC contactors. Each motor (M1 and M2) had its own inverter, which contained software to provide protection against several fault conditions including out of tolerance voltage and current. For some faults, the inverter would latch a hard fault and 'lockout', which cut power to the motor (M1 or M2) from the affected inverter. This included overvoltage and undervoltage conditions. The threshold for an overvoltage lockout was 820 V.

A simple schematic diagram of the system is shown in Figure 3.

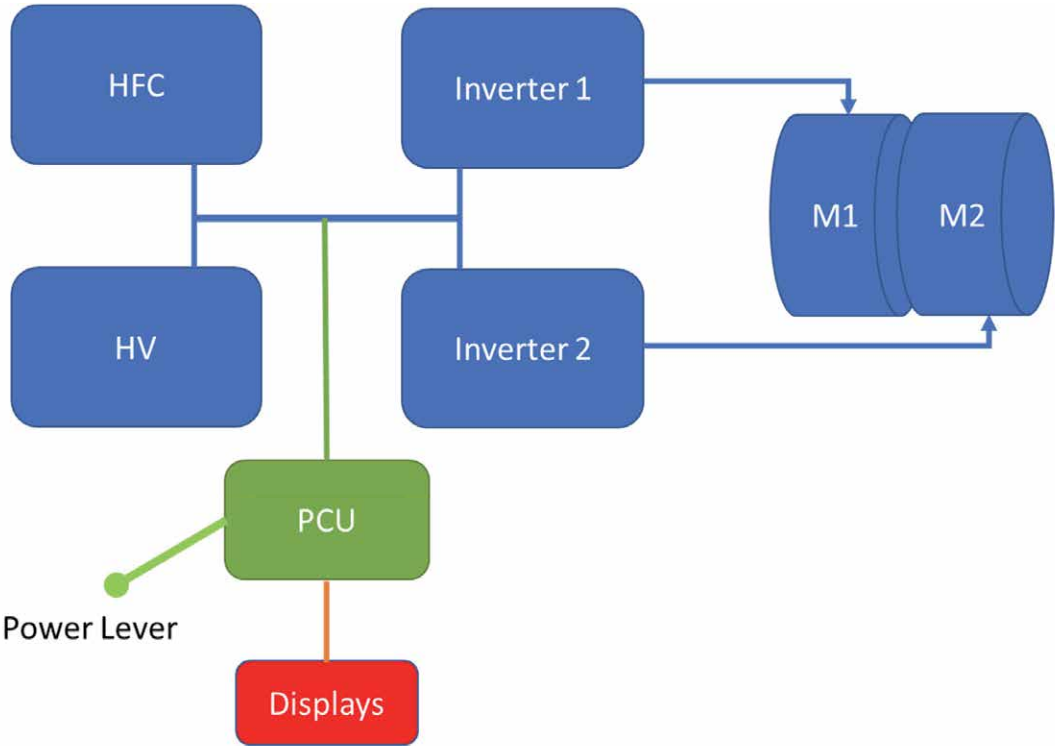

Figure 3

Power system schematic

Programmable control unit

A programable control unit (PCU) loaded with bespoke software controlled the delivery of power to the motors by sequencing the contactors to enable the HV battery and HFC power to be delivered to the inverters without causing voltage ‘spikes’[5]. It also ensured that the power lever position and demands were manageable to protect the power supply and inverters from over voltage. The data for the system displays came from the PCU. The fault clear button on the power lever provided a signal to the PCU to enable any latched faults in the inverters or HFC to be reset.

The PCU did not have a ‘soft start’ or ramp feature meaning that if an inverter was reset and the power lever position was not at idle, a step demand in power would be commanded. This step demand could exceed the available power which could lead to an undervoltage condition in the HFC, which would be detected by the inverters and trigger an inverter lockout.

Electric motor principles

In the event of a loss of electrical power to the motors in-flight, the propeller would windmill turning the motors which would then act as generators with the electrical energy produced being fed back to the inverters. The voltage produced would be dependent on the propeller rpm but could be sufficient to trigger the overvoltage protection which would cause the inverters to lockout. The back EMF of electrical motors is well known, and the principle is used on electrical road vehicles to provide regenerative braking. The operator advised that the control system had been designed such that at zero throttle setting, the motors would always receive a positive driving current just below that required to turn the propeller, which was intended to counter the back EMF and prevent activation of the inverter overvoltage protection logic.

Testing of the drive train system was carried out, which included ground runs and fast runway taxi tests. The results were compiled in an internal report dated 15 April 2021 and used to inform the next phase of the flight test programme. The ground testing covered all aspects of the operation of the power systems and included test procedures to check and clear a number of fault conditions; the taxi tests did not include the change of power source during the fast runway tests. Also, no wind tunnel testing or back-driving of the propeller on the ground was carried out to explore the magnitude and effect of the back voltage on the high voltage electrical system. However, the operator advised that there were no over voltage occurrences when the throttle was closed during the fast taxi tests up to rotate speed.

Footnote

[5] Voltage spikes, also known as surges, may be created by a rapid build-up or decay of a magnetic field, which may induce energy into the associated circuit.

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Powertrain electronic displays

The electronic displays showed the electrical power supply system status, HV battery control and configuration information in both numerical and graphical format.

Two display screens were fitted to show the power plant and motor parameters, one was located on the cockpit centre console next to the pilot, and the other on the right side of the cockpit next to the observer's seat (Figure 4). The pilot used the display below the throttle quadrant to adjust power and rpm settings throughout the flight. Of note, when the pilot's hand adjusted the power, it could obscure this display.

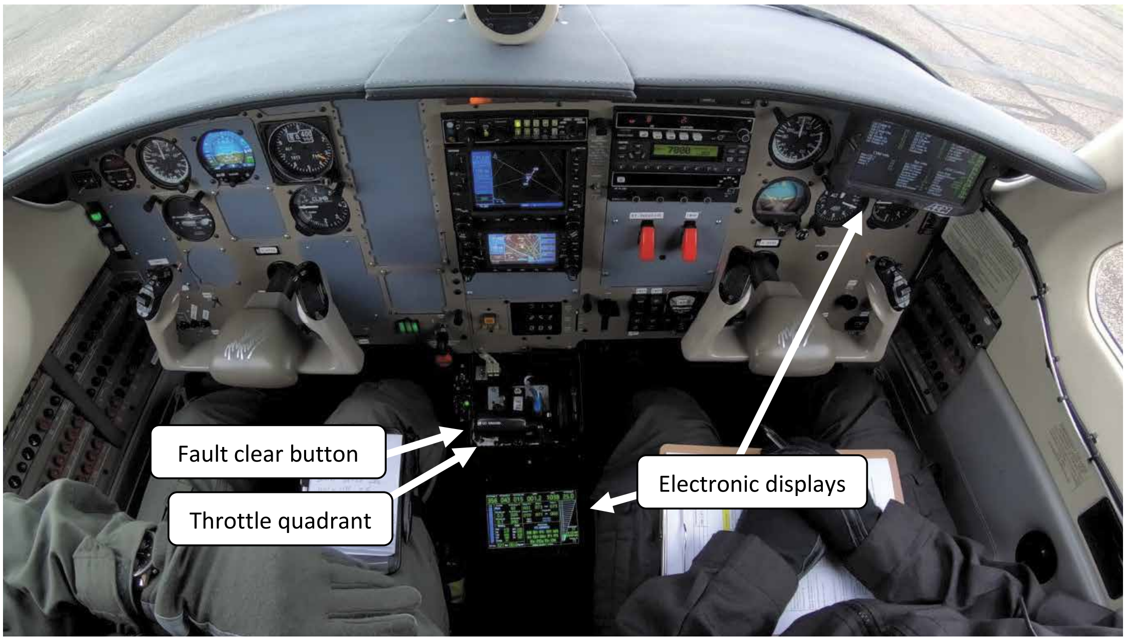


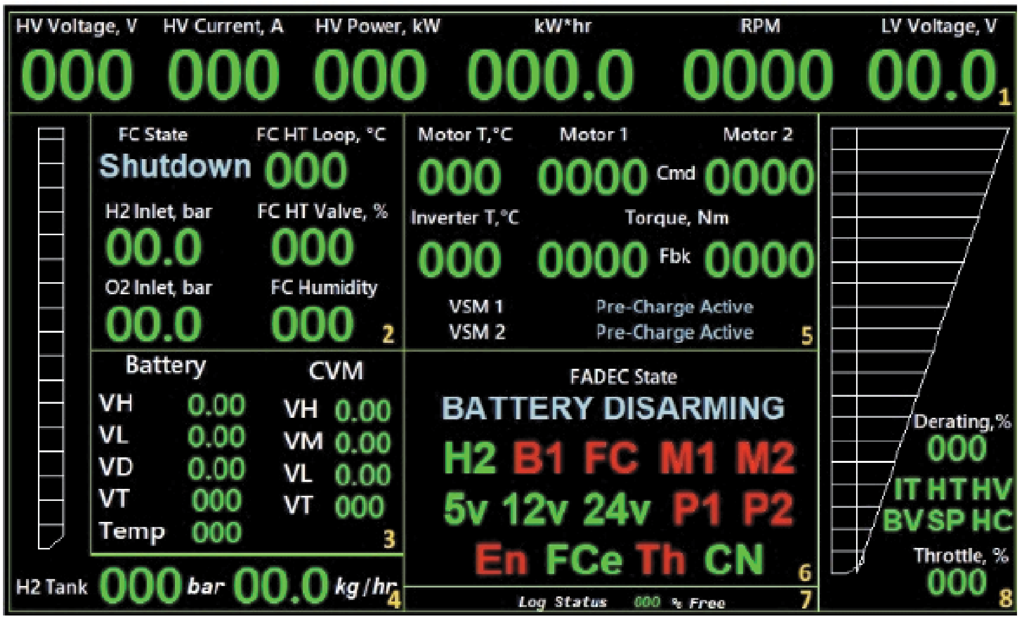
Figure 4

View from onboard camera of cockpit instrument panel

The pilot's display had a viewable area of 175 mm x 110 mm. It showed 28 parameters and 24 status, caution or warning captions in a variety of font sizes down to 4.5 mm (Figure 5).

The key parameters displayed in a larger font in field (1) at the top of the display were used by the pilot to operate the aircraft and were defined as:

- HV Voltage – Voltage measured at the inverter input showing the average of the two inverter DC bus voltages
- HV current – The sum of all the inverter current consumption
- HV power – The product of HV current and HV voltage
- Power consumption – Power integrated kW x hr
- RPM – Propeller / motor rpm
- LV Voltage - 28 V supply



HV Voltage, V 000
HV Current, A 000
HV Power, kW 000
kW*hr 000.0
RPM 0000
LV Voltage, V 00.0

FC State Shutdown
FC HT Loop, °C 000
H2 Inlet, bar 00.0
FC HT Valve, % 000
O2 Inlet, bar 00.0
FC Humidity 000

Motor T, °C 000
Motor 1 0000
Cmd
Motor 2 0000
Inverter T, °C 000
Torque, Nm 0000
Fbk
0000
VSM 1 Pre-Charge Active
VSM 2 Pre-Charge Active

Battery
VH 0.00
VL 0.00
VD 0.00
VT 000
Temp 000

CVM
VH 0.00
VM 0.00
VL 0.00
VT 000

FADEC State
BATTERY DISARMING
H2 B1 FC M1 M2
5v 12v 24v P1 P2
En FCe Th CN

Derating, % 000
IT HT HV
BV SP HC
Throttle, % 000

H2 Tank 000 bar 00.0 kg/hr
Log Status 000 % Free

Figure 5

Parameters displayed on pilot's powertrain electronic cockpit display

In the *'FADEC State'* field (6), each system had its own symbol displayed in green if no faults were detected. If a fault was detected, the symbol would change to either amber or red, depending on the severity of the fault detected. Aviation standards exist for caution and warning alerts detailed in the EASA Certification Standard 23.1322[6] and US Federal Aviation Regulations 23.1322[7]. The flight manual did not contain a description or key to the amber and red captions and there were no associated emergency procedures for each. There were also no associated audible warnings with these fault monitors.

The certification basis[8] of the PA-46 contains requirements for the design of electronic displays that represent good practice within aviation. As an E Conditions aircraft, G-HYZA was not required to comply with these standards; however, CAP1220 refers to guidance in CAP659[9] *'A guide to Approval, Construction and Operation of Amateur Built Aircraft'*. To assist those undertaking projects, Appendix 1 of this document sets out the design criteria for different types and weights of aircraft. The weight of G-HYZA would place it under Certification Standard (CS) 23, which includes a section on instruments and displays.

Footnote

[6] Certification Specifications (CSs) | EASA (europa.eu) [Accessed April 2022]

[7] FAR Part 23 Sec. 23.1322 effective as of 02/01/1977 (faa.gov) [Accessed April 2022]

[8] FAA Historical CFR Part 23 Amdt. 23-20, Effect 09/01/77. Further information is available in EASA CS 23.1311, Subpart F – Equipment : Electronic display instrument systems, Amdt 4, June 2018.

[9] https://publicapps.caa.co.uk/modalapplication.aspx?catid=1&pagetype=65&appid=11&mode=detail&id=146 [accessed April 2022]

Accident site

An assessment of the accident site was made from witness and photographic evidence.

The aircraft landed in a field which was 210 m wide, approximately 445 m in length, corner to corner, and bounded by a road and hedges. It touched down approximately one third along the length of the field and after 290 m struck a hedge where the left wing detached from the fuselage and the nose landing gear collapsed. The propeller, nose cowling and tailplane were also damaged (Figure 6). The aircraft remained upright, leaning to its left side sufficient to prevent the lower step section of the cabin door from fully opening. There was no fire.

Figure 6

G-HYZA accident site

Aircraft examination

An examination of the aircraft by the operator found the following:

- The nose landing gear had been forced upwards into the nose area and caused bending and displacement of the motor and HFC mounting frame by approximately 25 mm.
- The nose structure showed no other damage except for the pulling through of a fastener holding the coolant header tank, which was still attached and free from leakage. All the other components remained attached and in place with the mounting frame displacement being taken up by the flexing of the wiring and non-rigid pipework.
- The HV battery contactor box, also located in the nose area, was crushed such that the insulation within the cover was touching the top of some of the contactor terminals.
- There was no evidence of leakage from the motor cooling oil and inverter / HFC cooling systems.

- The hydrogen storage tanks, regulator and distribution systems were visually undamaged and there was no leakage. This was confirmed by the fact that the hydrogen detectors did not trigger.
- The cabin mounting structure for the hydrogen storage tanks and HV battery showed no signs of movement or damage, and all the attached items were retained in their original position.
- The egress path between the cockpit and the cabin exit door remained clear.

Conducting an experimental flight test programme

Schedule 3 of the Air Navigation Order (ANO) 2016 sets out two paths for the conduct of an experimental flight test programme in the UK for non-Part 21 aircraft. These are B Conditions and E Conditions. Flight testing of a Part 21 aircraft may only be conducted by UK Part 21 Subpart J approved organisations using a UK Part 21 Subpart P Permit to Fly.

B Conditions

B Conditions enable either experimenting with or testing of an aircraft. They can also be used to enable the aircraft to qualify for the issue or validation of a Certificate of Airworthiness, Permit to Fly or the approval of a modification to an aircraft.

Flight testing under B Conditions can only be carried out by an organisation specifically approved for the management and control of flights under those conditions such as holders of approvals under British Civil Airworthiness Requirements (BCAR) A8-1 and/or A8-9.

E Conditions

E Conditions, which were first published under CAP1220 in November 2015, enable a UK registered, commercially or amateur built, non-EASA aircraft with a Maximum Take off Mass (MTOM) of 2,000 kg or below to test a concept in the air without having to comply with the more stringent requirements of B Conditions.

A dossier of information on the project is compiled by a competent person who also signs the *'declaration to operate'* under these regulations. The declaration is the only document required to be provided to the CAA, though they may ask to see the full dossier. The background to the development of E Conditions, and a number of aspects relevant to this accident, are included in Annex A.

Requirements of E Conditions

Competent Person

E Conditions uses the mechanism of management and oversight by a competent person to keep the risk to third parties at an acceptably low level. The competent person takes sole responsibility for the safe conduct and management of the entire experimental test programme and is required to produce a dossier of information on the aircraft and the test programme, which includes a signed declaration.

CAP1220 states:

> *'It is anticipated that, where necessary, the Competent Person will enlist the help of other individuals with the appropriate skills and experience as required.'*

A footnote to this statement states:

> *'It is strongly recommended that even where the Competent Person can fulfil multiple or all roles the involvement of other technical experts should be sought for the purpose of peer review.'*

The responsibilities of the competent person include assessing all risks throughout the flight test programme; not permitting any flights to take place until they are satisfied that identified risks are mitigated to an acceptable level; and attending flight test briefings.

Any current member of the Royal Aeronautical Society (RAeS) who has obtained their Chartered Engineer status (CEng) through the RAeS is automatically eligible to be a competent person. At the time of this accident, 13 individuals had been registered for the role of competent person and nine projects were being progressed under E Conditions, not all of which had flown. G-HYZA was one of the more complex projects to have flown under E Conditions.

Members of the CAA and RAeS working group, that developed E Conditions, stated that the underlying intention was that the competent person would have a close involvement in the test flying programme.

The declaration

The declaration is submitted to the CAA by the competent person and contains a brief description of the project as well as the details of the competent person, test pilot and the registered aircraft owner. The competent person is also required to sign as accepting a number of statements which includes:

> *'I confirm that I will keep the registered aircraft owner and Test Pilot appropriately briefed on all aspects of the test programme…*
>
> *I declare that before the flight test programme commences, I will undertake all necessary risk assessments and must be satisfied that all risks in respect of the flight test programme have been mitigated to an acceptable level and that, in particular, the level of risk to uninvolved parties will be low enough to be acceptable….*
>
> *I declare that, throughout the flight test programme:*
>
> - *I will make such changes to the risk assessment and dossier of information as appear appropriate in light of the information gathered in connection with the programme; and*

- *I will keep under review the risks in respect of the flight test programme and in the event that I cease to be satisfied that all risks in respect of the flight test programme have been mitigated to an acceptable level, and in particular that the level of risk to uninvolved third parties is low enough to be acceptable, I will not permit a flight to take place.'*

G-HYZA E Conditions dossier

Background

The flight test programme was being carried out over four phases with the first two phases having been satisfactorily completed:

- Phase 1 was started in the US using another modified PA-46, registration N504EZ, and completed in the UK on G-HYZA, when registered as N866LP, under an FAA experimental permit. Phase 1 used a HV battery to demonstrate control and performance of the propulsion system.
- Phase 2 was carried out under E Conditions in the UK with the HFC fitted in addition to the HV battery to make it a hybrid aircraft. It was recorded in the introduction of the Phase 3 dossier that *'Overall, the second phase was a success with exception of an incident during Flight Test 52 where an in-flight shut-down of the system was required and a dead stick landing resulted'.*

Phase 3 required the introduction of an additional hydrogen storage tank with the HV battery and HFC power system remaining unchanged. The dossier authorising Phase 3 was dated 21 April 2021. The content of the dossier had been provided by the operator's staff and compiled and approved by the competent person with the assistance of his colleagues.

Phase 3

The aim of Phase 3, which was intended to last for seven hours spread over 14 flights, was to conduct longer duration flights at Cranfield before cross-country flights were attempted. Details of the test program were set out as subparts of Phase 3.

> Subpart 3.1 was to establish the operational parameters of the larger hydrogen capacity storage system. Specifically, it was designed to establish the aircraft performance parameters, thermal characteristics, efficiency, endurance, and range. The dossier stated that '*the proposed tests provide a logical and incremental build up in system experience, with flight durations slowly increasing'.* The accident happened during this phase.
>
> Subpart 3.2 was designed to expand the flight envelope within Cranfield airspace, and to demonstrate the elements required for an intermediate A to B flight of approximately 60 nm. The intention was to validate the systems over longer duration flights and to gather reliability data.

> Subparts 3.3, 3.4 and 3.5 were introduced as subsequent aims. Firstly, to fly the aircraft to a new operating base. Then to continue test flying at the new base with a larger hydrogen storage capacity to support and demonstrate an extended range flight of up to 200 nm. The flight requirements of these subparts of the programme were not presented in the dossier but were to be constructed using the data obtained from the completion of subparts 3.1 and 3.2.

The dossier cleared G-HYZA for Phases 3.1 and 3.2 of the programme only. The specific test procedures and requirements were set out in tables detailing the number of flights required, the objectives and system conditions required for each flight, including the planned power and rpm settings. All the flights were planned to be conducted in the normal and extended circuits at Cranfield. The dossier clearly stated that all the risks associated with the programme were defined within the documented risk assessment and related solely to system failures rather than flight manoeuvres.

The dossier for Phase 2 and 3 provided no guidance on the functional links between the individuals in charge of flight test activity, or how coordination between teams and individuals affecting the flight testing would be achieved.

Risk assessments

Loss of propulsion

E Conditions requires risk assessments to be carried out and suggests the use of a hazard identification and risk assessment method (details are at Annex A). The method used for Phase 3 was consistent with the suggested approach and classified the severity, likelihood and tolerability of each risk and listed any mitigations.

The risk assessment determined the probability of a loss of thrust to be 0.008 per flight hour and classified the risk severity as 2B, which means the probability is *'improbable'* with a severity of '*hazardous*'. This gave a tolerability criterion of *'moderate risk'* with a recommendation *'Schedule performance of a safety assessment to bring down the risk index to the low range if viable'.*

One of the occasions when propulsion might be lost is when switching between the two electrical power sources. The AAIB was informed that the mitigation for this risk was to switch power sources when the aircraft was at the end of the downwind leg where it could glide to the runway. However, this mitigation had not been included in the risk assessment and the only mention in the dossier was in Part C where the flight test programme required the power source to be changed at the end of the downwind leg without giving a reason why.

Propulsion loss was considered to have procedural mitigations that were '*no different from any other single engine aircraft where the possibility of a dead stick landing in a field is a possibility.'* The procedures and mitigations intended to minimise the risk of propulsion loss resulting in an off-airfield landing were:

- Inclusion in the Aircraft Flight Manual (AFM) of a '*power loss in flight*' emergency procedure.

- Avoiding flying above populated areas.
- Identification of possible emergency landing zones away from populated areas prior to flight. The pilot reported that this was done by reference to Google Earth.
- Hardware and software modifications made in response to an event that occurred during Phase 2, flight 52, which included the introduction of the fault clear button that would allow the inverters to be reset in-flight.
- A procedural requirement in the test plans to switch between the hybrid and HFC only energy source at the end of the downwind leg.
- Pilot qualification and experience.
- A process for post-flight learning.

Off-airfield landing

The area surrounding the climb-out path of Runway 03 at Cranfield is predominantly agricultural in nature, with a lattice of public roads, farm tracks, agricultural buildings and farmsteads. The fields are generally less than 500 m in length and frequently bounded by hedges and ditches.

E conditions states that:

> *'…the competent person must make it clear that all reasonable precautions have been taken to minimize risk to any third party',*

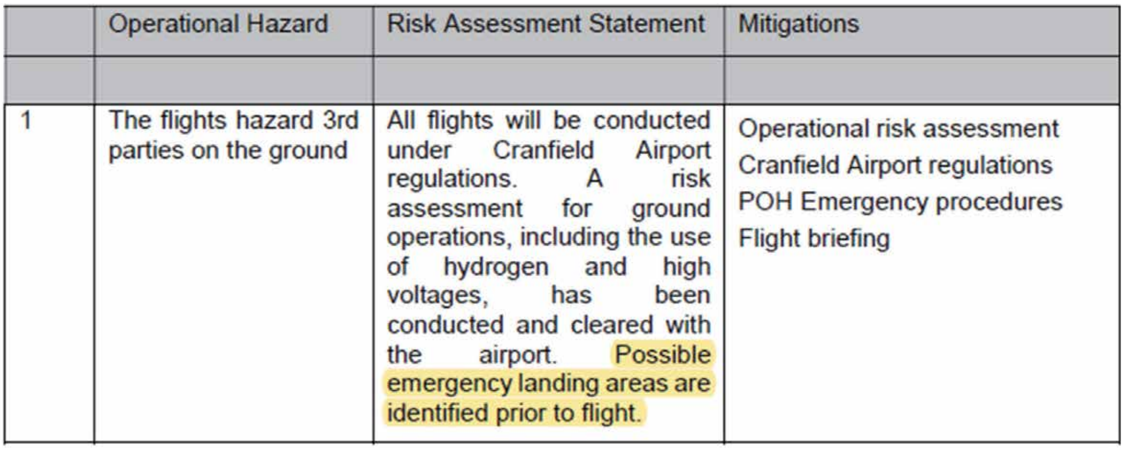
This includes persons on the ground and that:

> *'…the risk of serious injury to uninvolved third parties must be determined to be extremely improbable',*

where E Conditions define extremely improbable as:

> *'…almost inconceivable that the event will occur'.*

To satisfy the requirement that risk to third parties was extremely improbable, it would be necessary to demonstrate in the risk assessment that suitable areas existed that would allow the aircraft to be landed and stopped with a reasonable expectation that it would not encroach on areas either inhabited or frequently accessed by third parties on the ground. No such assessment was included in the dossier other than the operational hazard contained in the risk assessment and highlighted in Figure 7. A detailed study of possible landing areas, aircraft landing performance, and the risk to third parties had not been carried out.



	Operational Hazard	Risk Assessment Statement	Mitigations
1	The flights hazard 3rd parties on the ground	All flights will be conducted under Cranfield Airport regulations. A risk assessment for ground operations, including the use of hydrogen and high voltages, has been conducted and cleared with the airport. Possible emergency landing areas are identified prior to flight.	Operational risk assessment Cranfield Airport regulations POH Emergency procedures Flight briefing

Figure 7

Operational Hazards from dossier risk assessment

Operator's management of the test programme

The operator had established an internal flight test organisation for the project, and while functional links between the individual post holders existed, they were largely informal and not subject to a documented process. The operator did not nominate an individual responsible for risk and safety management who was independent of the flight test and management teams, as that responsibility was placed on the competent person by E Conditions.

Personnel involved with the project could be described broadly as belonging to one of the following sub-groups:

- The flight crew: the pilot and flight test observer.
- The flight test team: the flight crew, the ground crew that prepared and signed off the aircraft for each flight, and the engineering leads that assisted in the review of data from each test flight.
- The experimenting team: the wider team of people who undertook the project to design and build the experimental aircraft and conducted the flight test programme. Not all these individuals were co-located with the flight test team with some of them located in the USA.

The operator had also nominated a project manager who undertook and coordinated a number of their supporting activities.

Competent person

Qualifications and experience

The competent person was academically qualified in aeronautical engineering and had worked in the aerospace industry for over 30 years. He was a Fellow of the RAeS and a CEng. He considered that he was most knowledgeable in structures engineering though he had worked in a variety of areas during his career.

He was contracted to the G-HYZA project on a consultancy basis through his employer, a specialist aerospace company offering a range of services and approved as a design organisation under EASA Part 21 Subpart J . He was involved in two other electric aviation projects, with his employer, including one that planned to demonstrate the use of hydrogen fuel cell technology for passenger carrying airline services. G-HYZA was the first time he had acted as the competent person on an E Conditions project.

Role of competent person

The competent person undertook his role on G-HYZA in parallel with his work with his employer. He described himself as "busy" and perceived the competent person role as like being head of design on a B Conditions project.

When he initially became involved with the G-HYZA project, his place of work was co-located with the experimenting team located at Cranfield. From March 2020 he started to work from home due to restrictions associated with the COVID-19 pandemic and continued to primarily work remotely for the entire time leading up to the accident. Most of the communication between the competent person and the operator was by email and video conference.

The competent person reported that protection of the operator's intellectual property was an important consideration. He stated that the operator provided all the information and documents he requested but did not proactively offer additional information or progress updates. He also needed to share some information within his own organisation because he required assistance to assess the electrical and avionic aspects of G-HYZA and in reviewing the safety system analysis reports generated by the operator.

The competent person commented that most of his work on E Conditions was "getting to the point where the aircraft is safe to fly." His involvement in the project once test flying had commenced was "limited" and he was not involved in any flight-by-flight briefing process. He reported that he expected that the operator would approach him with any proposed deviations to the flight test programme and cited deviating from the parameters on the test card as an example of something he would expect to be informed of. However, he commented that "What would trigger that action wasn't really laid down." Therefore, no formal feedback process had been established to ensure the competent person was updated with data from flight test activity that could challenge the risk analysis as the programme evolved. The competent person was not aware of any technical issues experienced in the earlier Phase 3 flights.

Pilot

The pilot held the position of principal test pilot, which was defined in the dossier as the individual nominated by the competent person who would '*take responsibility for the safe conduct of airborne trials*'. He conducted all the flights in the test programme and held a current ATPL with a single engine piston rating; multi engine piston rating; PA-46T single engine turbine rating; IR and flight instructor rating. He had amassed 34,620 hrs on all aircraft types of which 1,588 hrs were as PIC on the conventional PA-46 and 12 hrs on the experimental PA-46 electric variant.

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The pilot did not hold a formal test pilot rating, nor was he required to do so to participate in the test programme under E Conditions[10]. The operator reported that the pilot was appointed as the principal test pilot due to his extensive previous flight test experience, including:

- Over 50 hours as test pilot for a similar programme where a diesel engine was retrofitted to Cessna 172 and Piper PA-28 airframes.
- LAA approved for test flights of home-built prototype aircraft.
- Approval to conduct CAA Certificate of Airworthiness testing on PA-46 and PC-12 aircraft.
- Piper PA-46T post-production flight testing.

The pilot last received Crew Resource Management (CRM) training in 2014 and was not required by regulations to undergo recurrent training for non-commercial operations.

Flight test observer

Qualification and experience

The observer was recruited by the operator in March 2020 as the lead engineer for the development of the HFC. His role evolved over the course of the programme, particularly during the phase requiring the integration of the HFC into the airframe, and he came to be regarded as the most suitable person to assist the pilot due to his knowledge of the systems. His involvement in the programme in the capacity of a flight test observer started in June 2020.

The observer had extensive experience in the field of HFC design and engineering, but had not completed any flight test training, nor was he required to do so under E Conditions. He had undertaken approximately 10 hours of PPL training in a private capacity. In a previous employment with a helicopter manufacturer, he had gained some limited experience as an observer on test flights.

Role of observer

The dossier described the observer's role variously as a *'passenger who shall act as a flight test observer',* and in a later section as a '*Flight Test Engineer*' who would record *'other parameters and observations'* during the flight. There was no formal definition of the role or description of duties that were expected to be conducted in flight. E Conditions state that:

> *'Observers should only be carried if it is considered that it would be beneficial to overall safety for an observer to participate in the testing and that this justifies the hazard to the additional person.'*

Footnote

[10] CAP1220 – '*Operation of experimental aircraft under E Conditions*', published by the CAA: '*The minimum requirement for carrying out test flying on an experimental aircraft is a valid pilot's licence with the appropriate ratings applicable to the class of aircraft in question and to comply with the applicable medical and recency requirements of the licence and associated ratings.'*

The operator regarded the observer's role as necessary for the successful conduct of the test programme and interviews with the flight test team revealed that a single crew operation was never considered. The observer believed that his role as part of the flight test crew was to "manage the propulsion system in the air" and to provide specialist knowledge of that system to the pilot.

The competent person assumed that the role of the observer was as documented in the dossier and stated that if the role was more like that of a flight test engineer it would have required more scrutiny to check that the person doing the role was suitably qualified and experienced for the role.

Flight test director

The operator established the role of flight test director, which was filled by a senior member of the operator's management team. The roles and responsibilities of this position were not defined in the dossier and there was no requirement to do so under E Conditions, which places sole responsibility for the management of the test programme on the competent person. The flight test director had daily contact with the flight test team. The holder of this role did not have any flight test training or aviation experience.

Crew training

E Conditions makes the following recommendation in relation to flight crew training:

> *'Testing may be preceded by a training and work-up programme during which specific flight test techniques and sortie profiles are rehearsed. This is particularly relevant to any testing that involves elevated risk profiles.'*

and that*:*

> *'Crew Resource Management (CRM) principles should be considered as part of the flight test planning process.'*

The observer had not received any training for his role or in the principles of CRM. The pilot and observer had both completed ground emergency egress training.

Flight test process

A number of steps were required before the aircraft was cleared to start the flight test programme and included: a flight test readiness review (FTRR); signing of the certificate of clearance; and preparation of the flight test cards.

Flight Test Readiness Review

The operator's experimenting team conducted an internal FTRR on 14 April 2021. While the operator's review was not required by E Conditions, the objective of a FTRR was, according to the operator, to *'make sure that unresolved issues are flagged and that the team are happy to proceed*'. A separate FTRR was conducted by the competent person on 20 April 2021, with key personnel from the operator, following which the certificate of clearance was issued. The FTRR delegated responsibility to the pilot for the preparation of each sortie flight test plan.

Certificate of clearance

The certificate of clearance was issued before flight testing commenced and was signed by the competent person and the test pilot. The certificate covered information relevant to the conduct of the test programme and according to E Conditions:

> *'…should be amended or replaced by a new certificate whenever a change is made to the aircraft design standard or to any document or action referenced by the Certificate of Clearance.'*

The certificate issued by the competent person for the operator's test programme, dated 21 April 2021, referred to Part C of the dossier which contained the *'details and phasing'* of the flight test programme. For flights 85 and 86 this stipulated the rpm settings to be used and included the requirement that the switching of power sources must be performed at the end of the downwind leg of the circuit. This requirement was not listed in the certificate of clearance under the section '*Other Restrictions Considered Necessary',* which did list*:*

- '*Flight over populated areas is prohibited.*
- *All operations must remain within 24 minutes of any diversionary airfield due to 24V battery capacity*.'

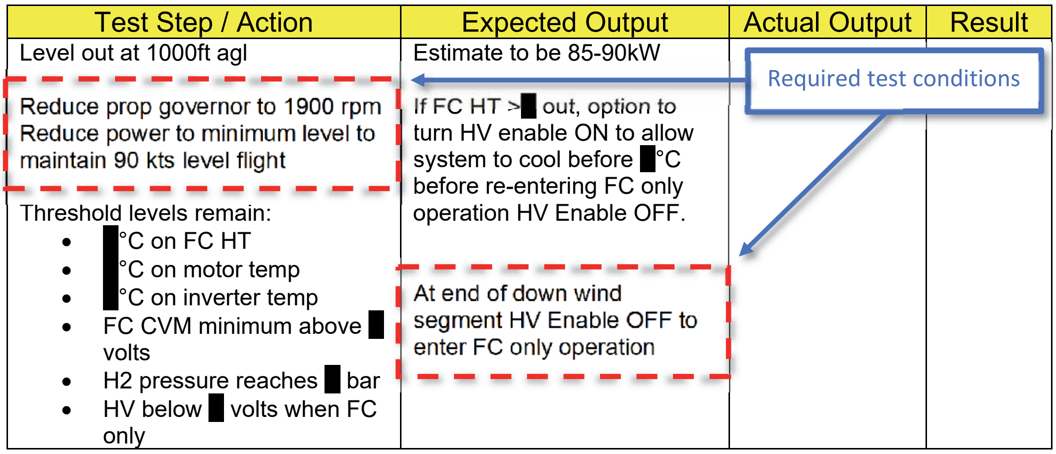
Contrary to the details in the certificate of clearance, during flight 86 a different rpm was used; the power source was also selected at other locations around the circuit during flights 85 and 86.

Flight test cards

Once the certificate of clearance was issued, the flight test team sought input from members of the experimenting team to establish how the propulsion system could be managed and controlled and how it had performed during previous flights. A series of test cards was then created containing a description of the test points to be flown on each sortie, including instructions necessary to conduct the flight and any special procedures required. Test cards were managed by the flight test team and were not subject to independent review by the competent person. An extract from the test card for the accident flight is shown at Figure 8. The flight test team, which included the flight crew, reviewed the contents of the test cards during the pre-flight briefing.

Post-flight debrief

At the end of each flight the results were shared with the flight test team in a post-flight debrief; the competent person did not attend. The observer placed the completed test card, log data and flight video on a network drive to enable others to access the information from remote locations. However, there was no formal process to share the results with the experimenting team or the competent person, and there was no feedback process to indicate that individuals had seen the information.



Test Step / Action	Expected Output	Actual Output	Result
Level out at 1000ft agl	Estimate to be 85-90kW		
Reduce prop governor to 1900 rpm Reduce power to minimum level to maintain 90 kts level flight	If FC HT >[redacted] out, option to turn HV enable ON to allow system to cool before [redacted]°C before re-entering FC only operation HV Enable OFF.		
Threshold levels remain: • [redacted]°C on FC HT • °C on motor temp • °C on inverter temp • FC CVM minimum above [redacted] volts • H2 pressure reaches [redacted] bar • HV below [redacted] volts when FC only	At end of down wind segment HV Enable OFF to enter FC only operation		

Figure 8

Redacted[11] extract from test card for the accident flight – flight 86

Some of the operator's staff mentioned that in previous phases everyone in the experimenting team had reviewed and discussed the data from every flight. However, fewer post-flight discussions and reviews had taken place in the lead up to the accident. The operator's project manager, and one of the lead engineers, reported that prior to the accident they intended to improve the sharing of information by bringing the experimenting team together as a matter of routine but this had not yet been implemented.

Flight 85

Flight 85 was conducted on the morning of the accident flight and shared common test conditions with the accident flight, flight 86. At the end of the downwind leg of the first circuit, on flight 85, the pilot reduced the propeller rpm to 1,900 rpm and then selected the HV battery OFF to fly on HFC only in accordance with the test card. The DC voltage measured at each inverter spiked to just less than 800 V which did not represent an overvoltage condition.

As flight 85 progressed, the crew observed a temperature rise in the HFC so selected the HV battery to ON to reduce the load on the HFC and allow the temperature to reduce. The HV battery switch was cycled on three more occasions to assist with HFC cooling before temperatures in the HFC became stable enough to allow a third circuit to be flown on HFC power only. With the propeller rpm at approximately 1,900 rpm, each time the HV battery was switched the DC input voltage to the inverters spiked, but in all cases stayed below 800 V. After the initial selection of the HV battery switch to OFF, subsequent switch selections were made at various positions in the circuit without incident, but contrary to the agreed conditions stated in the test card.

Footnote

[11] Data redacted as commercially sensitive.

Recorded information

The aircraft was fitted with an extensive recording system to help facilitate the test programme. This included data from the fuel cells, battery, inverters, GPS and five cameras located at various internal and external locations, which also recorded the pilot's headset audio. Data was recovered from the recording system for the accident flight and provided to the AAIB as part of the investigation.

After takeoff, the aircraft achieved an average vertical speed of approximately 425 ft/min. Circuit altitude of 1,300 ft amsl (approximately 1,000 ft aal[12]) was achieved just under three minutes after takeoff at the start of the downwind leg. Airspeed data was not recorded but the ASI could be read using the cockpit video recording. During the crosswind leg, the aircraft track extended beyond the 2 nm boundary (see Figure 1).

During the downwind leg the airspeed stabilised at 100 kt with propeller rpm approximately 2,500 rpm and HV power at 95 kW. Power lever adjustments were made to achieve 90 kW but due to a subsequent loss of airspeed the crew decided to revert to 95 kW. These adjustments required the pilot to read the figures at the top line of the lower display to confirm the power setting which required him to look down into the cockpit.

Once the adjustments were completed, the pilot looked to the right and commented to the observer on where the airfield was. The aircraft turned onto base leg during which it again flew beyond the 2 nm boundary.

During the turn, the pilot acknowledged that the airspeed reduced in order to maintain the altitude. The observer suggested some measures to get back to the test points of airspeed and HV power. He also suggested reducing the propeller rpm once the aircraft was straight and level. The pilot acknowledged the suggestions, and stated "ONCE YOU LOSE THE SPEED, YOU JUST CAN'T GET IT BACK".

The power lever was advanced in the base leg turn to capture the test airspeed of 95 kt and then reduced on final to achieve an HV power of 90 kW and airspeed of 90 kt.

At 1421:34 hrs, the pilot selected the HV battery OFF using a switch in the overhead panel. The aircraft was located 650 m (Figure 9) from the displaced threshold of Runway 03 at 1,300 ft amsl (942 ft aal).

The recorded power lever position was 41% and the motor rpm was 2,310 rpm. The pilot returned his hand to the power lever which then obscured his view of the lower display (Figure 10).

Footnote

[12] Cranfield Airport is 358 ft amsl.

Figure 9

G-HYZA track

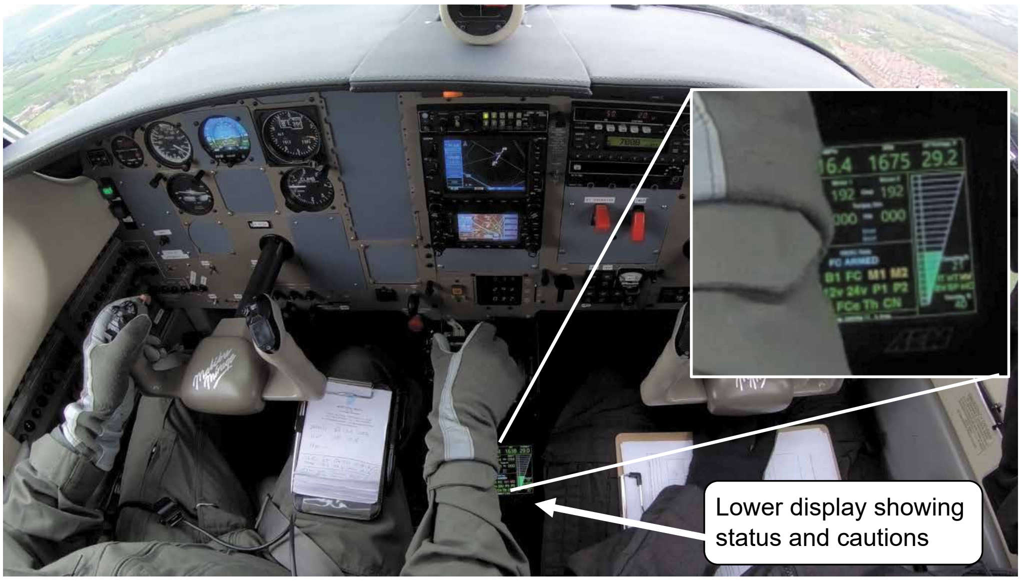


Figure 10

G-HYZA cockpit camera view, just after HV selected OFF, showing zoom of lower display

The on-board camera showed that immediately after the HV battery was selected OFF, the displays showed M1 and M2 initially in red, then amber, representing motor fault conditions. Four seconds later, the pilot noted the loss of power. Five seconds after this, the observer stated, "YOU'VE LOST THE INVERTER, PUSH THE BUTTON".

Power was still available from the HFC, although the voltage increased to 440 V. This was due to the load no longer being applied to the HFC which had defaulted to an 'open circuit voltage' state. As the propeller rpm was high, the motors acted as a generator feeding a large voltage into the inverters. Recorded inverter voltage reached 825 V which triggered an inverter lockout cutting all power to the motors.

The pilot pushed the fault clear button with the recorded power lever position still at 41%. This successfully reset the inverter; however, as the power lever was not at idle, the step demand for power after the reset could not be provided by the HFC leading to a voltage drop. This was detected by the inverter as an undervoltage and caused an additional lockout.

The observer instructed the pilot to select HV battery ON which was successful. However, due to the combination of an increased HFC voltage and continued windmilling action of the propeller, the inverters detected further overvoltage conditions which led to further lockouts. After HV battery was selected ON, further attempts were made to restore power over the next 38 seconds with the observer acknowledging that "THE VOLTAGE IS TOO HIGH". This included resetting the HFC and HV battery supplies with the fault clear button selection at various power lever positions, with no visual reference to checklists. The troubleshooting required the pilot to look down to the power lever and display and then look up to the HFC and HV battery switches in the overhead panel. Despite these attempts, power could not be restored to the motors. Figure 11 shows these data parameters throughout the event.

The observer then stated to the pilot "NO, YOUR CALL, WE'VE LOST EVERYTHING". This occurred 54 seconds after the HV battery was initially selected off with the aircraft located 90 m from the end of Runway 03, offset slightly to the right at 676 ft amsl (318 ft aal).

Forced landing

The pilot transmitted a MAYDAY call stating that they had "LOST POWER AND COMING BACK TO TRY TO GET ON TO TWO-ONE" while commencing a turn to the left. This was followed with a transmission stating that they were landing in a field.

The pilot lowered the flaps and landing gear, touching down in a field at a groundspeed of 87 kt, 23 seconds after the MAYDAY call. Touchdown occurred approximately one third into the field with the aircraft eventually impacting the ditch and hedge at the far end at a groundspeed of 45 kt.

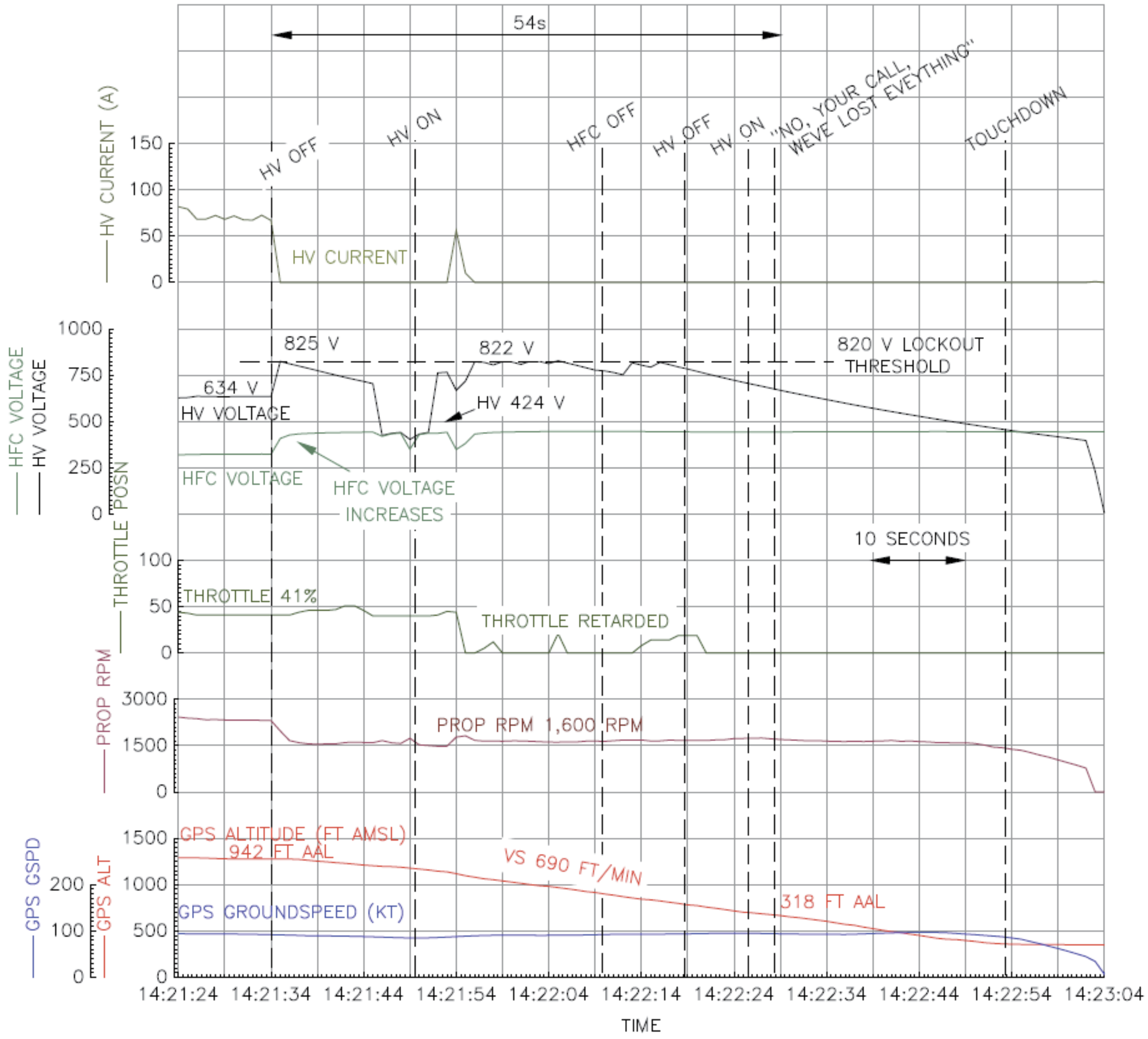


Figure 11

G-HYZA flight data parameters

Weight and balance

During the process of modifying G-HYZA and the subsequent phases of flight testing, it became necessary to operate the aircraft at a higher maximum weight than that certified for the aircraft type. The operator commissioned a third-party report which provided suitable mitigations for this increase and the dossier listed the following increased weights:

‘Parameter	*Basic Aircraft*	*Modified Aircraft*
Maximum Take-off Weight	*4300lb*	*4350lb*
Maximum Landing Weight	*4100lb*	*4350lb*
Maximum Zero-Fuel Weight	*4100lb*	*4350lb’*

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Aircraft performance

Predicted performance

The operator stated that G-HYZA retained the aerodynamic characteristics of a basic Piper PA-46 and that the handling, control and stability characteristics were unchanged. Glide performance was assumed to be unaffected by the modifications and was planned for 2 nm per 1,000 ft. This was the basis for the 2 nm test area around Cranfield to ensure the aircraft could safely return to the airfield following a complete loss of power at circuit height.

Based on test data gathered from Phase 2, the operator calculated the predicted takeoff and climb performance for the aircraft in the Phase 3 configuration. The data indicated that the aircraft could safely take off on the runways available at Cranfield and achieve a climb rate of 572 ft/min at a takeoff weight of 4,320 lb and speed of 90 kt. This rate of climb equated to a climb gradient of 6.3%. Annex B in the dossier stated, *'This is below the Part 23 requirement of 8.3%, although it is acceptable for the test flights planned'.* The operator included the following note in the Aircraft Flight Manual (AFM) Supplement for Phase 3 to address the rate of climb performance:

> ***'5.7 PERFORMANCE GRAPHS***
>
> *The following performance graphs must be read with consideration that the modifications to the aircraft may reduce performance. Therefore the data below should be used for guidance only.'*

Actual performance achieved during flight tests

The pilot reported that the actual rate of climb in Phase 2 was 500 ft/min and due to the 8% increase in weight the rate of climb in Phase 3 was around 300 ft/min. The pilot observed that the aircraft felt "heavy" to fly compared with the Phase 2 configuration, and that it was "flying like it was staggering". However, the recorded data from the accident and two preceding flights show that a rate of climb of 425, 465 and 436 ft/min was achieved in the climb to circuit height.

The reduced climb performance increased the time G-HYZA took to reach circuit height, which in turn meant running on both power sources for longer than anticipated. The pilot reported that each cycle of using the HV battery to halve the load on the HFC to allow cooling would take around 3 to 4 minutes. In combination, these factors increased the rate of depletion of the HV battery, which reduced the time available to complete the test schedule as a reserve of HV battery capacity was required to ensure at least one power source was available should the HFC fail.

The competent person was unaware that the aircraft did not achieve its predicted performance during the first flight of Phase 3.

Landing performance

The AFM indicated that for a full flap landing at 78 KIAS on a paved, level, dry surface at MLW, the landing distance required (LDR) from 50 ft was 1,950 ft (594 m) with a landing roll of 1,000 ft (305 m). The CAA published "*Safety Sense Leaflet 7c Aeroplane Performance*[13]" which states that unfactored manufacturer's data should be considered the minimum acceptable for planning. It includes additional factors to be considered for a number of scenarios including the landing surface condition. For example, dry grass requires a 15% factor plus an additional factor of 43% which increased the distances to 3,207 ft (977 m) and 1,645 ft (501 m). While the CAA strongly recommends these factors are applied to non-commercial flights, they are not normally required to be considered during an emergency landing.

Previous technical issues and actions taken

During phase two and three there had been four notable technical events:

- Flight 52 on 6 November 2020. Total loss of power in-flight; aircraft completed a power off landing on the runway.
- Flight 80 on 23 April 2021. While operating on both power sources, the HFC shutdown in-flight; aircraft landed using HV battery power only.
- Flight 81 on 26 April 2021. The HFC shutdown on the ground during the run-up and the flight was aborted.
- Flight 83 on 27 April 2021. Inverters locked out on landing; power restored after reset procedure carried out.

Flight 52

Flight 52 was subject to detailed analysis by the operator which led to several software changes and two modifications to introduce the fault clear button and an alteration to the HFC air intake. A number of procedural changes were also made.

Flight 80 and 81

Flights 80 and 81 had been subject to internal review by the flight test team and the cause of the HFC shutdowns was identified as 'flooding' due to the accumulation of condensate from excessive HFC cooling. Procedures were modified to prevent reoccurrence, including an amendment to the test cards to conduct the propulsion system run-up on the runway threshold, immediately before take-off, and not at the holding point where previous delays had led to excessive cooling. The competent person was not aware of these actions and no review of the existing safety assumptions was carried out.

Footnote

[13] CAA (2013). *Safety Sense Leaflet 7c: Aeroplane performance*. https://publicapps.caa.co.uk/docs/33/20130121SSL07.pdf [Accessed November 2021]

Flight 83

The incident on flight 83 was recorded on the test card after the flight as:

> *'steep descent resulted in full power reduction at around 500 ft. This resulted in both inverters giving "Error!" due to 819v overvoltage. Fault Clear on runway to restore power.'*

A review of the recorded data revealed that at the time of the incident, the power lever was at 0% demand, propeller 2,050 rpm with voltage peaking at 825 V. The issue was discussed with the flight test team, but as the flight crew did not consider it significant, a safety investigation was not carried out. The flight test director and the competent person stated they were not aware of this event.

Safety management

In addition to the safety management elements required under E Conditions, the operator had in place several other elements including an emergency response plan and a culture of continuous improvement as they worked towards becoming an approved design organisation. However, there was no formal safety reporting process in place, nor was their required to be. Nevertheless, the response to flight 52 showed that in practice the operator did investigate and responded to events that were recognised as significant. Mandatory Occurrence Reports were sent to the CAA following the loss of power during flight 52 on 6 November 2020 and the accident flight on 29 April 2021.

Immediately following this accident, the operator appointed a team of experts who were independent of the G-HYZA programme to conduct an internal investigation. This investigation resulted in the operator taking a number of safety actions which included the following:

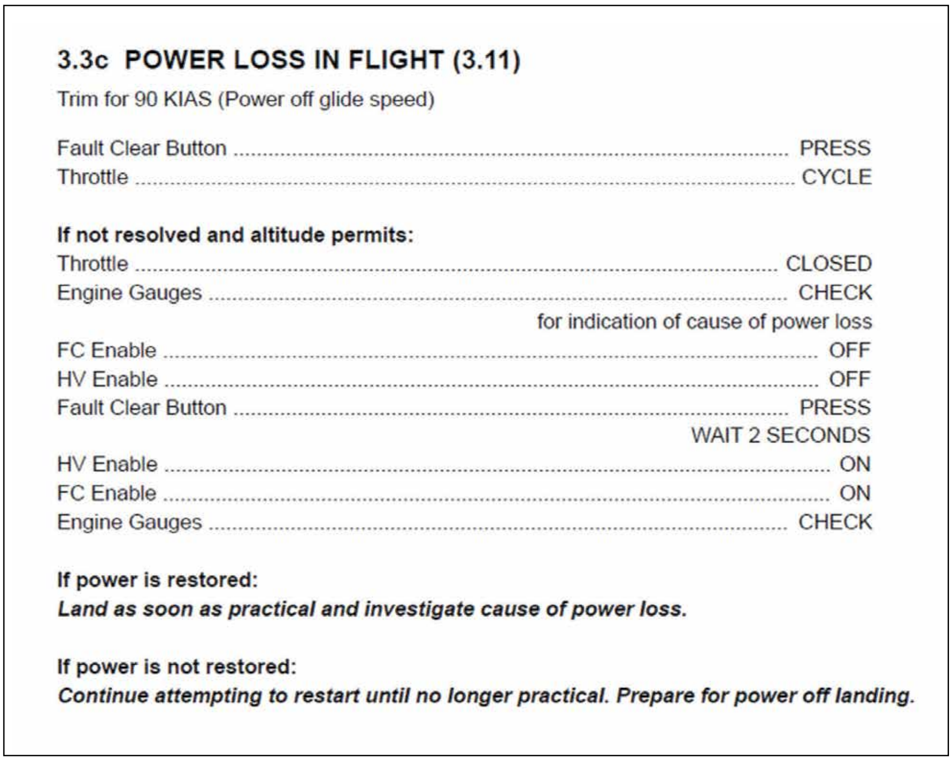
- The design for the operator's future project would incorporate the learning in terms of handling back-EMF [voltage] due to windmilling.
- Future prototype testing would be limited to non-critical redundant situations until the powerplant design matures.
- The design and flight test of future programmes would follow CAA/EASA part 21J and aviation industry best practice.
- A safety management system based on a 'just' aviation culture would be established and include occurrence reporting, investigation, and corrective actions functions.
- Commercial pressure would be actively managed to ensure that it does not compromise safety.

Aircraft Flight Manual

Supplement

The operator produced a supplement to the basic Piper PA-46 AFM to provide the limitations, procedures and information required to operate G-HYZA. The document was designed to be read in combination with the manufacturer's approved AFM.

The supplement contained an emergency procedure for a power loss in flight (Figure 12), which was dated 12 April 2021.



3.3c POWER LOSS IN FLIGHT (3.11)

Trim for 90 KIAS (Power off glide speed)

Fault Clear Button .... PRESS
Throttle .... CYCLE

If not resolved and altitude permits:
Throttle .... CLOSED
Engine Gauges .... CHECK
for indication of cause of power loss
FC Enable .... OFF
HV Enable .... OFF
Fault Clear Button .... PRESS
WAIT 2 SECONDS
HV Enable .... ON
FC Enable .... ON
Engine Gauges .... CHECK

If power is restored:
Land as soon as practical and investigate cause of power loss.

If power is not restored:
Continue attempting to restart until no longer practical. Prepare for power off landing.

Figure 12

Power loss in flight emergency procedure

A subsequent section of the supplement entitled '*Amplified Emergency Procedures (General)'*, contained the following guidance for loss of power:

> *'If the preceding steps do not restore power, prepare for a power off landing.*
>
> *If power is not regained and altitude permits, continue attempting to restart until no longer practical and then proceed with the Power Off Landing procedure.'*

Neither the manufacturer's AFM, nor the operator's supplement was carried on board G-HYZA during the accident flight. While there was no requirement to carry these documents on board, they contained the emergency check lists which might have to be referenced in-flight.

Design of power loss in flight emergency procedure

The operator's lead for airworthiness and certification was the author of the emergency procedures in the supplement, which included the action of pressing the fault clear button. He had consulted with the lead engineer for the HFC for technical input with the intention of producing a document from a "theoretical perspective". This procedure was never conceived to be used by a pilot unassisted by a technical expert.

Engineers from the operator, who had in-depth knowledge of other system aspects, indicated that pressing the fault clear button before reducing the power lever to idle would prevent the system resetting. This was due to the associated rapid onset of power required, and the fault would persist. They had not been consulted over the content of the emergency procedure.

The competent person reported that he reviewed the emergency procedure in detail.

Organisation

Introduction

The AAIB interviewed the operator's staff employed in key positions at the time of the accident, and one of the project's funding organisations. A review of the findings from the operator's internal investigation, covering organisational aspects, was also carried out.

People

A large proportion of the staff involved in the G-HYZA programme were recruited in late 2020 and early 2021. The project team consisted of specialist engineers who focused on specific system aspects including the HFC, drive train, software, power electronics and mechanical integration. While the majority of these specialists were from outside the aviation industry, they worked in collaboration with individuals who had a strong aviation background, which included the airworthiness lead, the licenced aircraft engineer who maintained the aircraft, and the competent person.

Pace of development

The electric aviation propulsion development space was competitive with a small number of organisations vying to be the first to market. The project had evolved with some changes of scope and extensions of timescales beyond the original plan to achieve a long-range flight on HFC only within a year of the start of the project. Nevertheless, they had achieved the world's first flight of a commercial grade hydrogen-electric aircraft. They had also commenced their next project to modify a 19-seat twin engine aircraft by replacing one of the engines with a zero emission drivetrain and to test fly it under B conditions.

The operator's investigation found that the experimenting team had a high workload and there was pressure on them to achieve a long duration demonstration flight by the end of May 2021. A milestone for the operator's 19-seat aircraft project also required significant preparation that was scheduled on the day before the accident. The operator's investigation found that some staff were showing signs that pressure was influencing them to make decisions based primarily on expediency.

Commercial aspects

The operator was in a period of rapid growth and had attracted sufficient funding to progress towards its goals. They had to report to some external parties on progress against the project plan and as the programme had already been extended, they appeared eager to avoid having to request any further extensions. However, there was no apparent threat of funding or investment being withdrawn if the planned test flying programme required more time to complete.

Operating bases

The operator had parallel and interdependent development programmes based in the UK and overseas. Within the UK, the operator was in the process of moving their base from Cranfield to another UK airport. The pilot and observer were still based at Cranfield for the flight testing of G-HYZA and many in the UK part of the experimenting team had already moved and began working in parallel on the 19-seat aircraft project.

At Cranfield there had been some operational constraints that, in the opinion of some of the staff, presented difficulties for the project. There was a perception that there would be fewer constraints at the new base.

Culture and working practices

The operator's staff appeared passionate about their mission and highly motivated to make aviation more sustainable. A fast pace of work and "goal-oriented problem solving" were prized within the organisation and this was communicated by the flight test director and the chief executive who were often present and actively engaged in the technical detail. As an example of this, the flight test director and the chief executive were present at Cranfield on the day before the accident flight and engaged with the observer in a lengthy discussion about how to solve a cooling problem which lasted until late in the evening.

The engineering team had a high degree of autonomy and the ability to request whatever resources they needed to solve problems. There were few prescribed procedures, and it was common for individuals to devise practical workarounds or adaptations to overcome problems or constraints.

When asked about safety during the interviews, staff at all levels agreed that it was important, but none of the interviewees proactively talked about safety as a key priority or value within the operator. There was no evidence that any member of the team had ever been asked or encouraged to compromise safety to progress the project.

Analysis

Introduction

The accident occurred because the aircraft lost propulsion when the HV battery was switched off to allow the motors to be supplied solely by the HFC when the aircraft was not in a position where it could safely glide to the runway.

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Reason for loss of propulsion

When the HV battery was switched off, the sequencing of the contactors, to allow the HFC alone to provide electrical power, resulted in a momentary interruption of the power supply to the motors. During this brief period the propeller was driven by the airflow which caused the motor to act as a generator. The resulting voltage was high enough to cause the inverter overvoltage protection to lockout the power supply to the motors.

The pilot attempted to reset the system with the HFC ON and the HV battery OFF by pressing the fault clear button. However, the power lever remained at 41% and as the motor control logic did not have a 'soft start' or ramp demand function, the HFC alone could not respond fast enough to meet the demand from the PCU. Consequently, the voltage at the HFC reduced and the invertor undervoltage protection operated locking out the inverters again. The HV battery was selected ON and the fault clear button selected several times at different power lever positions, which did reset the inverters but the high voltage resulting from a combination of increased HFC voltage and the windmilling propellor continued to trigger the overvoltage protection.

A similar flight test profile had been flown earlier in the day, as part of flight 85, when the propeller was operating at approximately 1,900 rpm. Data from that flight showed that while there was a momentary voltage spike when the HV battery was switched off, the lower propeller rpm meant the motors did not generate a high enough voltage to trigger the inverter overvoltage protection.

Previous losses of propulsion

Propulsion had been lost on two previous occasions (during flights 52 and 83), when the windmilling propeller resulted in the inverters locking out as a result of a high voltage. On both occasions the aircraft landed safely. The installation of the fault clear button following flight 52 was expected to allow the system to be reset, but an inverter lockout occurred again on flight 83 during the descent to land. This loss of power on flight 83 was not reported to either the competent person or the flight test director as the crew did not consider it to be significant at the time. Consequently, no investigation was carried out to establish the cause.

Procedure for clearing invertor lockout

Following flight 52, the AFM supplement was amended to include the procedure for clearing the inverter lockout by use of the fault clear button. After establishing a safe glide, the next step in the procedure was to press the fault clear button and then cycle the power lever. However, the members of the team who developed the procedure did not recognise that if the fault clear button was pressed with the power lever in any position other than idle, the system would see a load demand and try to respond. This was not a particular problem for the HV battery, but the HFC might not be able to react rapidly enough and the consequent drop in voltage could be sufficient to trigger an undervoltage condition at the inverters. Moreover, the PCU did not include an algorithm to ramp the voltage to maintain the demands on the HFC within achievable limits. Some members of the experimenting team were aware that the power lever should be retarded before pressing the fault clear button, but they were not involved in the development of the AFM procedure. The competent person also reviewed the AFM procedure, but it is likely that he did not have a detailed enough knowledge of the system to understand that the power lever first had to be retarded.

Propeller windmilling

If an electric motor is back driven, such as by a windmilling propeller, it will produce a voltage with the electrical energy produced being fed to the inverters. Ground or wind tunnel testing, encompassing the entire electrical system operating under simulated flight conditions, might have alerted the engineers to the magnitude of the voltage that the motors could generate when being driven by the propeller. A series of tests was undertaken after flight 52 and prior to the start of Phase 3; however, while the testing included fast taxi runs, the change of power source was not made during these tests. Consequently, no tests were carried out to establish the effect of the back voltage in the electrical distribution system from a windmilling propeller.

The engineers understood that the windmilling propeller generated a back voltage and after flight 52 made software changes to reduce the delay in the system during the reconfiguring of the power source. They also increased the high voltage threshold. However, by not carrying out relevant ground testing they did not appreciate the potential magnitude of the back voltage that might occur.

Loss of power from the HFC

The HFC had also shut down during flight 80 and during the run-up on the ground on flight 81 leaving the motors to be supplied by the HV battery only. On both occasions the cause was attributed to excessive HFC cooling. While the change to the operating procedures and amendment to the test cards were intended to prevent a reoccurrence, the competent person was not made aware, and no review of the risk assessment was carried out.

Aircraft performance

The predicted performance of G-HYZA was checked during the first flight of Phase 3 when the pilot reported that the rate of climb of 300 ft/min was significantly below the predicted 572 ft/min. Recorded data showed that a rate of climb of 425, 465 and 436 ft/min was achieved during the final three flights. This reduced performance would increase the time for the aircraft to reach the test height of 1,000 ft, which would require it to run for longer on both power sources. It was also have been necessary to have used the HV battery to offload the HFC to allow it to cool when required. Consequently, as the HV battery had a duration of around 20 minutes, it would have been difficult for each flight to complete the three or more circuits specified in the flight test card, while maintaining a minimum capacity to ensure a powered landing in the event of the HFC failing.

The competent person was not aware of the lack of performance and neither the certificate of clearance nor the risk assessment were reviewed following the finding that the predicted performance was not achievable.

Pre-flight decision making

In order to resolve the cooling problem with the HFC, a decision was made by the flight test team, following the flight in the morning, to experiment with the aircraft parameters by increasing the speed and rpm, and reducing the angle of attack to improve HFC cooling in-flight. Power and rpm settings were specified in the test programme within the dossier and were therefore associated with the certificate of clearance signed by the competent person and the principal test pilot. However, no changes were made to the flight test card and the planned changes were not discussed with the competent person, so he did not have the opportunity to review the certificate of clearance or the risk assessment prior to the flight. The flight test team appeared to see this adaptation as an incremental change within the remit of establishing the operational parameters of G-HYZA. They did not consider this change presented an additional risk or anticipate the effect it would have on the propeller windmilling speed and the possible effect on the electrical distribution system.

The plan was also not widely discussed with other engineers in the experimenting team. There was no formal process to require it and informal review and discussion with the whole team had become less frequent over time due to workload on the two parallel projects and the move to the new operating base. This had been recognised as an issue by some of the operator's staff, but they had not had time to improve the situation before the accident occurred.

The flight test team were highly motivated to achieve the project's goals because they believed in the potential of the technology and the need to improve sustainability in aviation. They were influenced to make an expedient decision by the culture within the operator and the competitive environment they were working in. None of the flight test team had formal flight test training or experience in a professional flight test programme, so there was nothing within their own experience to influence them to take a more cautious and systematic approach.

Accident flight

After the aircraft took off, it climbed and flew outside of the flight test area before turning to join the downwind leg where it reached the test altitude of 1,000 ft aal. The aircraft was established on the test conditions briefed prior to the flight, and the power setting was reduced to establish the impact on the aircraft performance. While the crew discussed the effect of the power change, the aircraft flew beyond the end of the downwind leg and out of the test area. The pilot was delayed in recognising their position in the circuit as his attention was focused on the power settings on his display, mounted below the throttle quadrant, and the flight instruments.

Once he recognised that he had flown past the planned point to change the power configuration, the pilot could have elected to fly through the circuit and re-establish the test conditions in the position required by the test card before selecting the HV battery OFF. However, it is likely that the decision to turn towards the runway and then select the HV battery OFF, was influenced by the flight earlier in the day when the changeover of power sources was successfully performed at various positions in the circuit. Previous testing of the changeover on the ground would have further reinforced his confidence in the system and the ability to reconnect the HV power source if required. The crew were also aware of the limited endurance of the HV battery and that it imposed a restriction on the duration of the test flight if its capacity was used for longer than necessary. After the accident, the pilot reported that flying an additional circuit to reposition on the downwind leg would have imposed an unnecessary drain of the HV battery. This decision was contrary to the specified mitigation in the test plan for the change of power source to be carried out at the end of the downwind leg. It was also contrary to the guidance in CAP1220 that '*ad-hoc testing should not occur*.'

Handling of the emergency

The pilot quickly identified the loss of power from the aircraft response rather than the display indications. Nine seconds after the loss of power the observer stated that the inverters had been lost. The aircraft was at 880 ft above the airfield.

The location of the system status display and the absence of aural warnings meant critical information regarding the motor operation was not readily available to the pilot. The only indication of a loss of power was a change in colour of the small symbols M1 and M2 on the cluttered system status display, which was obscured when the pilot's hand was on the power lever.

A copy of the emergency procedure, contained in the AFM supplement, was not carried on the aircraft. During the emergency the pilot did not call for the emergency check list, but instead the observer directed the pilot from memory. While the observer's memory steps were not in accordance with the AFM procedure, his actions did not affect the outcome as the AFM procedure did not include a step to move the power lever to idle before pressing the fault clear button. Therefore, the inverters would have remained locked out even if the AFM procedure had been followed.

The cockpit video showed that the aircraft was flown at its glide speed of 90 - 95 kt throughout the emergency and recorded a relatively straight track along the runway. The decision to attempt to restore power to the motors by switching on the HV battery rather than immediately committing to a manoeuvre to land on the runway was logical: the crew had no reason to expect the power source would not come back online when selected. They had performed the action on many occasions both in the air and on the ground. However, when this was unsuccessful, they continued to troubleshoot and made multiple attempts to reset the system, during which time the pilot's attention was focused inside the cockpit to the detriment of his awareness of position and height. Had the pilot's immediate response to the loss of power been to commit to a 360° turn, a series of 'S' turns or sideslip manoeuvre, it is possible that he could have landed on the runway but the risk of entering an undesired aircraft state, which could result in a loss of control close to the ground, would also have increased.

After 54 seconds the observer concluded that it was not possible to restore power, by which time the aircraft was at 320 ft above the end of the runway and the options for a field landing were extremely limited. The pilot's initial response was to attempt to turn back to land on the opposite runway, demonstrating that he was not aware of their proximity to the ground. However, on starting the turn he immediately recognised the threat and promptly configured the aircraft to land in a field directly ahead. The delay in recognising the aircraft's proximity to the ground revealed the challenge of managing a critical aircraft emergency and the importance of:

- Prioritising immediate actions necessary to ensure safe flight.
- Timely decision making and identifying when to stop troubleshooting to allow a full focus on flying the aircraft.
- Managing the inputs of crew members to ensure the PF remains focused on the task of flying the aircraft first.

Contingency for a forced landing

G-HYZA was most exposed during the period between taking off and reaching circuit height in the downwind position for the runway. A loss of propulsion at the end of the downwind leg would have presented a much lower risk as the aircraft could glide to the runway. This was a key factor in the risk mitigation to switch power sources at that point. The dossier stated that fields suitable for an off-site landing had been identified in mitigation of a loss of power scenario. However, there was no consideration of the landing performance, either factored or unfactored, or a detailed analysis of the landing distance available in fields around the airport. There were also few locations within the climb out path of Runway 03 at Cranfield with sufficient obstacle free length to allow for a safe forced landing where the associated risk to third parties could be regarded as *'extremely improbable',* which was a requirement of E Conditions.

Flight crew

The dossier stated that the role of the observer was to record '*parameters and observations'* on the flight, but in practice the pilot and observer were operating in a multi-crew environment. The flight test programme was never conceived by the operator to be conducted by a single crew member. The scope of general airmanship, parameters to be monitored, the depth of knowledge required of the propulsion system and the timely management of HFC temperature regulation required the effective coordination of both roles. This was not the understanding of the competent person.

The competent person's understanding of the pilot and observer roles was consistent with the dossier, which was prepared using information he requested from the operator. But the dossier was not an accurate description of the critical role of the observer. The competent person assumed that in the event of an emergency the pilot would execute the drills independently and, therefore, he did not consider the suitability of the observer for the role or require CRM or additional training to be carried out.

Crew performance

The pilot last received CRM training seven years prior to the accident, and the observer had never received any CRM training or instruction on how to work in a multi-crew environment.

During the emergency, when faced with confusing and unrecognised system indications, the observer's persistence with attempting to solve the problem, despite the approaching ground, indicates that he did not perceive the threat. It is probable that he considered flightpath management to be the sole responsibility of the pilot. However, the pilot remained confident in the observer's knowledge of the propulsion system and ability to restore power, which delayed his recognition of the emerging threat of ground proximity. It is likely that both individuals would have been better placed to react to the hazardous situation had they received recent CRM training and conducted regular multi-crew emergency handling review exercises as part of a threat and error management strategy. CAP1220 recommends that, '*Crew Resource Management principles should be considered as part of the flight test planning process'*.

Design and positioning of displays

During the accident flight the aircraft flew outside of the test area twice. The opportunity to switch power sources at the end of the downwind leg was missed and the pilot appeared not to recognise his proximity to the ground and his position in relation to the runways when it became clear that he had to conduct a forced landing. One potential factor, which might also have delayed the diagnosis of the power loss, was the design and positioning of the pilot's electronic display which contained important information, such as the rpm and motor power setting, that the pilot required to control the aircraft. However, the display did not conform to aviation good practice for the following reasons:

- The pilot's display unit was not positioned in his primary field of view.
- Most of the display was obscured by the pilot's hand on the throttle, including the warning and caution captions.
- The display was densely populated with many parameters in a small font.
- The warning and caution indications had no attention getting properties.

The cockpit video showed that during the emergency the pilot's attention appeared to be mostly in the cockpit moving between the overhead panel, main instrument panel and his electronic display located beneath the throttle quadrant. While CAP1220 did not require the aircraft to conform with the airworthiness requirements of a Permit to Fly or Certificate of Airworthiness, there are safety benefits in following existing design guidelines, where possible, to ensure that operational risk is kept as low as reasonably practicable and tolerable. In this case, the location of the aircraft controls did not present any issue but the principle of following existing design guidelines remains applicable. The following Safety Recommendation is therefore made to the CAA:

Safety Recommendation 2022–008

It is recommended that the Civil Aviation Authority develops guidance in CAP1220, Operation of Aircraft Under E Conditions, regarding the use of existing guidance on the design and positioning of controls and displays used in the operation of the aircraft.

Risk assessment

The risk assessment is a fundamental aspect of E Conditions and needs to be carried out prior to the start of each phase and reviewed whenever a new hazard is identified or there is a possible change to the risk.

Loss of thrust had been identified as a hazard and mitigations were recorded in a number of documents, which should have reduced the chance of an off-airfield landing had they been followed. Not all mitigations for loss of thrust were listed in the hazard identification and risk assessment section of the dossier, or in the certificate of clearance. One mitigation was the requirement to switch between the HV battery and HFC at the end of the downwind leg, but this was only documented in the flight test programme. While the flight crew and the competent person were aware of this mitigation, it was not followed. If it had been made more prominent by inclusion as an operating limitation in the certificate of clearance, which was signed by both the competent person and the principal test pilot, it might have been respected by the flight crew.

The risk assessment said that the loss of high voltage electrical power distribution and loss of thrust from two motors had a risk index of improbable, which is defined as *'very unlikely to occur (not known to have occurred')* with a tolerability of *'hazardous'*. However, propulsion had been lost on two previous flights, which meant the basis of the risk assessment was no longer valid and the tolerability was more likely '*high risk'*. Consequently, a review of the risk assessment following the loss of propulsion on flight 83 may have required the certificate of clearance to be suspended until action had been taken to bring the risk index down to the moderate or low range. A review of the risk assessment was not carried out.

Mitigation for a loss of power was to *'Land as soon as possible'* or to undertake a *'dead stick landing in a field',* which was considered to be no different to other single engine aircraft. While this is correct, the likelihood of it occurring exceeded that of other aircraft due to the experimental nature of the propulsion system.

Organisational factors

The operator was a relatively new organisation that formed in the USA in 2017. Part of the operation then moved to the UK to take advantage of the regulatory environment of E conditions and available funding. Initially the operator had limited aviation experience in the conduct of experimental test programmes but was still growing in preparation for the 19-seat project that would be flown under B conditions. By the end of 2020 they had recruited an airworthiness and certification lead, both of whom had the relevant experience and qualifications to fill their roles. In March 2021, they recruited a head of design whose focus was on the new project and not G-HYZA.

To manage the project, the operator had established an informal organisation loosely consisting of the flight test and experimenting team led by the flight test director. At the time of the accident some of the team were working in parallel on the 19-seat project and had relocated to the new operating base. Neither the competent person, who was responsible in CAP1220 for managing the project, nor the principal test pilot were employees of the operator. The competent person's availability to oversee the project was constrained by his primary work commitments from his employer, COVID-19 restrictions and the long hours and pace of the project.

It would be difficult for one individual, particularly when their availability is limited, to manage such a complex project without there being a clear organisational structure that defines roles, responsibilities, and reporting loops. No such information was in the dossier or captured elsewhere. Consequently, the competent person was unsighted on much of the detail of the daily operations, and so was not consulted about changes to the flight test programme or informed of a number of significant technical issues. The flight test director had informally assumed many of the responsibilities that CAP1220 required of the competent person.

The experimenting team had a strong personal motivation to make aviation more sustainable and felt that their technology was a viable solution. They were working in a competitive commercial environment with several other projects vying to achieve similar goals first. Most of the other people who worked at the operator displayed a similar enthusiasm and the culture within the operator was accordingly fast paced. Solving problems and making progress was prized. The incentive for solving the cooling problem and therefore being able to fly for longer was to be able to do an A-B flight to the operator's new base. This would have been a great achievement and a clear demonstration of the capability of hydrogen fuel cell technology in aviation. It would also have allowed the operator's team to be reunited at the new base and would have provided more operational freedom when flying G-HYZA. But as the apparent pace of the project increased there appeared to be fewer flight debriefs with the full experimenting team and less information was fed back to the competent person, partly due to concerns regarding his work on a competing project.

While some elements of a Safety Management System were present within the organisation, a safety culture was still emerging as the organisation grew. Sole responsibility for safety was placed on the competent person by E Conditions, but given his availability, and the pace of the programme, it would have been prudent for the operator to also have nominated an individual responsible for risk and safety management, who was independent of the experimenting and management teams. This accident demonstrates the importance in a complex, fast paced, experimental project in putting in place an appropriate safety management system at the start of the programme.

E Conditions nominated roles

The safety of an E Conditions project is dependent on the leadership of the competent person. As well as meeting the eligibility criteria, G-HYZA's competent person had relevant experience that made him an appropriate choice for the role. He had a long and broad engineering experience, and accountability for aircraft design and modification projects in the UK under other regulatory requirements.

The basic eligibility criteria for a competent person ensures they have a level of engineering competence and overall professionalism but does not ensure that they are equipped to provide effective safety leadership in a complex project like G-HYZA. The criteria in

CAP1220 would allow engineers with much less experience than G-HYZA's competent person to be authorised to be a competent person. This project had many different interacting aspects and was conducted in a team culture that was quite different from more typical aviation organisations. It was difficult for the competent person to provide effective leadership as an external contractor, particularly as he was physically remote and had a workload of other projects.

This was the competent person's first E Conditions project. The dossier he prepared was comprehensive and he believed that it would be followed and that his level of involvement in the programme was appropriate. He did not take account of differences between E Conditions and the more familiar EASA Part 21J projects in terms of qualifications, experience, procedures and cultural aspects of the team he was working with and realise that more oversight was needed.

Once the certificate of clearance was issued and test flying started, the competent person's involvement was limited for a combination of reasons. He assumed that G-HYZA's flight test team would behave in a similar way to trained test pilots and flight test engineers, that they would strictly follow the documented processes and would be aware of the issues they should contact him about. Accordingly, neither the competent person nor the operator had established a mechanism to ensure that the competent person was consulted about changes to the flight test programme or about technical issues experienced earlier in Phase 3.

CAP1220 states that, '*…it is for the Competent Person to keep the owner and Test Pilot appropriately briefed on all aspects of the test programme*'. It also requires that the principal test pilot *'will take responsibility for the safe conduct of airborne trials'.* As a cosignatory to the certificate of clearance, the test pilot also had a responsibility to understand the contents of the dossier and advise the competent person on safety issues related to the airborne trials, and on planned changes to the cleared test programme.

Post-flight briefings between the competent person, the operator and the principal test pilot were not always carried out and the competent person was not made aware that the predicted performance was unachievable, or informed of the significant technical issues that occurred on flights 80, 81 and 83. Had the competent person been aware of the previous loss of power events and the plan for the accident flight, he might have introduced some checks and balances such as a review of the risk assessment, additional ground testing or a re-emphasis of the pre-existing risk mitigations. This reveals the importance of establishing a comprehensive and robust feedback process, without which the competent person could not make an informed and timely assessment of the emerging risks as the programme progressed. CAP1220 is already clear about what the expectations on the competent person are.

Review of E Conditions

The technology used in G-HYZA was already established outside aviation and the use of E Conditions provided the operator with a useful steppingstone towards developing a commercially viable, zero emission propulsion system.

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At the time of the accident, E Conditions had been in force for a relatively short time. G-HYZA met all the criteria to operate under CAP1220; however, it was at the top end of the weight criteria, was multi-crew and one of the more complex of the nine projects to have started test flying. It was also a fast-moving international project, where many of the engineers did not have an aviation background and those that did were not experienced in experimental flight testing.

The reduction in the burden of regulation makes E Conditions attractive to a wide range of parties who wish to test a proof of concept ranging from relatively simple designs to high-profile, leading-edge technology. The scope of CAP1220 allows for a wide range of experimental projects some of which may be beyond the original intent of the authors in 2015 and beyond the experience and resources of some parties. Complex and commercially dynamic projects, or those involving multi-crew aircraft operation, may require additional provisions to ensure that they can be safely managed. Therefore, the following Safety Recommendation is made to the CAA:

Safety Recommendation 2022–009

It is recommended that the Civil Aviation Authority clarify the scope of projects considered suitable to be carried out under CAP1220, Operation of Aircraft Under E Conditions, and introduce additional provisions, where necessary, to cater for the full range of project complexity envisaged.

Apart from the basic details submitted on the declaration, there is no independent review of the suitability of a project for E Conditions or if all the required conditions have been fully addressed in the dossier. That judgement is delegated to the competent person who may be supported in this decision by the operator and the experimenting team where one exists. There is an option for the CAA to review the dossier, but it is unclear what would trigger this additional scrutiny. It was not triggered for G-HYZA, which at the time of the accident was one of the more complex projects conducted under E Conditions. Therefore, the following Safety Recommendation is made to the CAA:

Safety Recommendation 2022-010

It is recommended that the Civil Aviation Authority require an independent review of the Dossier for aircraft operating under the provisions of CAP1220, Operation of Aircraft Under E Conditions, to ensure the project meets the intent of the guidance and can be safely managed by a competent person.

There are a number of routes to be a competent person. In this accident, the competent person achieved his competent person status on the basis that he was registered as a CEng and member of the RAeS. CAP1220 states *'Within the scope of E Conditions there will be no limitations imposed on the Competent Person.'* This means that, any chartered aeronautical engineer recognised by the RAeS is automatically considered suitable to lead any E Conditions project as a competent person without further scrutiny or assessment.

Currently, there is no assessment required to ensure the competent person is able to fulfil their responsibilities, considering factors such as organisational relationships, conflicting interests, availability, skills and knowledge. A closer assessment could identify if the individual is suitable, or if additional measures are required, to assist the competent person manage the project. Therefore, to ensure the suitability of an individual to act as a competent person on a project undertaken under E Conditions, the following Safety Recommendation is made to the CAA:

Safety Recommendation 2022–011

It is recommended that the Civil Aviation Authority requires that the individual nominated as a competent person under CAP1220, Operation of Aircraft Under E Conditions, has the knowledge, skills, experience, and capacity to manage and oversee the experimental test programme registered on the Declaration.

CAP1220 clearly states that the competent person is responsible for the entire experimental test programme and is required to be involved on a flight-by-flight basis. There is also recognition that an individual might not be able to meet all the expectations of this role and the delegation of some responsibilities and establishment of a team might be required. In this accident a number of informal teams and an organisational structure developed without the necessary responsibility having been delegated. Feedback loops were not effective in ensuring the competent person could fulfil his responsibility in ensuring the safe conduct of the programme.

CAP1220 provides limited guidance on how to organise a complex experimental flight test programme, nor does it address the management of human, organisational and cultural factors that were seen in this accident. The safety of operating under E Conditions could be strengthened through additional guidance and training to help the competent person anticipate and manage factors that may be prevalent. The principal test pilot also has a key role in the safety of the programme, as well as the management and organisation of the flight, and would also benefit from this training and guidance. Therefore, the following Safety Recommendation is made to the CAA:

Safety Recommendation 2022–012

It is recommended that the Civil Aviation Authority enhance the guidance for the competent person and principal test pilot in the organisation, management, and conduct of the flight test programme, for an experimental aircraft project operating under CAP1220, Operation of Aircraft Under E Conditions.

Survivability

The aircraft cabin, hydrogen storage and HV battery pack remained intact during the accident with no evidence of leakage of hydrogen or shorting of the HV battery. The hydrogen system was made safe by the observer operating the manual dump valve which vented the hydrogen to atmosphere.

Conclusion

The accident occurred when electrical power was lost to both motors as the power source was changed, and the inverters locked out, at a position in the circuit where the aircraft could not safely glide to the runway. A number of factors contributed to the accident:

- Sufficient ground testing had not been carried out to determine the effect of the back voltage from a windmilling propellor on the inverter protection system.
- The emergency procedure to clear an inverter lock out after the protection system operated was ineffective.
- An investigation had not been carried out into a previous loss of power resulting from an inverter lock out, which occurred three flights prior to the accident flight.
- The risk assessment had not been reviewed following the loss of propulsion on two previous flights.
- Ad hoc changes were made to the flight test plan, including the position where the electrical power source was switched, without the knowledge of the competent person.

G-HYZA met all the requirements to be flown under E Conditions and a comprehensive dossier was produced by the competent person. However, this was a complex project, and the competent person was unable to completely fulfil his responsibilities as detailed in CAP1220. The competent person's involvement was restricted in a number of areas due to issues within the organisational relationships, the fast tempo of the project, other work commitments and restrictions from the COVID-19 pandemic. The operator's chief executive and the flight test director took on the day-to-day management responsibility for much of the programme. However neither individual had the necessary safety and flight test experience for that role and their focus was primarily on meeting key project targets.

Safety Recommendations

The following Safety Recommendations were made to the CAA:

Safety Recommendation 2022–008

It is recommended that the Civil Aviation Authority develops guidance in CAP1220, Operation of Aircraft Under E Conditions, regarding the use of existing guidance on the design and positioning of controls and displays used in the operation of the aircraft.

Safety Recommendation 2022–009

It is recommended that the Civil Aviation Authority clarify the scope of projects considered suitable to be carried out under CAP1220, Operation of Aircraft Under E Conditions, and any additional provisions that might be required for more complex projects.

Safety Recommendation 2022–010

It is recommended that the Civil Aviation Authority require an independent review of the Dossier for aircraft operating under the provisions of CAP1220, Operation of Aircraft Under E Conditions, to ensure the project meets the intent of the guidance and can be safely managed by a competent person

Safety Recommendation 2022–011

It is recommended that the Civil Aviation Authority requires that the individual nominated as a competent person under CAP1220, Operation of Aircraft Under E Conditions, has the knowledge, skills, experience, and capacity to manage and oversee the experimental test programme registered on the Declaration.

Safety Recommendation 2022–012

It is recommended that the Civil Aviation Authority enhance the guidance for the competent person and principal test pilot in the organisation, management, and conduct of the flight of an experimental aircraft project operating under CAP1220, Operation of Aircraft Under E Conditions.

Safety Actions

As a result of this accident the operator undertook the following safety actions:

- The design for the operator’s future project would incorporate the learning in terms of handling back-EMF [voltage] due to windmilling.
- Future prototype testing would be limited to non-critical redundant situations until the powerplant design matures.
- The design and flight test of future programmes would follow CAA/EASA part 21J and aviation industry best practice.
- A safety management system based on a ‘just’ aviation culture would be established and include occurrence reporting, investigation, and corrective actions functions.
- Commercial pressure would be actively managed to ensure that it does not compromise safety.

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G-HYZA - ANNEX A

SIGNIFICANT ASPECTS OF CAP1220, OPERATION OF EXPERIMENTAL AIRCRAFT UNDER E CONDITIONS

Background

In 2006, the Royal Aeronautical Society (RAeS) raised concerns that UK aviation was not moving forward with new ideas or innovative technologies with the same vigour as in the past[1] and that fewer one-off projects were being undertaken. In response, the CAA formed a working group with the RAeS. The group concluded that there needed to be a simpler and more flexible system to enable projects to take to the air and the solution reached was E Conditions, which were first published under CAP1220[2] in November 2015.

A minor revision of E Conditions was published in November 2019 after a review by the CAA and RAeS working group. The working group planned to conduct a further review in 2022.

Competent person

Under E Conditions, a registered competent person takes sole responsibility for the entire experimental test programme. Their responsibilities are listed in CAP1220 and include:

- Signing the declaration.
- Preparing the dossier.
- Managing the whole programme and taking sole responsibility for its safe conduct.
- Specifying the flight test area.
- Assessing all risks of the flight test programme, especially those to third parties, throughout the flight test programme.
- Signing the certificate of clearance.
- Not permitting any flights to take place until they are satisfied that identified risks are mitigated to an acceptable level.
- Ensuring that all participants in the test team are properly aware of the risks of the test programme.
- Attending flight test briefings.

One route to become a competent person is current membership of the RAeS and professional registration with the Engineering Council as a Chartered Engineer (C Eng) via the RAeS. The Engineering Council's '*Competence and Commitment Standard for*

Footnote

[1] Royal Aeronautical Society (2006). *The design, development and production of light aircraft in the UK. Case for regeneration through regulatory change.*

[2] Civil Aviation Authority (2019). CAP1220 *Operation of experimental aircraft under E Conditions.* http://publicapps.caa.co.uk/docs/33/CAP1220EConditions_Edition2_Nov2019.pdf [Accessed on 29/11/2021]

Chartered Engineers' and the '*Statement of Ethical Principles'* in conjunction with the *'RAeS Codes of Conduct'* were considered sufficient to ensure the capability of such engineers to be solely accountable for the safety of E Conditions projects. Nevertheless, E Conditions envisaged that the competent person may need to enlist the help of other individuals to be able to fully fulfil their responsibilities.

Members of the CAA and RAeS working group stated that the underlying intention was that the competent person would have a close involvement in the test flying programme.

Experimenting team

The experimenting team is the group of people who undertake the project to design, build and undertake the flight test programme. This team acts under the authority of the competent person.

Principal test pilot

The principal test pilot is nominated by the competent person and is a principal member of the experimenting team. With regard to qualifications and experience, E Conditions states:

> *'No person may act as pilot in command of the aircraft except a person who has been judged by the E Conditions Competent Person to be appropriately qualified and trained for the purpose.'*

Dossier

The dossier consists of four parts:

- Part A contains the declaration which provides a summary of the flight test programme and confirms that all identified safety risks had been assessed.
- Part B provides details of the aircraft, an assessment of its airworthiness. It also includes the instruments used during the flight.
- Part C provides details of the flight test programme, and specific conditions and limitations relating to the operation of the aircraft. This included the test area.
- Part D contains the risk assessment including any hazard mitigations.

The level and scope of the detail within the dossier is at the discretion of the competent person; CAP1220 provided guidance to assist the competent person in this regard.

Risk assessment

The following philosophy is to be adhered to:

- The associated risk of serious injury to uninvolved third parties must be determined to be extremely improbable, where '*Extremely improbable has*

> *been determined to mean 1x 10-6 in FAA AC23.1309-1E. This figure is also an acceptable numerical value for the risk calculations within this guidance.'* and

- The associated risk of serious or fatal injury to the pilot and ground crew should be reasonably mitigated, and the pilot and groundcrew understand and have consented to the residual risk.

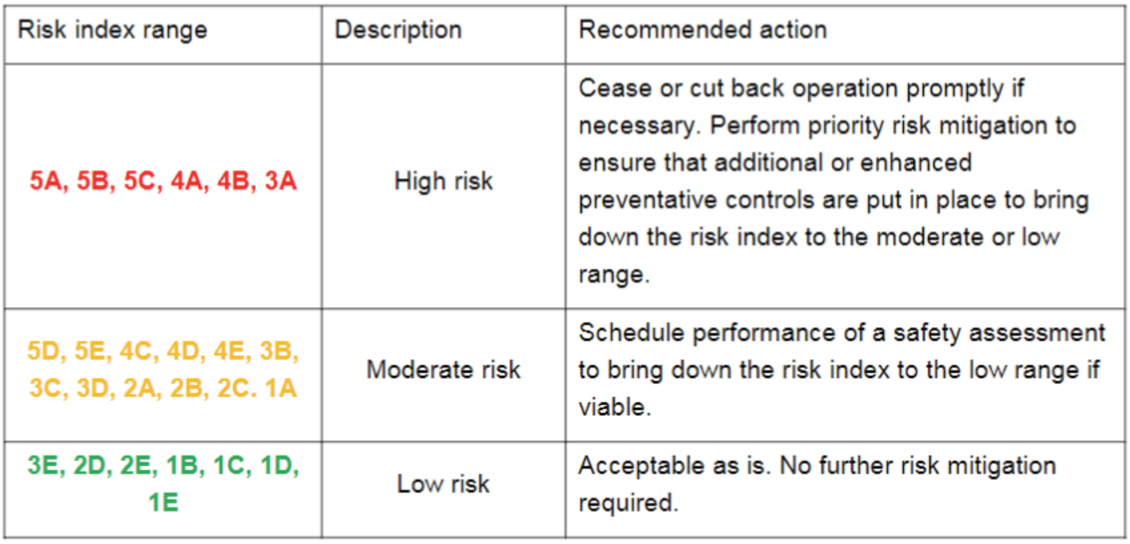
The ICAO Severity Table defines *'Hazardous'*, which has the value *'B'* as:

> *'A large reduction in safety margins, physical distress or a workload such that the operators cannot be relied on to perform their tasks accurately or completely'*

Probability is the likelihood or frequency that a safety consequence or outcome might occur:

Likelihood	Meaning	Value
Frequent	Likely to occur many times (has occurred frequently)	5
Occasional	Likely to occur sometimes (has occurred infrequently)	4
Remote	Unlikely to occur, but possible (has occurred rarely)	3
Improbable	Very unlikely to occur (not known to have occurred)	2
Extremely improbable	Almost inconceivable that the event will occur	1

The tolerability criteria is the combine value where 5A, 5B, 5C, 4A, 4B and 3A are considered as high risk with the following recommended action:



Risk index range	Description	Recommended action
5A, 5B, 5C, 4A, 4B, 3A	High risk	Cease or cut back operation promptly if necessary. Perform priority risk mitigation to ensure that additional or enhanced preventative controls are put in place to bring down the risk index to the moderate or low range.
5D, 5E, 4C, 4D, 4E, 3B, 3C, 3D, 2A, 2B, 2C. 1A	Moderate risk	Schedule performance of a safety assessment to bring down the risk index to the low range if viable.
3E, 2D, 2E, 1B, 1C, 1D, 1E	Low risk	Acceptable as is. No further risk mitigation required.

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Flight test area

E Conditions aircraft are only permitted to operate in a specified flight test area unless operating a ferry flight with permission of the CAA. This flight test area, including maximum and minimum safe heights, is required to be specified by the competent person.

Flight test safety

CAP1220 provided guidance on good practice to maximise flight safety and includes the following points:

- Aircrew should be suitably experienced and current to carry out the intended flight test programme.
- Observers should only be carried if it is considered that it would be beneficial to overall safety for an observer to participate in the testing and that this justifies the hazard to the additional person.
- Crew Resource Management principles should be considered as part of the flight test planning process.
- For any flight test, a comprehensive flight briefing should be conducted. The briefing should be attended by the flight crew participating in the flight, the competent person and other specialists as required.
- Each test flight should be planned, and only planned test points should be addressed during any sortie. Ad-hoc testing should not occur.
- The criteria for terminating individual tests should be defined, especially for any testing entailing elevated risk levels.
- Plan the flight, fly the plan – only planned test points should be addressed during any sortie. Contingency test points may be carried into a sortie; however, ad-hoc testing should not occur.

Certificate of clearance

All flights are required to be covered by a certificate of clearance which is signed by the competent person and pilot.

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