ACCIDENT

Aircraft Type and Registration:	HPH Glasflugel 304 eS, G-GSGS	
No & Type of Engines:	1 LZ Design D.O.O FES-HPH-M100 brushless electric motor	
Year of Manufacture:	2016 (Serial no: 059-MS)	
Date & Time (UTC):	10 August 2017 at 1121 hrs	
Location:	Parham Airfield, West Sussex	
Type of Flight:	Private	
Persons on Board:	Crew - 1	Passengers - None
Injuries:	Crew - None	Passengers - N/A
Nature of Damage:	Fire damage to FES[1] batteries and FES battery compartment	
Commander's Licence:	British Gliding Association Gliding Certificate	
Commander's Age:	55 years	
Commander's Flying Experience:	314 hours (of which 25 were on type) Last 90 days - 9 hours Last 28 days - 7 hours	
Information Source:	AAIB Field Investigation	

Synopsis

During a normal touchdown following an uneventful flight, the glider's forward FES lithium polymer battery ignited due to an electrical arcing event. The pilot was unaware that the glider was on fire and the battery continued to burn, generating smoke and fumes which entered the cockpit during the latter stages of the landing roll. The pilot was not injured and the fire was extinguished using foam retardant, although the glider's fuselage battery box and surrounding structure were extensively damaged by the fire.

A comprehensive investigation of the failed battery did not identify the cause of the electrical arcing event. The AAIB published a Special Bulletin, S3/2017, in September 2017 that contained three Safety Recommendations relating to the provision of fire warning systems in FES-equipped sailplanes.

As a result of this investigation the sailplane manufacturer and FES system manufacturer have implemented a number of safety actions including modifications intended to prevent recurrence, or to mitigate the effects of a battery fire.

Footnote

[1] Front Electric Sustainer, a battery-powered electrical propulsion system for powered sailplanes.

History of the flight

The pilot had fully charged both Front Electric Sustainer (FES) batteries on 4 August 2017, after which they were disconnected from the chargers for storage. He installed them in the glider on the morning of 10 August, with the intention of flying the glider that afternoon. He initiated the FES battery self-checking procedure before conducting a daily inspection of the glider, after which the self-checking procedure had completed with no faults indicated on the FES Control Unit (FCU). He then fitted the FES battery compartment cover and applied tape around the edges of the cover.

The pilot conducted a ground run of the FES propeller, which operated normally. He then switched the Power Switch OFF, and also turned the FCU OFF, which was contrary to his normal practice of leaving the FCU switched ON.

The pilot launched from Parham Airfield by aerotow at 1021 hrs and flew in ridge lift for a period of 38 minutes before encountering a rain shower. He decided to use the FES propulsion system and turned the Power Switch ON. He then noticed that the FCU was switched OFF, so he switched the FCU ON without moving the Power Switch position[2].

After waiting a few seconds for the FCU green LEDs to show that the FES propulsion system was available, the pilot operated the FES motor which responded normally and operated for 4 minutes. The pilot did not recall observing any fault messages on the FCU during the motor operation.

After stopping the FES motor the pilot noticed that the propeller did not realign itself correctly against the nose of the glider. The pilot had experienced this problem previously and did not consider it to be a significant issue, so he did not attempt to realign the propeller. He switched the Power Switch OFF, leaving the FCU switched ON and continued in soaring flight for a further 1 hour 15 minutes before positioning the glider to land on grass Runway 04 at Parham Airfield. The circuit was flown normally to a smooth touchdown, however at the moment of touchdown the pilot heard an unexpected noise.

As the glider slowed during the ground run, the pilot smelled burning and the cockpit filled with smoke that was moving forward from behind his head. The pilot did not report observing any warning messages or illuminated LEDs on the FCU, although his attention was drawn outside the cockpit during landing. He vacated the cockpit normally, without injury, and observed that the FES battery compartment cover was missing and that smoke, followed shortly by flames, was coming from the battery compartment (Figure 1). The airfield fire truck arrived promptly and an initial attempt was made to extinguish the fire using a CO_2 gaseous extinguisher, but this proved unsuccessful. Aqueous film-forming foam (AFFF) retardant was then sprayed into the FES battery compartment and the fire was extinguished.

Footnote

[2] The FCU User Manual and HPH304 eS Flight Manual both state that the FCU should be switched ON at all times that the sailplane is in flight, with the Power Switch only switched ON when the pilot wishes to operate the FES propulsion system. The FES system manufacturer stated that despite this departure from approved procedures, the sequence that the FCU and Power Switch were turned ON in this event would not affect the operation of the FES propulsion system.

Figure 1
Fire in the FES battery compartment following the landing roll

The FES battery compartment cover was found close to the glider's touchdown point. The cover's rear carbon fibre catch was fractured, consistent with an upward load acting on the inside of the cover. The cover did not exhibit any overheating damage.

Aircraft information

The HPH Glasflugel 304 S is a single-seat flapped sailplane of 18 m wingspan, constructed from composite materials with a retractable mainwheel. The 304 eS is a powered variant, capable of self-sustaining flight using a FES propulsion system (Figure 2) consisting of the following components:

- One 23 kW brushless electric motor installed in the nose of the sailplane, with a foldable two-bladed propeller
- One motor controller
- Two 'GEN2' 58 V battery packs, connected in series, each with an internal Battery Management System (BMS)
- One FES control unit (FCU) instrument, mounted in the instrument panel, displaying FES system monitoring information and a motor throttle knob
- One LXUI box with a shunt, for current and voltage measurements

- One FES connecting circuit (FCC) box
- One Power Switch, to provide a 12 V power supply to the battery contactor, which connects the FES battery packs to the motor controller. It also provides a 12 V power supply to the motor controller
- One DC-DC converter to convert FES battery pack voltage to 12 V, to power the avionics and components of the FES system requiring a 12 V supply (battery contactor, cooling fans, LXUI box and FCC box)

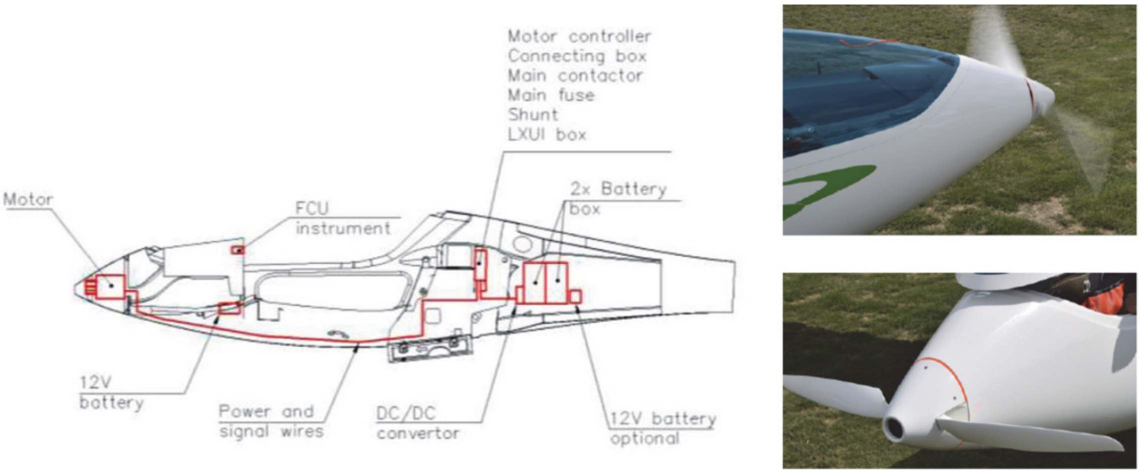

Figure 2

FES system installation in the HPH Glasflugel 304 eS powered sailplane (courtesy HPH Spol. S.r.o.)

The HPH Glasflugel 304 eS powered sailplane has an European Aviation Safety Agency (EASA) Restricted Type Certificate (RTC), number EASA.A.030. The sailplane does not have an unrestricted Type Certificate as the FES engine and propeller are not EASA Type Certified in their own right, and are therefore considered part of the sailplane for certification purposes[3]. There are no operational restrictions related to the RTC.

The FES propulsion system is also installed in two other powered sailplanes that hold EASA RTCs – the Schempp-Hirth Flugzeugbau Discus-2c FES (EASA.A.050) and the Sportinė Aviacija LAK-17B FES (EASA.A.083). In addition, there are a number of other powered sailplanes equipped with the FES propulsion system currently operating on EASA Permits to Fly, that are part-way through the EASA Type Certification process.

The FES propulsion system is also installed in two commercially-available Regulation (EC) No 216/2008 Annex II microlights – the Alisport Silent 2 Electro, and the Albastar AS13.5m FES. These aircraft are not subject to EASA airworthiness regulations and may operate in the UK under the Single Seat Deregulation (SSDR) airworthiness exemption from the Air Navigation Order (ANO).

Footnote

[3] EASA Part 21.A.23 (c)(2).

The AAIB is also aware of a number of other FES-equipped Regulation (EC) No 216/2008 Annex II microlights, produced as modifications to existing sailplane designs that are currently in operation. These include two Pipistrel Apis 15M M FES sailplanes operating in the UK under SSDR regulations and one Diana 2 Versvs FES sailplane operating in Italy on an ENAC Permit to Fly. In addition, one FES-ASW-27 operates in the USA under FAA Experimental Category regulations.

Battery pack description

The 'GEN2' FES battery packs are removable for charging remotely from the sailplane. Each battery pack is built up from 14 Kokam Superior Lithium Polymer Battery (SLPB) cells, connected in series and contained within a carbon fibre battery box with a machined aluminium alloy cover plate/heatsink (Figure 3). The inside of the battery box has layers of glass fibre to prevent the battery cells from contacting the carbon fibre case, which is electrically conductive. The maximum total voltage for each battery pack is 58.3 V, giving a maximum voltage of 116.6 V for the assembly of both battery packs connected in series. An integral battery management system (BMS) controls the charging and discharging of the individual cells to balance the cell voltages and also provides over- and under-voltage protection. The capacity of each SLPB cell is 41 Ampere-hours (Ah), providing a total capacity for each battery pack of 2.1 kWh, or 4.2 kWh for both battery packs connected together. Each battery pack has a mass of 15.7 kg.

The SLPB cells, part number SLPB100216216H, are lithium-ion polymer battery cells with a carbon-coated copper sheet anode (negative electrode) and a lithium nickel manganese cobalt oxide (NMC) coated aluminium sheet cathode (positive electrode). The cells have a gel electrolyte consisting of a solution of lithium hexafluorophosphate in an organic solvent.

The cell contents are contained in a sealed pouch consisting of layers of polypropylene, aluminium foil and nylon-PET[4]. The anodes and cathodes are terminated with two tab-style connectors at the top of the battery cell. The cell tabs are connected together by pairs of connector plates; the upper plate is manufactured from brass and the lower plate from stainless steel, with the tab sandwiched between the plates. Each connector plate pair is assembled with four screws; the lower connector plate has threaded holes to accept the screws.

The battery cells are retained within the battery case by a measured amount of clear silicone, poured into the case in liquid form during battery assembly and subsequently cured to form a semi-rigid support to the cells.

The battery packs are connected together with power cables. To prevent incorrect connection, the positive terminal has a 10.3 mm diameter connecting pin and the negative terminal has an 8.0 mm diameter connecting pin.

Footnote

[4] Nylon-PET is a mixture of nylon and polythene terephthalate (PET).

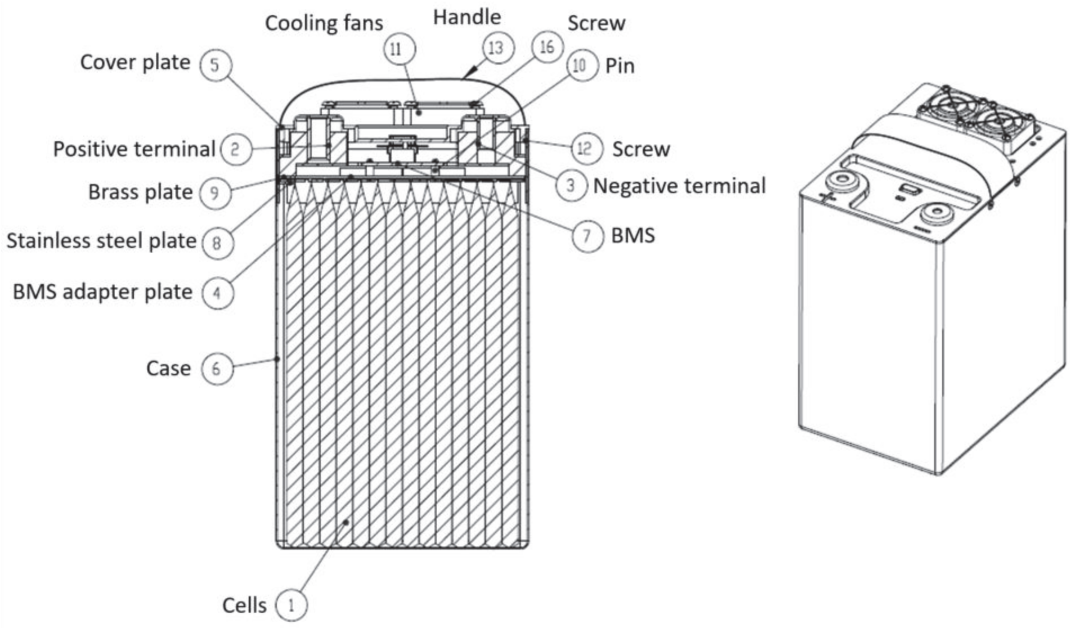

Figure 3
FES battery assembly

FCU description

The FCU is an instrument installed in the instrument panel that informs the pilot of the status of the FES propulsion system via a display screen (Figure 4). A rotary throttle knob is provided at the bottom of the FCU that controls the power delivered to the propeller during powered flight. The rotary knob may also be pushed to confirm warning messages displayed on the FCU screen.

Coloured LEDs on the FCU instrument are used to confirm the FES system status and alert the pilot of system warning messages. Two levels of warnings are provided[5]:

- YELLOW warning: This is first level of warning, which means that the pilot needs to be aware of the parameter indicated in the warning message and to manage the suggested solution to solve the problem. YELLOW warnings indicate that there is no immediate danger. The top ‘ALARM’ LED appears as a continuous red light. The LED and warning message on screen are confirmed by pressing the throttle knob.
- RED warning: This is the second level of alarm, which means that the pilot has to manage the solution of the indicated problem immediately. The top ‘ALARM’ LED appears as a flashing red light. The warning message on the screen is confirmed by pressing the throttle knob, but the flashing top LED persists whilst the fault condition is present. Red warning messages may be recalled by pressing the throttle knob.

Footnote

[5] Note that following the G-GSGS accident, the FCU caution and warning system was re-designed as described at the end of this report.

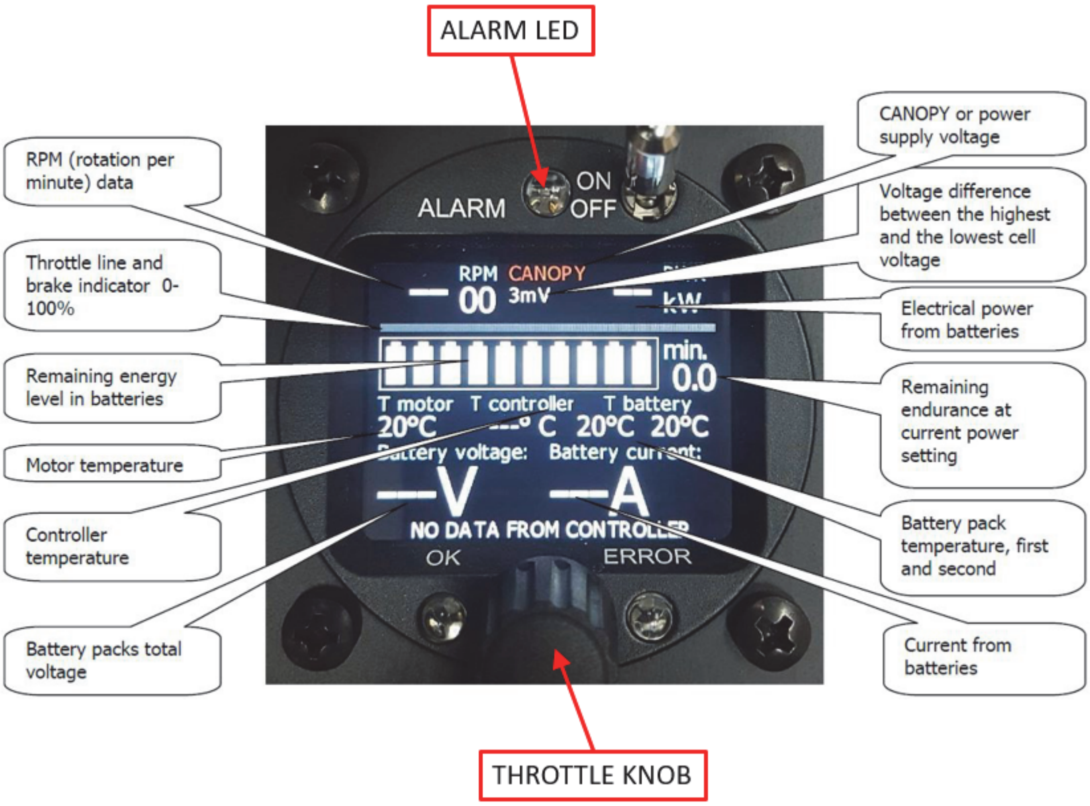

Figure 4

FCU main screen (courtesy LZ design d.o.o.)

In a fault scenario where multiple warning messages are generated, the pilot is not aware of how many messages are present until all have been confirmed by pressing the throttle knob. Warning messages are displayed in the order they were generated and red messages, including the change in the ALARM LED indication from a steady red to a flashing red illumination, are not prioritised over yellow warning messages.

In this accident, the FCU did not record any data or fault messages and therefore it is not known which messages were displayed to the pilot of G-GSGS during the battery fire event. The FES system designer confirmed however that for the configuration G-GSGS was in when the event occurred (Power Switch OFF, propeller not rotating), the following warning messages may have been generated, Table 1.

Warning level	FCU screen warning message	ALARM LED	Required pilot action
YELLOW	Battery diff. >3°C, Reduce power!	Steady red, cancellable	Reduce power
RED	Battery diff. >6°C, Stop FES motor!	Flashes red, persistent	Stop FES motor
RED	Batt. Critical >75°C, Land immediately!	Flashes red, persistent	Stop FES motor and land ASAP

Table 1

Possible FCU warning messages during the G-GSGS FES battery fire event

The first two warnings are generated when the FCU senses a temperature difference between the two FES battery packs. The third warning occurs when the temperature of either FES battery pack exceeds 75°C and each message is reliant on data sent from a functioning BMS of a FES battery pack. Apart from alerting the pilot to a battery pack temperature exceeding 75°C, the FCU does not provide any indication of a fire occurring in the FES battery compartment. As the FES battery compartment is behind the pilot within the fuselage, a pilot cannot see such a fire if it occurs. The warning messages may also be confusing to the pilot as the required pilot action refers to reducing or stopping the FES motor, when the motor is not in operation.

Aircraft examination

The origin of the fire was the forward FES battery; its battery box was ruptured along the rear left corner and the battery assembly was heavily fire damaged (Figure 5). The rear battery box suffered from external fire damage although the internal components were only slightly damaged and the cells remained charged.

Figure 5

Fire damage to the forward FES battery

The FES battery compartment was heavily fire damaged with burning of the composite material's resin on the internal faces of the battery compartment and around the external cut-out in the upper fuselage skin. The top edge of the removable access panel that forms the front panel of the battery compartment (Figure 6) was also burned on its forward face and the FES electrical components in the equipment bay between the cockpit and the battery compartment were covered in soot deposits, demonstrating that the battery compartment had not contained all of the smoke and fumes released by the FES battery fire.

Figure 6

Fire damage to the FES battery compartment front access panel
(left image, looking forwards),
and to the forward face of the front access panel
(right image, looking aft)

The electrical cable glands in the left side of the front bulkhead of the battery compartment remained intact. The main 325 A power fuse was intact, as were fuses on the instrument panel. The DC-DC converter, installed in the battery compartment forward of the FES batteries, was externally fire damaged but when inspected it was apparent that the damage had been caused by external heating of the DC-DC converter during the fire. No evidence of overheating or fire damage internally within the DC-DC converter case was observed.

Other information

The pilot reported that in January 2017 one of the FES battery packs from G-GSGS fell from his car onto a paved surface through a vertical distance of around 0.2 m. There was no sign of damage to the battery pack following this event. The pilot did not record the serial number of this battery pack and therefore it is not possible to determine whether this pack was the battery that caught fire during the landing at Parham Airfield.

Other FES battery fire events

The AAIB became aware of the occurrence of two other FES battery fire events; one event occurred before the G-GSGS battery fire and the other afterwards. The first event occurred at Benesov Airport in the Czech Republic on 27 May 2017. An HPH 304 eS powered sailplane, registration OK-6634, was de-rigged for storage in its trailer with both

FES battery packs installed and connected together in the sailplane. This was contrary to an instruction in the sailplane's Flight Manual, which required the connecting cable between the FES battery packs to be removed after landing. The FES battery packs remained charged to approximately 80% capacity after the flight that day. The FES Power Switch was OFF, as were the avionics master switch and FCU switch. The fire, which occurred approximately four hours after the sailplane had landed, started in the forward FES battery pack, causing significant damage to the battery compartment. The pilot of this sailplane had reported running over a "hard bump" during the latter stages of the landing roll, but apart from this the flight was unremarkable and no signs of heat emission were present when the sailplane was de-rigged and placed in the trailer after the flight. The serial number of the battery pack involved in the fire was 103-A, produced on 25 October 2016.

The third event occurred at the Chicago Glider Club Gliderport, Minooka, Illinois in the United States on 2 December 2017[6]. A Schempp-Hirth Discus 2c FES powered sailplane, registration N930DE, was being prepared for its second flight following delivery from the manufacturer, with the battery packs fully charged and the FCU switched ON. As the connecting cable was inserted to connect the two FES batteries together, white smoke was seen to emanate from the battery compartment. The connecting cable was removed but the smoke emission continued, becoming thicker and following a "bang" noise from the battery compartment, black smoke and flames were observed coming from the rear FES battery. Fire-fighting was attempted using powder fire extinguishers, which were successful in supressing the flames and black smoke, although the white smoke continued. The flames and black smoke recurred shortly thereafter in a cycle repeated over approximately 20 minutes and the contents of eight powder fire extinguishers were used in the fire-fighting effort. The batteries were later removed from the sailplane, revealing that the epoxy material of the rear battery's case, and the battery contents, had been largely consumed in the fire. The sailplane had been recently delivered to the owner and the FES battery packs installed in the sailplane had only been used in flight once by him. The owner stated that the battery packs had not been mishandled and had only been subjected to two charging cycles whilst in his possession. The serial number of the rear battery pack was 133-A, produced on 16 May 2017.

As neither of the above battery fires occurred whilst the gliders involved were in operation, neither event was subject to an ICAO Annex 13 air safety investigation in the respective State of occurrence. Despite this limitation, the AAIB has liaised closely with both sailplane manufacturers and the FES system manufacturer to gather information on both events, in support of the G-GSGS investigation.

Footnote

[6] This event occurred after EASA issued Emergency AD 2017-0167-E on 6 September 2017, requiring modification of the FES battery packs before further flight of the Discus 2c FES. The FAA however did not issue an AD mandating similar safety action for US-registered aircraft. FAA regulations only require owner/operators of US-registered aircraft to comply with the requirements of ADs issued by the FAA.

Tests and research

Investigation of the G-GSGS failed battery

The fire-damaged battery from G-GSGS, serial number 080-A, was received in a dismantled state following an initial examination by the battery manufacturer and the British Gliding Association. The battery remains were subjected to detailed visual and microscopic examination. The battery exhibited swelling of the individual cells and rupture of the outer case along the rear left corner. The glass fibre isolation layer on the rear wall of the battery case was found to be delaminated and detached from the case. The isolation layer on the right side of the battery has also partially delaminated, with some glass fibre sheets adhered to the battery top cover and some sheets still attached to the case wall. Visual examination of the individual cells showed that the pouches of each cell were split along all edges.

A localised hot-spot was observed between cells 5 and 6 on the upper edge of the cells in between the electrode tabs (Figures 7 and 8). The hot-spot was observed on the cell pouches and a number of the internal sheet electrodes were also exposed. The hot-spot did not appear to penetrate the whole cell pack thickness.

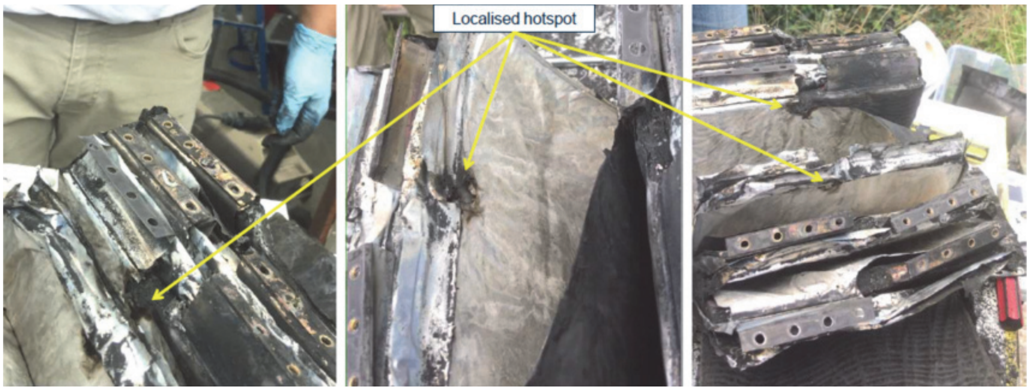

Figure 7

Localised hot-spot between cells 5 and 6 apparent during initial disassembly of the battery (courtesy British Gliding Association)

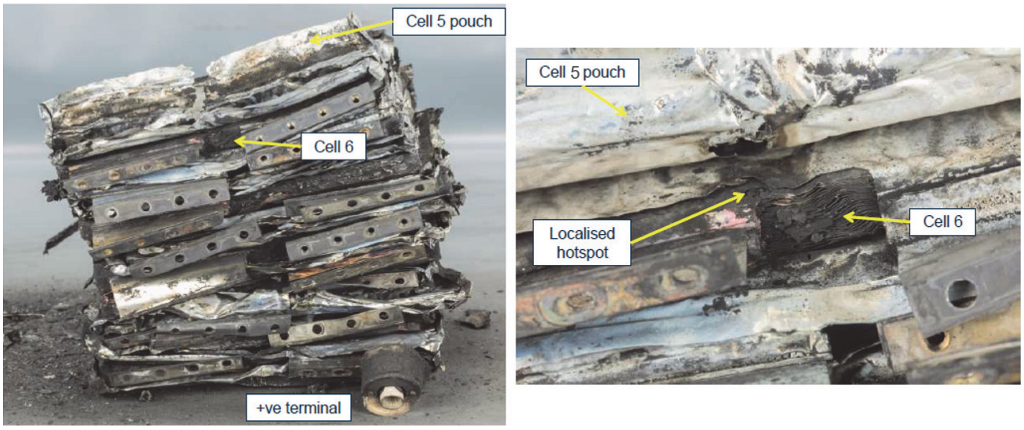

Figure 8

Localised hot-spot between cells 5 and 6 (courtesy QinetiQ)

Examination of the hot-spot at cell 6 revealed localised melting of both the aluminium cathode and copper anode electrode sheets (Figure 9) indicating that the temperature at the hot-spot had exceeded 1,085°C, the melting point of copper. The presence of solidified molten copper was further confirmed by examination of the hot-spot location using a scanning electron microscope, and energy dispersive X-ray analysis of the molten copper deposits.

Figure 9
Localised hot-spot at cell 6, with solidified molten copper present
(courtesy QinetiQ)

When cell 5 was disassembled, a radiating pattern of combustion-deposit ‘beachmarks’ was apparent, originating at the hot-spot (Figure 10). This indicated that ignition of the cell’s gel polymer electrolyte had begun at the hot-spot location before burning downwards through the cell. Detailed examination of the hot-spot sites did not reveal the presence of any foreign objects at these locations. There was no evidence of ‘welding’ of the individual cell electrodes; the cell packs appeared to be fused together with combustion products, most likely the gel electrolyte residues.

Examination of the lower stainless steel cell connector plates showed a burr present on a number of the drilled and threaded holes, on the lower surface of the plates (Figure 11). The visual examination also showed the potential formation of swarf from these burrs.

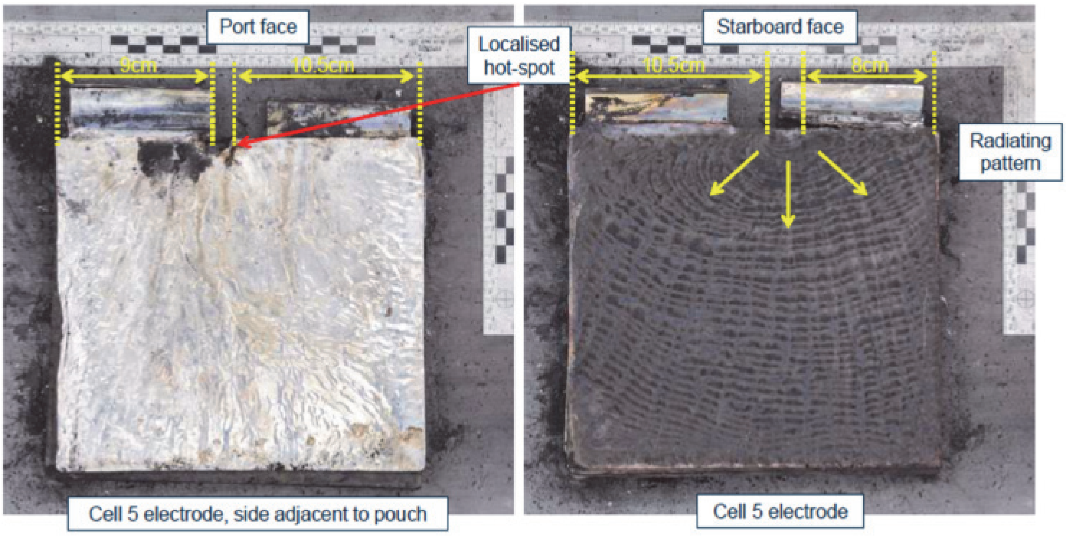

Figure 10

Combustion front ‘beachmarks’ evident on cell 5 electrodes (courtesy QinetiQ)

Figure 11

Thread-cutting swarf present on the lower surface of the connector bars (courtesy QinetiQ)

AAIB battery cell abuse testing

In order to create an internal short circuit within a battery cell under controlled conditions, the AAIB conducted a series of tests in which fully charged cells were penetrated with a 2.0 mm diameter steel nail. The nail, which was ground to a sharp point at both ends, was positioned between two cells and the cells were then moved together until the nail penetrated the cells. The testing showed that the nail initially penetrated only one of the cells and that shortly after cell penetration occurred, electrical arcing took place with ejection of sparks from the penetrated cell pouch due to the internal short circuit of that cell's electrode (Figure 12).

The electrical arcing was immediately followed by rapid inflation of the cell pouch and the ejection of light grey smoke, followed shortly by flames. The fire continued for approximately two minutes until the gel electrolyte polymer, which was the main fuel source involved in the fire, was fully consumed.

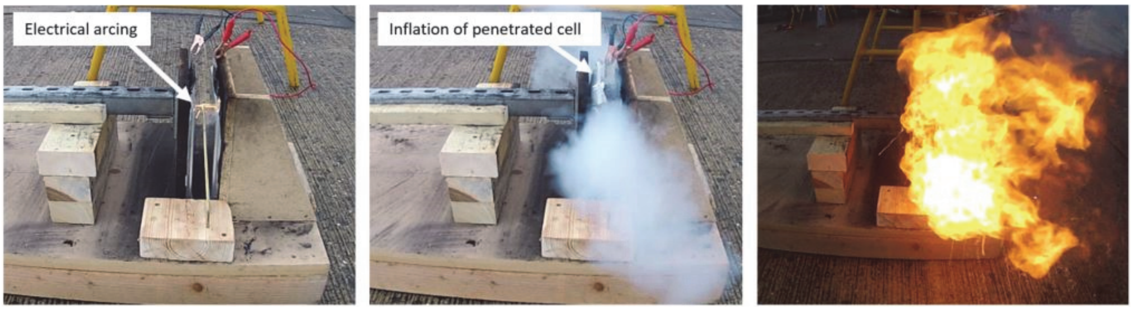

Figure 12
Electrical arcing following cell penetration

Examination of the steel nail after the tests showed that it had melted in the initial electrical arcing event, indicating that the temperature generated during the arcing was in excess of 1,400°C. The cell electrodes at the penetration site had a hole of larger size than the nail diameter, the edges of which were formed from solidified molten electrode material, consistent with the melting of the electrodes during the arcing event. The remaining copper and aluminium electrodes were relatively intact, demonstrating that the temperature reached during the combustion of the cell's gel electrolyte was relatively cool compared to the electrical arcing temperature. A pattern of combustion 'beachmarks' originating at the nail penetration site was observed (Figure 13) these were similar to those observed in the fire-damaged battery from G-GSGS.

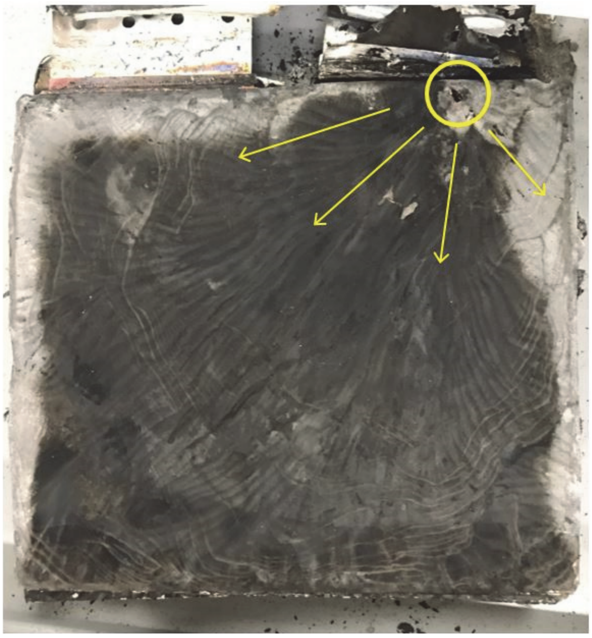

Figure 13

Combustion beachmarks from AAIB cell penetration tests

CT scanning results from samples of the FES battery fleet

In view of the potential for release of metal debris into the battery packs from the connector plates, the internal condition of 11 FES battery packs were subjected to CT[7] X-ray examination. The selection of the batteries for examination was partly based on their manufacturing date, to provide a representative sample across a range of battery production.

Serial No.	Manufactured	Findings
026-A	03/08/2012	8mm low-density object detected
026-B	03/08/2012	Three metal particles detected (one 4mm, two <1mm)
034-A	29/01/2014	Six <1mm metal particles detected
034-B	29/01/2014	One <1mm metal particle detected
059-A	13/04/2015	No debris noted
059-B	13/04/2015	No debris noted
064-A	06/07/2015	One <1mm metal particle detected
064-B	06/07/2015	Two metal particles detected (one 2mm, one <1mm)
080-B	12/02/2016	Case removed. One 2mm metal particle detected, below silicone
087-A	17/05/2016	Two <1mm metal particles detected
087-B	17/05/2016	No debris noted

Table 2

Findings from battery CT-scanning

Footnote

[7] Computed Tomography is an X-ray scanning technique in which X-ray images are computer-processed to produce individual ‘slice’ images through an object.

The CT scans identified features consistent with metallic debris present in seven out of the 11 batteries examined. An eighth battery contained an 8.0 mm non-metallic foreign object within the battery assembly but on disassembly this was revealed to be a plastic tool that had been left in the battery following disassembly of the battery pack by its owner.

The CT scan of battery pack 080-B, the rear battery pack from G-GSGS, contained one metallic object lying between two cells at the top of the pack (Figure 14). This object was beneath the silicone layer indicating that the foreign object has been present when the battery pack was assembled.

The battery pack was disassembled and the metallic object was recovered. The object was a piece of metal swarf, 2 mm in length, with a distinctive curved shape consistent with the swarf generated during the thread-cutting process of the connector plates.

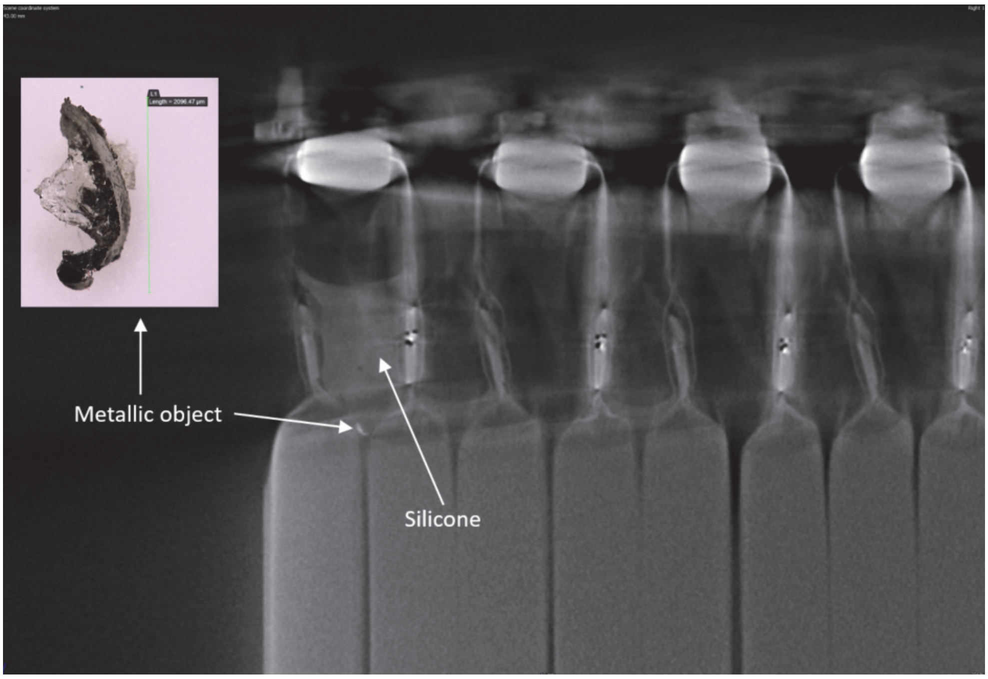

Figure 14

Metallic swarf debris within battery pack 080-B (courtesy QinetiQ)

Battery cell vibration testing

In order to determine whether the presence of metal swarf between the battery cells could lead to penetration of the cell pouch material, the AAIB carried out vibration testing. An assembly of two SLPB100216216H cells was held within a fixture to simulate a portion of an assembled FES battery, with the cells bonded to the fixture using silicone sealant and restrained across the cell faces, but otherwise free to move relative to one another. The cell fixture could be mounted in one of two positions, such that the axis of applied vibration of the cells was either vertical to or lateral to the cells; this was to simulate vertical or lateral cell vibrations of the battery as mounted in an aircraft.

The cell fixture was mounted on a milling machine bed on a linear bearing allowing displacement along the machine bed axis only (Figure 15). The cell fixture was connected via a pushrod to a crank pin mounted in a boring bar head in the milling machine spindle. The eccentricity of the driving crank pin was adjusted to achieve the desired peak-to-peak amplitude displacement of the cell fixture of 2.5 mm for the frequency range 5 – 15 Hz, and 1.0 mm for 15 – 40Hz[8]. Using the variable spindle speed on the milling machine, the cell fixture could be vibrated across a frequency range of 1 – 40 Hz. Laser displacement sensors were used to measure the relative displacements between the cells within the cell fixture.

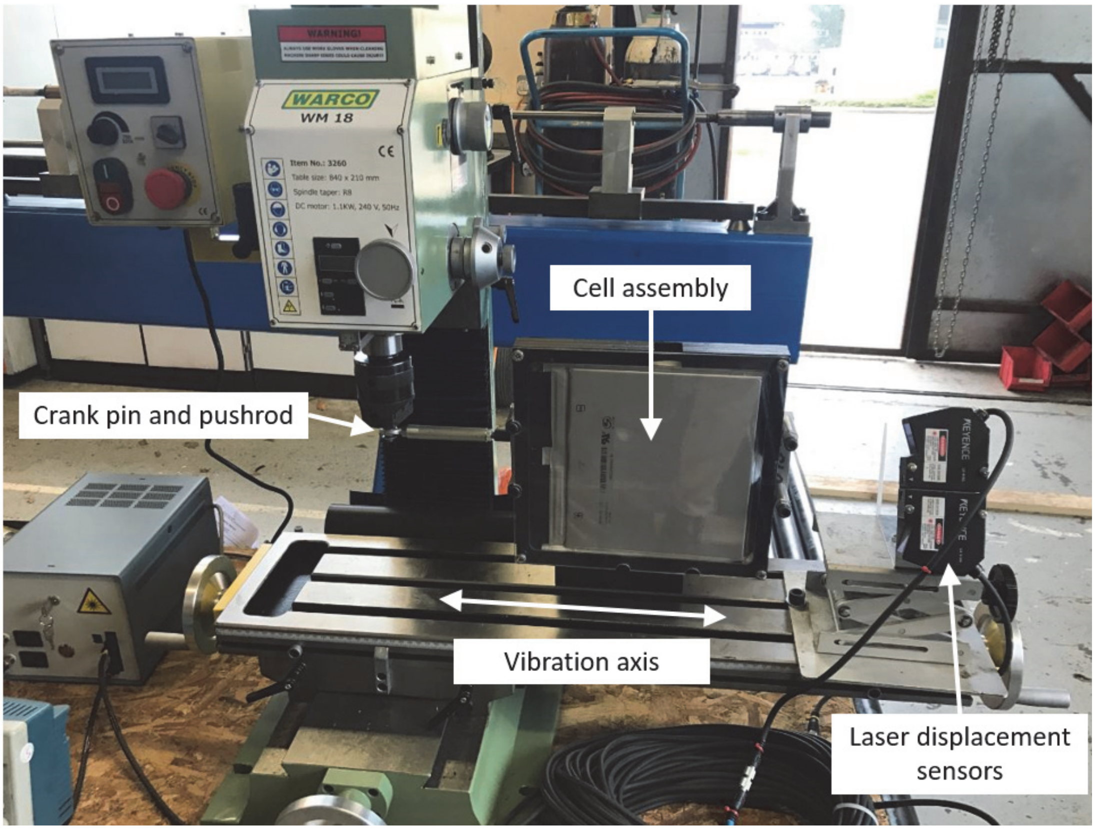

Figure 15

Cell vibration testing equipment

The first set of tests were conducted without any swarf present between the cells. The frequency of the applied vibration was increased in 5 Hz steps between 5 Hz and 40 Hz, and where resonances were noted, additional tests were performed at the resonant frequencies. With the cells vibrated in the vertical axis, simulating the most likely oscillatory loading axis in a glider during landing and takeoff ground rolls, resonant frequencies were noted at 18.8 Hz and 22.8 Hz. No signs of fire, smoke or unusual odours were noted during these tests. The cells were then vibrated in the horizontal axis for 30 minutes at

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Footnote

[8] This frequency-amplitude vibration schedule is defined in RTCA/DO-160G '*Environmental Conditions and Test Procedures for Airborne Equipment*' and is the vibration schedule specified in EUROCAE/DO-311 '*Minimum Operational Performance Standards for Rechargeable Lithium Battery Systems*'.

a resonant frequency of 20 Hz and again no abnormalities were noted with either cell during the test. Once testing was complete the cells were removed from the cell fixture and subjected to detailed visual examination, which confirmed that no external damage was evident to the surface of either cell.

A second test was conducted with 3.0 mm lengths of steel swarf inserted between the cells (Figure 16). The cells were vibrated in the horizontal axis for 30 minutes at a resonant frequency of 20 Hz, during which there were no signs of fire, smoke or unusual odours. Following this test, the cell fixture was disassembled and it was noted that there had been migration of the swarf within the cell fixture and some fretting of the cell pouch material due to contact with the swarf, but the fretting depth had not exceeded the pouch thickness and no electrolyte had been released.

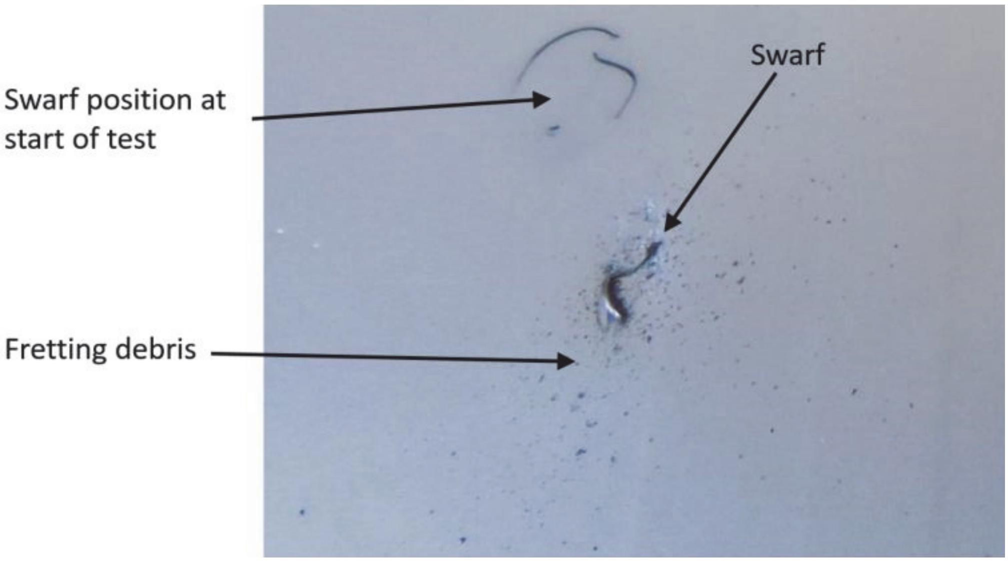

Figure 16

Cell pouch fretting during vibration testing with metal swarf present

A third vibration test with metal swarf present between the cells was carried out for 30 minutes at a resonant frequency of 28 Hz, with vibration in the horizontal axis. This test resulted in similar cell pouch fretting as observed in the second test, with no fire, smoke or unusual odours detected.

Certification requirements

Aircraft-level requirements

The HPH Glasflugel 304 eS was certified by EASA in November 2016 to EASA Certification Specifications for Sailplanes and Powered Sailplanes (CS-22 (Amendment 2)). The sailplane's Type Certificate also included compliance with Special Condition SC-22.2014-01 '*Installation of electric propulsion units in powered sailplanes*' which contained additional airworthiness requirements for all components of the electric propulsion system, including the batteries and their installation in the sailplane.

The Special Condition contained the following requirements for the batteries:

> *'CS 22.963 Batteries or other energy storage devices*
>
> *(a) The suitability and reliability of batteries or other energy storage devices shall be proved due to experience or tests.*
>
> *(b) Characteristics of the energy storage devices, including failure modes (e.g. thermal runaway, expansion, explosion, toxic emission) should be identified. Battery cells and other subcomponents of the system should be assembled and installed minimizing the effects of failures.'*

The Special Condition also included Guidance Material for CS 22.963(a):

> *'GM CS 22.963(a): Battery cells should be qualified according to accepted standards (e.g. EUROCAE/DO311, UN T 38.3*[9]*).'*

The installation of the batteries in the sailplane was also covered by this Special Condition in CS 22.967, including the following:

> *'CS 22.967 Installation of energy storage devices*
>
> *(d) Each energy storage device shall be installed to minimize the effects of the failure mode identified under CS 22.963. Design precautions might include:*
>
> - *Providing the crew with the relevant information allowing to take proper actions (e.g. temperature or pressure monitoring),*
> - *Mitigating the effect of thermal runaway or fire, and ensuring the surrounding structure might be able to withstand the thermal loads,*
> - *Designing the compartment for the battery in order to cope with overpressure or expansion.'*

Battery requirements

The battery cells were qualified to UN T 38.3 by the cell manufacturer. In order to achieve UN T 38.3 certification, 60 individual cells were subjected to tests including altitude simulation, thermal testing, vibration, shock, external short circuit, impact and forced discharge. UN T 38.3 test requirements may be applied to individual cells, or to assembled batteries. It is typically used to qualify battery cells for shipment under Dangerous Goods transport requirements.

The alternative battery qualification standard included in the CS 22.963(a) Guidance Material is EUROCAE/DO311 '*Minimum Operational Performance Standards for*

Footnote

[9] United Nations Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria, Section 38.3, Amendment 2, 2001.

Rechargeable Lithium Battery Systems'. This qualification standard is applicable to assembled batteries and contains additional test requirements compared to UN T 38.3. DO311 is a common qualification requirement for large lithium batteries forming part of the electrical systems in EASA CS- 23 normal, utility, aerobatic, and commuter category aircraft and EASA CS-25 Transport Category aircraft.

The UN T 38.3 qualification at the individual cell level was accepted by EASA as proof of compliance against CS 22.963(a) for the assembled FES battery system in the HPH 304eS sailplane.

Analysis

Cause of the battery fire event

The G-GSGS battery fire started in the forward FES battery due to an electrical arcing event that occurred at the top of cells 5 and 6, as evidenced by melted copper and aluminium cell electrodes. The available evidence suggests that the electrical arcing began when the glider touched down during a normal landing. The temperature reached in the electrical arcing event exceeded 1,085°C and probably exceeded 1,400°C, based on the results of AAIB tests. The release of pressurised combustible gas from the forward battery caused over-pressurisation of the glider's battery compartment, leading to the detachment of the battery compartment cover. Once the battery's gel electrolyte had ignited, the fire continued to burn and consumed all of the electrolyte and also ignited the glider's composite structure, until the fire was extinguished by the application of AFFF foam retardant.

There was no remaining evidence of what had caused the battery fire to start. No metallic foreign objects were observed at the electrical arcing site, however the high temperatures generated during the arcing event would have probably melted a metallic foreign object if one had been present.

Investigation of intact FES batteries revealed the presence of metallic foreign objects within the battery assemblies on 7 of the 11 battery packs investigated. Most of these metallic objects were less than 1.0 mm in length, although metallic objects up to 4.0 mm in length were detected. One battery pack was disassembled as part of the investigation which revealed that a 2.0 mm long metallic object was a piece of metal swarf, probably produced as part of the thread-forming operation on one of the battery's stainless steel lower connector plates. The location of this metal swarf, which was beneath a silicone layer, showed that it was present during the battery manufacturing process.

The vibration testing conducted by the AAIB showed that whilst cell pouch fretting did occur due to the presence of swarf within a battery assembly, the fretting was not severe enough to cause the swarf to penetrate the cell pouch and cause an internal short circuit within a cell.

Fire containment

In the accident to G-GSGS, the smoke and fumes generated by the battery fire were not contained within the battery compartment, and entered the cockpit due to fire damage of the forward battery compartment bulkhead. This bulkhead was constructed of composite materials which ignited once the battery had begun to burn. Apart from this failure, the remainder of the battery compartment structure remained intact and prevented the fire from spreading further within the fuselage.

Cockpit warning systems

The pilot reported that he did not recall observing any warning messages on the FCU display. As the FCU did not record which messages were displayed during the battery fire event, it was not possible to confirm whether any messages were displayed. Based on the FCU system logic, it is likely that battery temperature and voltage warning messages were generated, but by this time the glider had landed and the pilot's attention was drawn to controlling the glider during the landing roll.

The design of the FCU caution and warning system was such that had a battery fire occurred during flight, the sequence of messages would not have alerted the pilot to the presence of a battery fire and some of the warning messages may have been confusing. It would also have been necessary to manually scroll through the list of warning messages, without the ability to recall warnings which had been viewed.

The other FES battery fires

The other two FES battery fires that have occurred to date are different to the G-GSGS event. Both fires occurred whilst the sailplanes were stationary, and therefore vibration of the FES battery involved in each fire does not appear to be the initiating event for the battery fire, unlike the G-GSGS event.

The N930DE battery fire (in the USA) occurred when the battery link cable was inserted, electrically connecting the two FES batteries together in series and allowing a small current to flow between the batteries due to the current draw of the DC-DC converter.

The OK-6634 battery fire (in the Czech Republic) occurred more than four hours after the glider had landed, when the glider was stationary and de-rigged in its trailer. The battery link cable remained installed, contrary to the flight manual instructions, again allowing a small current to flow from the FES batteries due to the current draw of the DC-DC converter.

The causes of both fires have not been determined, although the effects of the fires were similar to the G-GSGS event in that the fire consumed the affected FES battery and did not spread to the second FES battery. In each case the thermal effects of the fire were largely contained within the battery compartment.

Battery certification procedures

The battery certification procedures used to qualify the FES battery system relied on the demonstration of compliance against the requirements of UN T 38.3 at the individual cell level, rather than at the assembled battery level. This certification approach is contrary to that applied by EASA and the FAA for larger (Part 23 and Part 25) aircraft, where the assembled battery as a system is subjected to the more stringent certification requirements contained within EUROCAE/DO311.

The reliance on UN T 38.3 at the cell-level only was accepted by EASA following comments received during the Notice of Proposed Rulemaking process that resulted in the issue of Special Condition SC-22.2014-01 'Installation of electric propulsion units in powered sailplanes', published in 2014. In particular, the EASA position articulated in SC-22.2014.01 recognised that whilst:

> *'Lithium Polymer batteries have specific failure and operational characteristics that could affect the safety of those battery installations and cause hazards to safety, on the other hand it is understood that the characteristics of existing* [two-stroke piston engine] *propulsion systems have contributed to quite a number of accidents and electric propulsion systems with a simple and reliable start procedure can improve safety significantly*[10]*.'*

As it has not been possible to identify whether the G-GSGS battery fire event originated within a particular battery cell, or occurred due to a physical or electrical anomaly between two cells forming part of the battery assembly, it is unclear in this case whether certification of the battery assembly to a more stringent set of regulations by EASA would have prevented the battery fire.

Conclusion

During a normal touchdown following an uneventful flight, the glider's forward FES lithium polymer battery ignited due to an electrical arcing event. The pilot was unaware that the glider was on fire and the battery continued to burn, generating smoke and fumes which entered the cockpit during the latter stages of the landing roll. The pilot was not injured and the fire was extinguished using foam retardant, although the glider's fuselage battery box and surrounding structure was extensively fire-damaged.

A detailed examination of the forward FES battery did not determine the cause of the battery fire. The G-GSGS battery fire was the second of three such FES battery fires that have occurred to date.

A survey of other FES batteries from the in-service fleet revealed the presence of metallic debris in a significant proportion of those batteries examined. Vibration testing conducted by the AAIB showed that the presence of metallic debris can cause battery cell pouch fretting although this was not sufficiently severe to cause an internal short circuit and electrical arcing.

Footnote

[10] Special Condition SC-22.2014-01 '*Installation of electric propulsion units in powered sailplanes*'.

As a result of this investigation the sailplane manufacturer and FES system manufacturer have implemented a number of safety actions intended to prevent recurrence, or to mitigate the effects of a battery fire should such a fire occur.

Safety actions

Fire detection systems

At an early stage in the investigation, the AAIB made the following three Safety Recommendations relating to fire detection systems in Special Bulletin S3/2017, published in September 2017:

Safety Recommendation 2017-018

It is recommended that the European Aviation Safety Agency (EASA) requires that all powered sailplanes, operating under either an EASA Restricted Type Certificate, or an EASA Permit to Fly, and fitted with a Front Electric Sustainer (FES) system, are equipped with a warning system to alert the pilot to the presence of a fire or other hazardous condition in the FES battery compartment.

Safety Recommendation 2017-019

It is recommended that Alisport Srl modifies the Silent 2 Electro microlight to incorporate a warning system to alert the pilot to the presence of a fire or other hazardous condition in the Front Electric Sustainer (FES) battery compartment.

Safety Recommendation 2017-020

It is recommended that Albastar d.o.o. modifies the AS13.5m Front Electric Sustainer (FES) microlight to incorporate a warning system to alert the pilot to the presence of a fire or other hazardous condition in the FES battery compartment.

In response to these Safety Recommendations, the affected FES-equipped sailplanes have been modified with an independent warning system to alert the pilot to the presence of a fire in the FES battery compartment.

Battery and sailplane improvements

The HPH 304 eS sailplane manufacturer has replaced the composite battery compartment forward bulkhead with a stainless steel bulkhead to improve the fire-resistance of the bulkhead in the event of a battery compartment fire. The internal surfaces of the battery compartment are now painted in an intumescent fireproof paint finish.

The existing fleet of FES batteries was withdrawn from use and is currently being refurbished to a new design standard, to which new production batteries are also being produced. The new design standard includes replacement of the battery case with a stronger glass fibre case, constructed using high-temperature resin, that has been demonstrated in testing to remain structurally intact during a battery fire. The new battery case also features an impact label that permanently records if the battery has been subjected to a shock loading of 50g or more, to allow the battery to be withdrawn from use for inspection if subjected to abuse.

The new FES battery features additional nomex-mylar insulation between the cells and an increased quantity of silicone encapsulation of the battery cells to prevent foreign objects from falling between the cells. The edges of the battery cells pouches are covered in an electrically-insulating tape to prevent electrical discharge of the cell should the cell pouch seal fail. The stainless steel battery cell connector plates have been replaced with anodized aluminium plates which have been demonstrated not to eject machining swarf from screw threads when the connector screws are inserted during assembly.

Sailplanes equipped with the FES system also now feature a pressure-relief valve in the battery compartment cover, designed to allow the cover to remain attached to the sailplane in the event of over-pressurisation of the battery compartment should a battery fire occur.

FCU caution and warning system changes

The FCU caution and warning system has been redesigned such that red warnings are prioritised over lower-level yellow warning messages. Different audio warning tones now accompany red and yellow warning messages. All warning messages are recorded in the FCU's non-volatile memory for recall during operation and certain warning messages are recorded for subsequent fault investigation.

Battery certification requirements

An Electric Propulsion Working Group has been established including experts from the OSTIV[11] Sailplane Development Panel, EASA, certain sailplane manufacturers and the manufacturer of the FES system. This group will review the existing EASA battery certification requirements and to coordinate research activities in electric propulsion integration in powered sailplanes, including battery fire detection and containment.

Footnote

[11] Organisation Scientifique et Technique International du Vol á Voile / International Scientific and Technical Soaring Organisation.