INCIDENT

Aircraft Type and Registration:	Boeing 737-377, G-CELF
No & Type of Engines:	2 CFM56-3B1 turbofan engines
Year of Manufacture:	1988 (Serial no: 24302)
Date & Time (UTC):	2 August 2013 at 0617 hrs
Location:	On departure from Leeds Bradford Airport
Type of Flight:	Commercial Air Transport (Passenger)
Persons on Board:	Crew - 5 Passengers - 119
Injuries:	Crew - None Passengers - None
Nature of Damage:	Broken generator harness and over-heated battery charger
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	56
Commander's Flying Experience:	8,130 hours (of which 3,300 were on type) Last 90 days - 66 hours Last 28 days - 34 hours
Information Source:	AAIB Field Investigation

Synopsis

The aircraft suffered an electrical failure after departure, which led to the loss of the commander's primary flight instruments, navigation equipment and other electrical services. There was also a smell of electrical burning in the passenger cabin, so an immediate return to the airport was carried out.

The loss of power was caused by a fatigue failure of the terminal lug on the end of the No 1 generator phase 'A' ground cable. An inspection revealed a number of other lugs which had cracked in the same location, two of which were close to failing in the same manner. The lugs had probably cracked as a result of a combination of engine vibration, a rough surface finish and bending of the lug during installation.

History of the flight

The flight crew reported for duty at Leeds Bradford Airport at 0500 hrs, for a 0600 hrs departure to Schiphol Airport, Amsterdam. Pre-flight preparations and engine starting proceeded normally and the aircraft taxied for a departure from Runway 14. The co-pilot was the Pilot Flying (PF), with the commander as the Pilot Monitoring (PM). The commander was the fleet training manager and was experienced in carrying out abnormal checklist procedures in the simulator.

A reduced-thrust takeoff was carried out with the auto-throttle (AT) engaged. Shortly after

lift off, the commander heard a click and noticed that the AT had disengaged. During the initial climb, the master caution and amber FLT CONT caption illuminated, indicating a failure of the Mach trim. At about the same time, the commander's electronic attitude director indicator (EADI) and electronic horizontal situation indicator (EHSI) went blank and his altimeter, vertical speed indicator, Mach ASI and radio altimeter failed, with OFF flags showing. The No 1 Transformer Rectifier Unit circuit breaker tripped and the commander attempted to reset it, but it tripped again. The flight management computer (FMC) failed and both control display units (CDUs) locked up and could not be programmed. The PF's flight instruments and displays still functioned but he was unable to display the departure track on his EHSI. The commander briefly confirmed that the standby instruments were operating correctly by comparing them with the PF's instruments.

After the aircraft's landing gear and flaps had been retracted, the after-takeoff checks were completed. The climb was stopped and the aircraft levelled at 4,000 ft. The commander used the DC and AC meter rotary selectors to check the condition of the electrical power system, which appeared normal other than a slightly higher indication on the No 2 generator. The flight crew discussed the situation and decided to return to Leeds Bradford Airport. They also identified that the yaw damper, left forward window overheat, a fuel pump and normal exhaust fan were also inoperative. In addition, the flight crew noted that the battery charger, electric hydraulic pump 'B' and normal exhaust fan circuit breakers had tripped.

The commander started the APU and called the Senior Cabin Crew (SCC) member to the flight deck and gave her a NITS[1] briefing, after which she left the flight deck and walked to the rear galley to brief her colleagues. On the way, she noticed a distinct smell of electrical burning but with no signs of smoke. When she arrived at the rear galley, her colleagues both mentioned the electrical burning smell. The SCC alerted the flight deck to the smell and pulled the circuit breakers, isolating the galley electrical systems. The commander transmitted a PAN call and requested an immediate return to the airport. He also selected the flight deck galley electrical power switch OFF.

ATC provided radar vectors for a visual approach to Runway 14, and the ILS was set on the co-pilot's instruments as a backup. The weather was good with the 0620 hrs METAR indicating: surface wind 210º/05 kt, varying between 160º and 250º, visibility 20 km, scattered cloud at 1,600 ft, OAT 18ºC, dew point 16ºC and a QNH of 1005 hPa.

The commander re-briefed the SCC that they would be landing sooner than previously stated and, whilst at that stage there was no intention to carry out an emergency evacuation, the cabin crew were briefed to be at their stations after landing, in case the situation deteriorated. Without the use of the FMC, the commander elected to use flap 40º and a V_{APP} of 140 kt, as he knew from his training role that this was a safe speed and was not runway limiting. When the aircraft was established on the final approach, the No 1 generator tripped offline. The cabin emergency lighting illuminated and then extinguished. The commander selected the APU generator to generator bus 1 and his EADI, EHSI, analogue instruments and the FMC, with the associated CDUs, were all reinstated. The commander used the FMC to establish

Footnote

[1] Nature, Intentions, Timings and any Special instructions.

the V_{APP} speed, which was calculated as 127 kt. After an uneventful landing, the aircraft was taxied clear of the runway, on to Taxiway D, and brought to a stop at holding point D2. The aircraft engines were shut down and the AFRS carried out an external inspection, before the passengers were disembarked onto coaches and the aircraft was towed back to a stand.

Recorded data

The aircraft was fitted with a 25-hour FDR and a 30-minute CVR.

The FDR recording stopped 4 seconds after the aircraft lifted off the ground and re-started 3 minutes and 25 seconds before touchdown. The FDR installation is powered by phase 'A' from the 115V AC generator bus 1, which was lost after takeoff and restored 12 minutes and 41 seconds later, during the approach. There are no parameters relating to the electrical power system status or crew selections.

Limited sets of flight parameters were transmitted to ATC's radar, throughout the flight, via Mode S transponder returns. These covered a period of 26 minutes and 30 seconds. Figure 1 shows the recorded aircraft track.

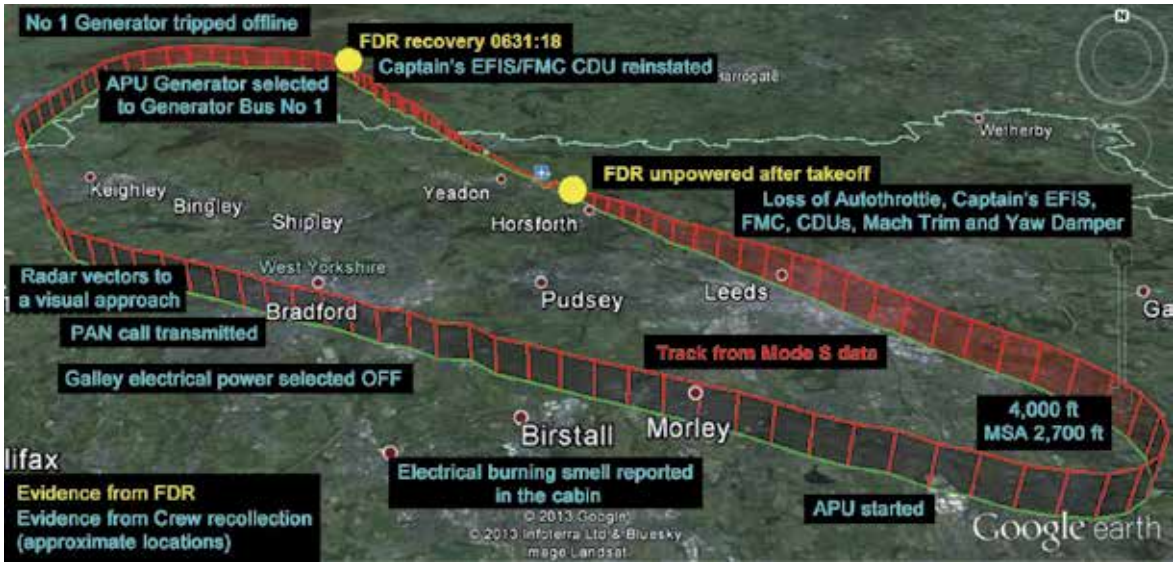

Figure 1

Aircraft track from Mode S transponder data, with approximate positions of events from crew recollections

The CVR is powered from phase 'B' of the No 1 generator and it continued to operate during the period when FDR power was lost. However, it also continued recording after the aircraft had landed and the pertinent evidence from the incident was not preserved.

Aircraft examination

Examination of the aircraft's electrical system revealed that the red phase 'A' ground cable from the No 1 generator had separated from the T191 stud on the side of the No 1 engine (Figure 2). This cable had separated due to a failure of its terminal lug (Figure 3). Further

examination of the generator harness revealed a cracked terminal lug on the blue phase 'C' ground cable at the T191 stud (also shown in Figure 2) and a further cracked terminal lug at the firewall end of the grey ground cable (opposite end of grey cable shown in Figure 2). The crack on the blue phase 'C' lug was only visible after the heatshrink insulation was removed.

Figure 2

Location of separated red phase 'A' generator cable, and cracked blue phase 'C' lug at T191 stud on G-CELF's No 1 engine

The red phase 'A' cable had a tight bend radius but it was within limits for a cable in a restricted area.

The battery charger in the avionics bay was removed because it smelt of burnt material. Internal examination revealed that a coil had burnt – this coil was connected in three-phase to the internal transformer.

The following circuit breakers in the flight deck were found to have tripped: Transformer Rectifier (TR) Unit No 1, Battery Charger, Electric Hydraulic Pump System B, and Normal Exhaust Fan Power.

Following replacement of the No 1 generator harness and the battery charger, functional tests and a flight test revealed no faults or smell of electrical burning.

Figure 3

Failed terminal lug on the end of the phase 'A' generator ground cable

Electrical system description

On the Boeing 737-300, primary electrical power is provided by two engine-driven generators which supply three-phase 115 V 400 Hz alternating current. Each generator supplies its own bus system (Figure 4) in normal operation and can also supply power to the transfer bus of the opposite side; this is accomplished automatically via the Bus Transfer (XFR) relay if one generator fails or is disconnected. The APU drives a generator that can supply power to one of the AC Generator busses in flight. The system design does not allow parallel operation of two generators on one bus, so prior to a different generator being connected to a bus, the existing generator is disconnected. Transformer rectifier (TR) units and a battery supply DC power. The battery also provides backup power for the AC and DC standby systems.

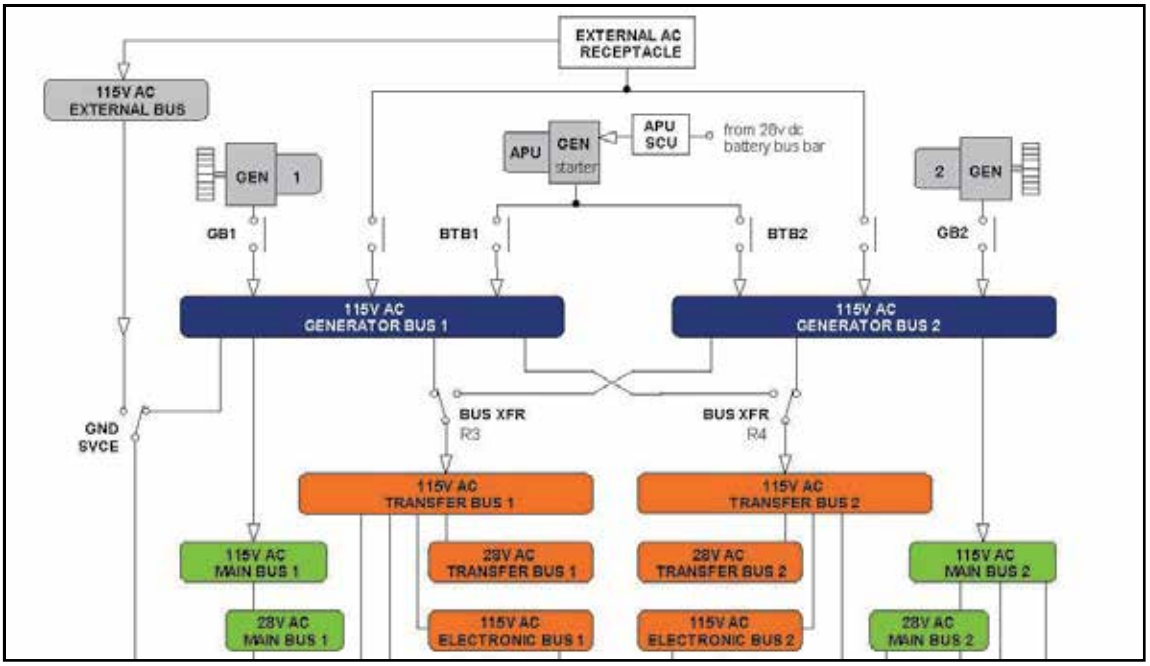

Figure 4

Top level electrical system schematic for the Boeing 737-300
(orange denotes busses carrying essential loads and green denotes busses carrying non-essential loads; schematic courtesy of B737MRG)

Effect of a loss of phase

There are a number of electrical components on the aircraft that require 3-phase power for operation, such as hydraulic pumps, fuel pumps and transformers. Other lower power components, such as the EFIS screens, instruments and auto-throttle operate using single-phase power. When the phase 'A' generator cable broke at the T191 stud, there would have been a drop in voltage in the phase 'A' line. However, the voltage on phase 'A' would not have dropped to zero because the 3-phase loads, still powered by phases 'B' and 'C', would have induced current and voltage on phase 'A'. This occurs because 3-phase loads are connected across the phases rather than from each phase to ground. This effect is illustrated in Figure 5. There is no current flow in the phase 'A' line between ground and the generator bus, so the current transformers at the generator and generator bus measure the same current and therefore the differential current protection is not tripped. On the Boeing 737-300 there is no measurement of differential current between phases. Inside the generator bus there is current flow in the phase 'A' line due to the voltage induced from the 3-phase components.

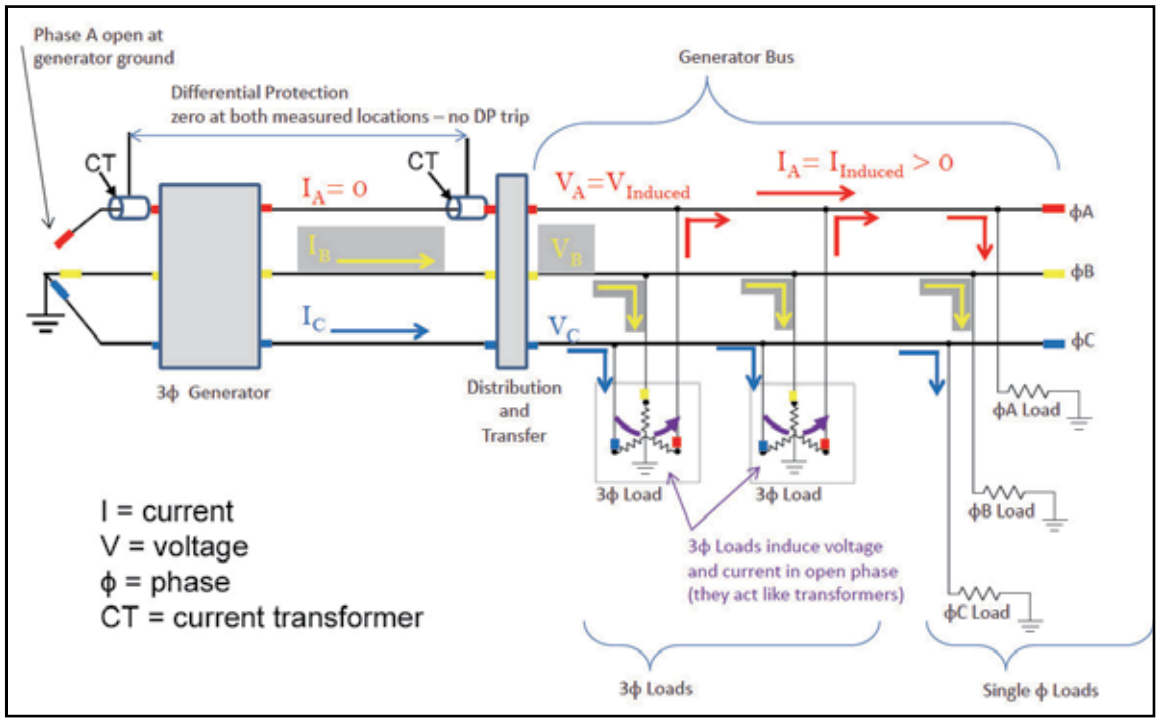

Figure 5

Operation of a 3-phase system with phase 'A' open circuit at the generator ground

Under-voltage protection trips off the generator when the average voltage across all 3-phases drops below a certain value[2]. Using the aircraft manufacturer's estimate for the induced voltage on phase 'A' at the beginning of this incident, the calculated average across all three phases was high enough to prevent the under-voltage protection being

Footnote

[2] This value is proprietary information so cannot be published although it was shared with the investigation team.

triggered. Thus, the No 1 generator did not trip offline when the terminal lug failed. The single-phase equipment is designed to operate at 115 V, but the aircraft manufacturer stated that some equipment might still operate at the lower voltage induced on phase 'A'. This explains why the single-phase equipment using phase 'A' did not fail simultaneously.

The following single-phase AC components that failed in the incident all operate from phase 'A': Auto-throttle, Captain EFIS displays, Captain's Airspeed Indicator (ASI), Captain's Altimeter, Captain's Vertical Speed Indicator (VSI), FMC, Mach Trim, Yaw Damper and the Flight Data Recorder (FDR). This aircraft was equipped with only one FMC, and without an FMC the CDUs lock up.

The loss of phase 'A' to the 3-phase devices, such as the pumps and transformers, results in the remaining phases 'B' and 'C' drawing more current. This excessive current draw eventually results in the thermal circuit breakers (C/Bs) for these devices tripping. This explains why the C/Bs for the electric hydraulic pump B, the normal exhaust fan, TR1 and the battery charger[3] eventually tripped. The excessive current draw also caused the coil inside the battery charger to overheat.

As each C/B for a 3-phase device tripped, the induced voltage on phase 'A' reduced. Eventually, once enough 3-phase devices had tripped offline, the phase 'A' induced voltage probably dropped sufficiently that the under-voltage protection tripped off the generator during the final approach. Figure 6 shows an expanded diagram of the No 1 Generator Bus system, highlighting the components which are fed from the different busses, and the C/Bs which tripped in the incident.

Consequently, once the No 1 generator tripped offline, the Bus Transfer (XFR) relay automatically switched to the Alternate position, causing the No 2 generator bus to power the No 1 transfer bus. This restored power to the essential single-phase AC equipment operating on phase 'A'. This explains why the captain's instruments were restored after the No 1 generator tripped offline. The captain also manually selected the APU to feed the No 1 generator bus at about the same time, which restored power to all loads powered by Generator Bus 1. The TR1 C/B remained tripped but a closed TR3 disconnect relay[4] (Figure 6) allowed the No 2 side to feed the No 1 DC busses.

Findings from operator's fleet inspection

Following the incident the operator carried out an unscheduled visual inspection of the generator harness terminal lugs on their fleet of 32 Boeing 737-300 aircraft. This consisted of a detailed visual inspection of the lugs without magnification, and it was reported that the engineers removed the lugs from the T191 stud to inspect them. However, the heatshrink insulation was not removed. On one aircraft, G-GDFB, on the No 2 engine, the terminal lug from the ground cable at the T191 stud was found to have cracked (Figure 7). There were differences in how the heatshrink insulation had been applied to the lug ends of the cables,

Footnote

[3] The battery charger contains a 3-phase transformer.

[4] The TR3 disconnect relay would have opened if Glideslope (GS) mode had been engaged on the autopilot or flight director, but this mode was not engaged during the approach.

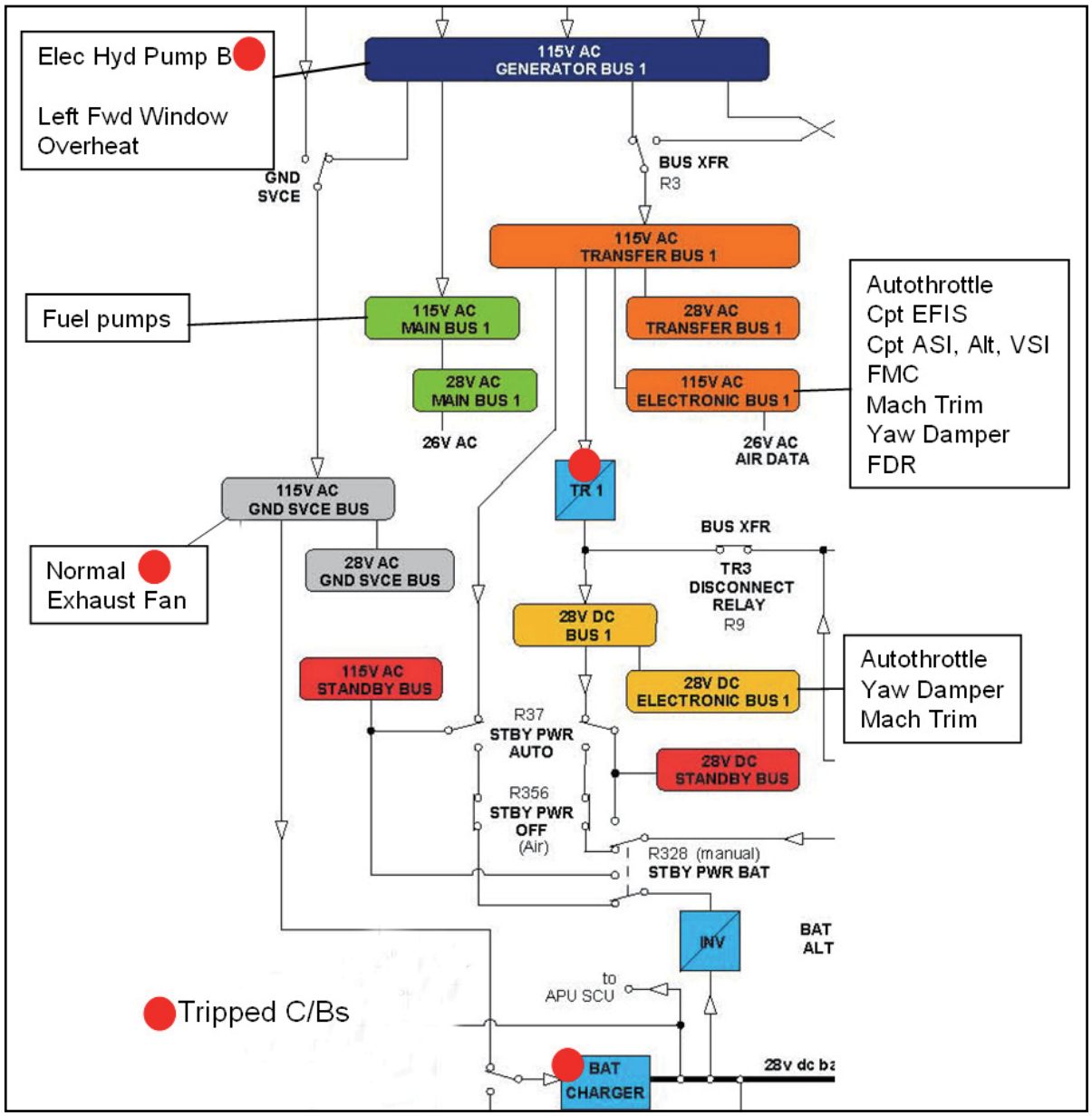

Figure 6

Electrical system schematic detail for Generator Bus 1
(red dots denote equipment with tripped circuit breakers;
schematic courtesy of B737MRG)

and the vulnerable bend area of the blue phase 'C' lug was not visible. The cracked lug was removed and bent open which revealed that it had cracked through half its thickness (Figure 8).

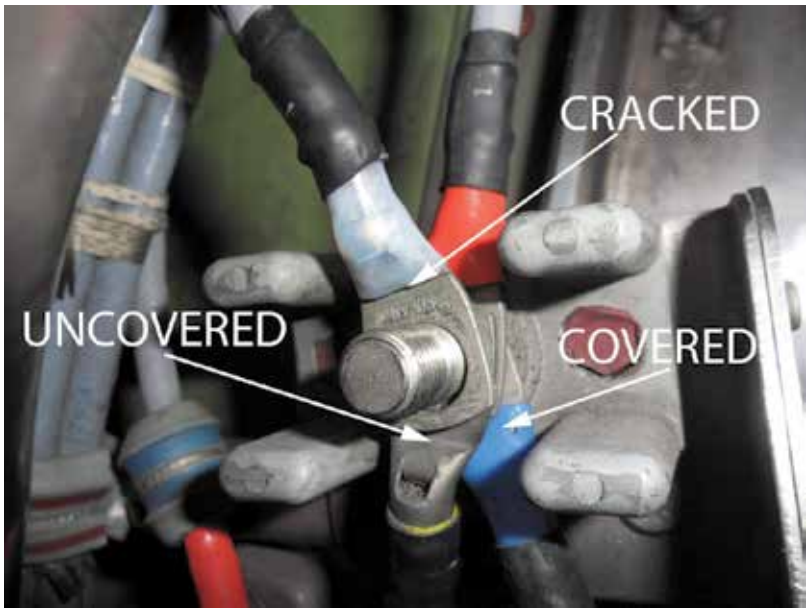

Figure 7

Cracked terminal lug from ground cable at T191 stud on G-GDFB's No 2 engine

Figure 8

Close-up of cracked terminal lug from ground cable on G-GDFB's No 2 engine

The fleet inspection also revealed two terminal lugs with cracked coatings on another aircraft, G-CELI.

Maintenance history

According to the aircraft operator, no removal or maintenance of the No 1 generator harness on G-CELF had been carried out since the engine's last overhaul in March 2008. According to the engine overhaul records the harness had been removed from another engine and installed on engine s/n 722273 which was later fitted to G-CELF. According to these records the harness was:

> *'only visual inspected for external damages in accordance with Standard Wiring Practices Manual [SWPM] D6-54446 Rev. 39 and is in serviceable condition.'*

The harness is not a tracked part with a serial number and therefore it was not possible to determine the age of the harness or the cables and lugs within it.

On 13 July 2013 the flight crew of G-CELF reported high vibration on the No 1 engine. The vibration level had reached a maximum of 2.5 units, which was within permissible limits, although normal vibration levels are below 1 unit. The operator elected to install a new set of fan blades on 30 July 2013 which resolved the vibration issue.

There had been no incidents of high vibration on the No 2 engine from G-GDFB since the operator took ownership in May 2010. The last recorded maintenance on the harness was during the engine's last overhaul in 2008.

Maintenance requirements

In the aircraft manufacturer's Maintenance Planning Data (MPD) there is a requirement to '*Perform a detailed inspection of the generator power feeders and connected EWIS*[5] *on Engine No.1*'[6]. The same requirement exists for Engine No 2 and these are to be carried out at the 1C interval which is every 4,000 hours. The EWIS includes termination devices such as the terminal lugs. The definition of 'detailed inspection' in the MPD is:

> *'An intensive examination of a specific item, installation or assembly to detect damage, failure or irregularity. Available lighting is normally supplemented with a direct source of good lighting at an intensity deemed appropriate. Inspection aids such as mirrors, magnifying lenses, etc. may be necessary. Surface cleaning and elaborate access procedures may be required.'*

There are no removal instructions as part of this inspection and to examine both sides of all the terminal lugs at the T191 stud would require the cables to be removed from the stud. Some terminal lugs have the bend area covered by heatshrink insulation and cannot be inspected without removing the insulation. The specification for the terminal lugs states that the heatshrink must be 1/4 inch ± 1/16 inch clear of the rear edge of the hole, and because of the tolerances on the distance from the rear edge of the hole to the bend, the bend area could be covered or uncovered. According to the operator this inspection was carried

Footnote

5 EWIS is the Electrical Wiring Interconnection System.
6 Task B20-60-03-6A-8 in 737-300/400/500 Maintenance Planning Data D6-38278, Sep 2013.

out during G-CELF's last 1C check in March 2012 and during G-GDFB's last 1C check in May 2012. However, the operator stated that this was an inspection of many components and would not necessarily pick up cracked terminal lugs, and the inspection would not involve removing the cables or the heatshrink insulation.

According to the aircraft manufacturer the same detailed inspection called for during the 1C check should be carried out during engine overhaul. The engine overhaul organisation that overhauled G-CELF's No 1 engine in 2008 had since closed down so it was not possible to obtain any further information on what their visual inspection of the harness entailed.

The records for the overhaul of G-GDFB's No 2 engine state that a '*visual inspection'* and a *'continuity and insulation test*[7]*'* were carried out on the generator harness in-situ on the engine. The overhaul organisation stated that the inspection was carried out in accordance with the aircraft manufacturer's SWPM. This manual does not detail any specific inspections, but in a section on '*Permitted Bends in a Terminal'* it states '*Make sure that there are no cracks in the bend area*'. They also stated that the heatshrink insulation would not be removed if it was covering the bend area of the terminal lug. However, they also reported finding cracked terminal lugs in about 1 in 100 harnesses.

The engine overhaul period is based on the component with the most limiting cycles remaining. The shortest lifed item on an overhauled engine usually has at least 12,000 cycles remaining. For the operator of G-CELF with an average annual utilisation of 1,000 cycles, this would equate to an overhaul every 12 years.

Manufacture of terminal lugs

The failed and cracked terminal lugs from G-CELF and G-GDFB had part number YAV6CL2NK[8] (AN6). The lugs with the cracked coating from G-CELI, part number YAV4CL2NK[9] (AN4), were slightly larger. Both types of lugs are manufactured in the same way by the same manufacturer, using an automated machine to flatten the end of a copper tube to form the tongue. A hole is then punched into the tongue and the lugs are annealed to a maximum hardness of Rockwell F50, as measured at the barrel[10]. The lugs are then coated with nickel plating. The composition of the copper tube is 99.9% minimum copper and the nickel plating is 99.9% minimum nickel. The lug manufacturer reported that the lugs had been manufactured in the same location since 1978 and there had not been any recorded design or manufacturing changes since then.

The lugs meet the Boeing specification BACT12M which does not require fatigue testing. However, the lug manufacturer conducted fatigue testing on tin plated versions of the lugs to SAE standards[11].

The aircraft manufacturer's SWPM specifies that the lug of a BACT12M standard connector

Footnote

[7] A continuity and insulation test will check for short-circuits but will not detect, and is not intended to detect, cracked terminal lugs.

[8] Boeing part number BACT12M6-4.

[9] Boeing part number BACT12M4-4.

[10] The lug manufacturer does not specify a maximum hardness for the tongue.

[11] They were tested to SAE-AS20659 in accordance with SAE-AS7928.

may be bent once only, through a maximum of 30º, in either the up or down direction, and that this bending must be performed with a tool before installation. Crazing of the nickel plating is permitted after bending, provided there is no exposed copper. The lug manufacturer's specification does not state whether the lugs can or cannot be bent although the lug manufacturer stated to the AAIB after the investigation that they do not support bending of the lugs by customers.

Metallurgical examinations

Detailed metallurgical analysis was carried out on the lugs from G-CELF, G-GDFB and G-CELI. The fracture surfaces of the failed lug on the end of the phase 'A' generator ground cable (G-CELF) are shown in Figure 9. This revealed that fatigue cracks had initiated at multiple sites on the lug's upper surface and then coalesced after a short distance to form a single crack front which propagated downwards to the centre of the lug, and then curved round the edges. The crack tips then propagated towards each other, along the lower wall, until they reached a point where the remaining section failed in overload. The large surface area of fatigue crack growth, compared with that of the final separation, indicated that the cyclic loading was of low magnitude, repeated for a large number of cycles.

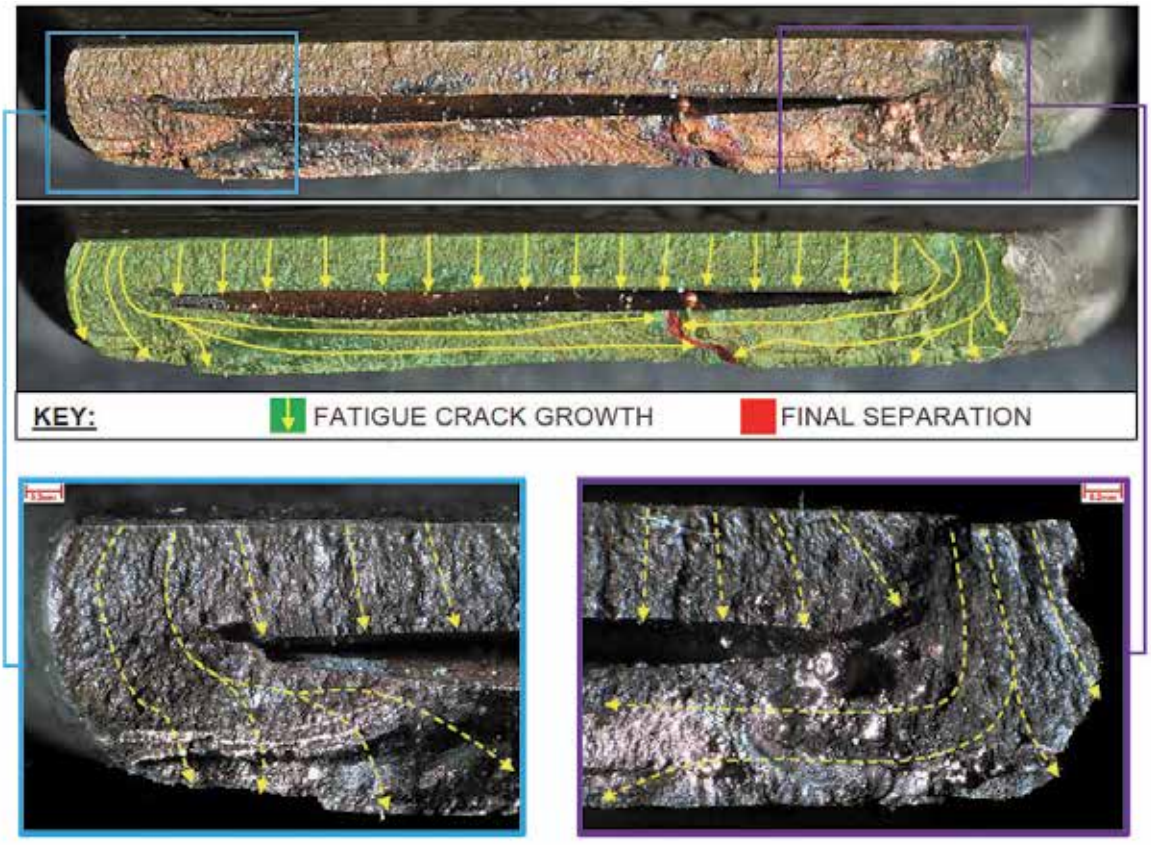

Figure 9

Fracture surfaces of failed terminal lug on the end of the phase 'A' generator ground cable (G-CELF)

Examination of the lug's upper surface revealed a series of parallel grooves that had been formed by the flattening tool used to make the lug. The fatigue cracks had initiated within one of these grooves.

Examination of the fracture surfaces under SEM[12] revealed regions of both transgranular and intergranular crack propagation, which was consistent with corrosion fatigue. Transgranular crack growth would have dominated during periods when the cyclic stress was relatively high and/or the severity of the corrosive environment was low. Intergranular crack growth would have dominated when the converse was true. Fatigue striations were evident in both the transgranular and intergranular regions and their fine spacing was consistent with a load spectrum of high frequency vibrations.

In order to examine the fracture surfaces on the two cracked lugs from G-CELF and the cracked lug from G-GDFB, the lugs were forced open until they failed. The fracture surfaces of all three lugs displayed the same downward fatigue crack growth from multiple initiation sites from within one of the parallel grooves formed by the flattening tool. The fatigue crack on the blue phase 'C' lug from G-CELF had propagated through half its thickness but had not yet propagated around the corners. A secondary fatigue crack had initiated on the lower surface and propagated upwards (Figure 10). The presence of this crack indicated that there had been a degree of reversal in the cyclic bending loads exerted on the lug. The fatigue crack on the ground lug from G-CELF was at an early stage of development and had propagated through less than a quarter of the lug's thickness. The fatigue crack growth on the lug from G-GDFB was similar to that of the phase 'C' lug from G-CELF, and had propagated through over half of the lug's thickness.

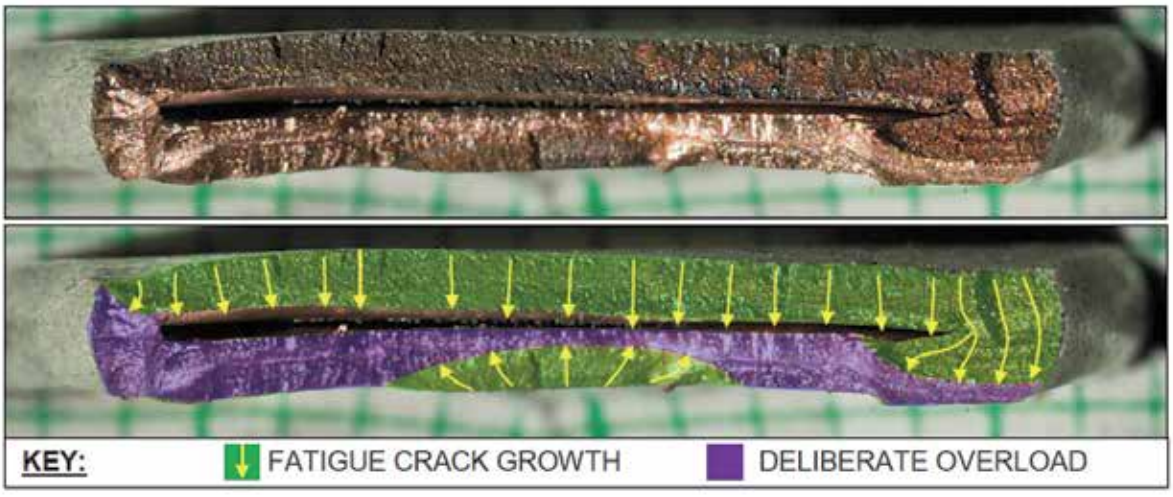

Figure 10

Fracture surface of cracked terminal lug on the end of the phase 'C' generator ground cable (G-CELF)

Footnote

[12] Scanning Electron Microscope.

Detailed examination of the pattern of the parallel grooves from which the cracks had initiated revealed that they were the same, indicating that these four lugs had probably been flattened by the same tool. The grooves did not disturb the lettering stamped on the lugs, which indicated that the grooves were made either before or at the same time as the lettering. A sample of new terminal lugs had much shallower grooving (Figure 11). The lug manufacturer stated that lug inspection checks are performed on a sample basis with the naked eye, and that these checks had not noted any grooves of the extent shown in the left and middle images of Figure 11.

Figure 11

Comparison of the parallel grooves on the G-CELF lugs and a new unused lug (right)

The two lugs from G-CELI had an array of parallel cracks that appeared to extend through the nickel plating and not the underlying copper; one of these lugs had significant flaking of the nickel at the bend line exposing the underlying copper.

Material composition

Analysis of the cracked lugs by Energy Dispersive X-Ray Spectroscopy revealed that they were composed of 100% copper with a measurement accuracy of 0.1%, which was within specification for the lug. Microhardness testing revealed that the failed G-CELF lug and the cracked G-GDFB lug had hardness levels remote from the cracked or bent locations of 83 and 70 HV[13] respectively, where 65 HV would be equivalent to 50 HRF in a Rockwell hardness test. These figures are above the maximum hardness specified by the manufacturer, although they were measured at the tongue instead of the barrel, so this might account for some difference. However, it might also indicate that the annealing of the lugs after flattening was not fully effective.

Footnote

[13] HV is the unit measurement of hardness using the Vickers hardness test.

Microsections of the crack surfaces did not reveal any evidence of hydrogen embrittlement and there was no evidence of any microstructural anomalies at the fatigue initiation sites. The thickness of the lugs was also measured and found to be within specification.

Lug bending

The failed red phase 'A' lug from G-CELF appeared to have minimal bending, although it could have been previously bent and re-flattened. The blue phase 'C' lug from G-CELF was bent downwards by 12º, and the ground lug from G-CELF was bent upwards by about 30º (Figure 12). The cracked lug from G-GDFB was bent downwards by 10º[14], and both connectors from G-CELI were bent upwards by 15º.

Figure 12

30º upwards bend of cracked G-CELF ground lug

As part of the investigation, bend testing was carried out on a sample of five AN6 and five AN4 terminal lugs. Bending of the AN4 lugs through 30º caused flaking of the nickel plating in one case, and an array of parallel cracking in another – this flaking and cracking was similar to that present on the AN4 connectors from G-CELI. However, the flaking had not exposed the underlying copper, while the cracking had exposed the copper.

Bending of the AN6 lugs once through 30º caused an array of shallow, parallel cracks to form. They were just detectable with the unaided eye, but easily visible with x10 magnification, and the underlying copper was exposed. Bending the lugs once through 15º caused cracks in the nickel plating which were just detectable with x10 magnification. Bending the lugs more than once caused the extent and severity of the cracking to increase. Bending the lugs upwards by 15º and then down by 15º twice produced cracking which was easily detectable and extended through the plating into the copper. If the final bend was up, then this had the effect of closing the cracks making them more difficult to detect.

Previous instances of cracked lugs

The aircraft manufacturer reviewed operator reports of open phase events on the Boeing 737 Classic[15] fleet for the period 1983 to 2004. There were 11 reports of open phase events, of which one in June 1998 was traced to a damaged ground lug. There was

Footnote

[14] This downwards bend had been made by the operator to expose the crack after removal. The pre-removal angle was not recorded.

[15] The term 'Classic' refers to the 737--300, -400 and -500 series of aircraft.

an additional report of a fractured lug in 1990 in which the operator had not reported the symptom of 'open phase event'. However, there is no requirement for these failure events to be reported to the manufacturer.

The lug manufacturer reviewed their customer complaint log dating back to 2004 and this did not contain any reports of cracked lugs.

Two organisations that overhaul CFM engines were contacted to determine the rate of cracked lugs found during their visual inspections. One organisation estimated that their rejection rate of harnesses due to cracked lugs was 1 in 100. The other organisation reviewed its data and found two instances of harnesses with cracked terminal lugs between 2008 and 2013. Both of these harnesses had been on engines that had had been subjected to heavy vibration caused by bird strikes.

Electrical system on the Boeing 737NG[16]

On the Boeing 737NG aircraft the electrical system incorporates under-voltage protection that monitors each phase separately. If the voltage of a single phase drops below a specified threshold for a specific number of seconds[17], the affected generator will trip offline and automatic bus transfer will occur. Therefore, if the G-CELF failure event had occurred on a 737NG, power to the Captain's instruments and other phase 'A' systems would have only been lost for a few seconds. The 737NG electrical system also incorporates 'Unbalanced Phase' protection which can detect a single loss of phase and will trip the generator offline after a 19-second time delay. When this system activates it will prevent bus transfer.

Analysis

Operations

The initial loss of the AT was recognised by the commander who was aware that it was not a 'no go' item in the Minimum Equipment List (MEL) and expected to continue the flight. As his instruments and other services failed, he realised that there had been a significant electrical failure although he did not recognise the situation as one which was covered in the abnormal checklist. The PF continued to fly the aircraft, using his instruments, and ATC were notified of the situation. The crew agreed that there was no abnormal procedure for their circumstances and that they should return to Leeds Bradford Airport. At that stage, there was no urgency to return and the Standard Operating Procedures (SOPs) regarding briefing the cabin crew were carried out as normal.

When the SSC made the commander aware of the burning smell, the flight crew decided to expedite their return and transmitted a PAN call. From his training background, the commander knew that 140 kt was a safe approach speed and would not be runway limiting. When the No 1 generator tripped offline, the commander carried out the abnormal procedure and the FMC became available, enabling the appropriate approach speed to be obtained.

Footnote

[16] 737NG refers to the 'Next Generation' models consisting of the 737-600, -700, -800 and -900.
[17] This value is much less than a minute. The exact number of seconds is proprietary information.

System failure

The electrical failure symptoms experienced by the flight crew could all be explained by the failure of the red phase 'A' generator ground cable lug end. The electrical burning smell could be explained by the overheated coil inside the battery charger which occurred as a result of excessive current draw in the remaining 'B' and 'C' phases. The Boeing 737-300 and the other 737 Classic aircraft do not have systems that can detect a single loss of phase so there was no clear annunciation to the crew as to the failure condition or what action to take. If the flight crew had turned off the No 1 generator, then the No 2 generator bus would have powered the No 1 transfer busses automatically and this would have restored the EFIS, Auto-throttle, FMC and the other phase 'A' systems. However, there was no checklist instructing them to do this. The aircraft manufacturer stated that writing a checklist for this situation would be difficult because the electrical failure symptoms would be different depending upon which phase was lost. They also considered that instructing the crew to turn off a generator in this situation could result in the wrong generator being turned off, resulting in the loss of instruments on both sides.

It took just over 12 minutes from the initial failure event until the No 1 generator automatically tripped offline which allowed power to all instruments and essential systems to be restored. This was probably triggered by the under-voltage protection which monitors the three-phase average voltage.

Lug failures

The red phase 'A' ground cable terminal lug failed due to corrosion fatigue under the influence of loads consistent with high frequency vibrations. The blue phase 'C' terminal lug and the grey ground terminal lug had started to crack in the same manner and would probably have failed eventually as well. This engine had been subject to higher than normal vibration in the month preceding the failures, which was probably a contributory factor. However, this level of vibration was not unusual and given the large size of the worldwide 737 Classic fleet and the low reported incidents of cracked lugs, it is unlikely that high vibration alone caused the lugs to crack. The terminal lug on G-GDFB had cracked through almost half its thickness without any reported high vibrations in the engine's previous 3 years of service. However, it was possible that this engine had suffered from high vibration prior to 2010 when the operator had taken ownership of it.

Another factor which probably contributed to the cracks was the rough surface finish on the upper surface of the lugs. All the cracks on the G-CELF and G-GDFB lugs had initiated within one of the parallel grooves at the bend. These grooves were visibly deeper than those compared to a small batch of new lugs. It was probable that these lugs had been flattened using the same tool which was more rough than usual. It could not be established how common rough grooving was on these lugs and there was no surface finish specification in BACT12M, and therefore the grooving was considered a contributory factor rather than a sole causal factor.

A third factor which probably contributed to the cracks was the effect of bending. Bending tests revealed that cracks in the nickel plating would form when the bending was within the

limits of the SWPM. If bending exceeded these limits, cracks could develop in the underlying copper. The cracked lugs from C-CELF and G-GDFB were bent to varying degrees and it was not possible to establish how much prior bending they had had. Since generator harnesses are 'on-condition' items and can be re-used many times on different engines it is possible that the lugs had been bent more than once, although such a practice is not approved in the SWPM. Even if the lugs had only been bent once, the resulting cracking in the nickel plating combined with the grooving and the higher than normal vibration could explain the failures.

A fourth possible contributory factor was that the hardness of the G-GDFB lug and failed G-CELF lug was higher than the manufacturer's specification. Harder materials are more brittle and therefore more susceptible to cracking.

The red phase A cable had a tight bend radius but it was within the limits specified by the SWPM for a cable in a restricted area, and none of the other cracked lugs were on cables with a tight bend radius, so this was probably not a significant factor.

The cracking of the nickel plating present on the two larger AN4 connectors from G-CELI was consistent with the effect of bending alone. These cracks had exposed the underlying copper which was not permitted by the BACT12M specification but there was no evidence that fatigue cracks had initiated from them.

In the lug manufacturer's view, the fatigue cracks are not the result of the manufacturing process but are due to the installation and bending processes used during maintenance, and in-service vibration.

Lug inspections

The aircraft manufacturer's maintenance requirements do not include a specific inspection of the terminal lugs on the generator harness. They stated that the detailed inspection of the EWIS that is required at every 1C check should suffice. However, this inspection does not require removal of the lugs from the T191 stud or removal of any heatshrink insulation covering the susceptible bend area. Due to the stacking of the lugs at the T191 stud and the possibility that the lugs can be installed upside down[18], it is not possible to inspect the susceptible bend area on all the lugs without removing them from the stud and without removing any covering insulation.

It was not clear what level of visual inspection had been carried out on the generator harness terminal lugs when the G-CELF and G-GDFB engines were overhauled. However, it was clear that the organisation which overhauled the G-GDFB engine was detecting cracked lugs at a frequency of about 1 in 100 harnesses, so there was a degree of effectiveness in their procedures despite them not removing the heatshrink insulation.

The operator of G-CELF intends to carry out a special detailed inspection of the terminal lugs at the T191 stud at every future 1C check. This is because a phase A lug failure

Footnote

[18] 'Inverted' installation of the cables with the bend area face down is permitted by the SWPM.

causes a system failure that is not detected by the electrical system, has no checklist, and is likely to generate an electrical burning smell from the battery charger. These effects have significant consequences for the workload of the crew.

The effect of a phase 'B' or phase 'C' lug failure might be less serious than failure of the phase 'A' lug due to the systems they affect but further detailed analysis would be required to confirm this. Failure of the grey ground lug at either the T191 lug or at the engine firewall would not result in a loss of power because the phase loadings would remain balanced.

Failure of any of the generator harness terminal lugs on a Boeing 737NG would have minimal effect for the flight crew, because the system would detect the fault and the power to the instruments would be interrupted for much less than a minute.

The current inspection requirements as detailed in the MPD would miss some lugs that had started to crack because the bend area of the lug is not visible on some lugs without removing the cable or removing the insulation.

The aircraft manufacturer stated:

> *'The possibility of modifying the inspection requirements to require removal of the generator lugs for a more complete inspection was considered. It was noted, however that additional inspections requiring removal of the lugs will introduce the possibility of damage caused by the disassembly as well as the potential for assembly errors that degrade overall reliability. Given the current low rate of ground lug fractures leading to open phase failures, such additional inspection actions would likely present a greater risk of open phase failure than currently exists.'*

The aircraft manufacturer re-iterated that it considered bending of the lugs in the field acceptable but that the preferred option would be to use lugs that had been pre-bent by the lug manufacturer. The aircraft manufacturer is moving towards using only pre-bent lugs on new designs and will be considering the use of pre-bent lugs as replacements for lugs on aircraft currently in service.