ACCIDENT

Aircraft Type and Registration:	BAE Systems Jetstream 31, G-CCPW
No & Type of Engines:	2 Garrett Airesearch TPE 331-10UGR-5164 turboprop engines
Year of Manufacture:	1987 (Serial no: 785)
Date & Time (UTC):	8 March 2012 at 1757 hrs
Location:	Runway 26, Isle of Man Airport
Type of Flight:	Commercial Air Transport (Passenger)
Persons on Board:	Crew - 2 Passengers - 12
Injuries:	Crew - None Passengers - None
Nature of Damage:	Right main landing gear yoke pintle fractured, right engine and propeller blades damaged
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	58 years
Commander's Flying Experience:	6,000 hours (of which 2,300 were on type) Last 90 days - 140 hours Last 28 days - 48 hours
Information Source:	AAIB Field Investigation

Synopsis

The aircraft's right main landing gear failed as it landed on Runway 26 at Isle of Man Airport. The right main landing gear detached, the aircraft slid along the runway on its remaining landing gear, right wingtip and luggage pannier before coming to rest on the grass adjacent to the runway. The passengers and crew vacated the aircraft without injury.

The right landing gear failed as a result of intergranular corrosion / stress corrosion cracking of the forward yoke pintle. Four Safety Recommendations are made.

History of the flight

The aircraft and crew were operating a passenger service from Leeds Bradford International Airport to Isle of Man Airport. The flight had been routine and the crew were flying a day, visual approach to Runway 26, in good weather, with the surface wind reported as 210° at 14 kt. The commander was the pilot flying (PF) and the co-pilot, who had recently joined the company, was nearing the end of his line training on type.

The approach was flown with full flap and the landing gear locked and confirmed down by the three green gear indicators. The landing weight was estimated to be 13,448 lb (6,099 kg) and the crew recalled that the V_{REF} was about 105 kt.

The aircraft touched down and almost immediately leaned to the right accompanied by an unusual noise. The commander levelled the aircraft with a left roll input. However, as the speed decayed the lean increased and it became apparent that there was a problem with the right landing gear. The commander continued to apply left aileron and rudder. Both pilots recognised that the aircraft was likely to leave the paved surface and so the co-pilot held the control wheel and rudder to allow the commander to apply nosewheel steering and operate the feather levers[1]. The left engine was shut down and feathered as the aircraft departed the runway. The right engine was also shut down but its propeller did not feather. The aircraft left the paved surface, yawed to the right and slid sideways before it came to a stop 90° to the runway heading.

After the aircraft stopped the commander instructed the co-pilot to "GET THEM OUT" and, as all three landing gear green lights were still illuminated, he transmitted on the tower radio frequency that he thought the aircraft had burst a tyre. The commander then shut down the aircraft. He confirmed that both feather levers were pulled, their respective fuel valve lights on the overhead panel showed SHUT, and selected both hydraulic shut off switches to SHUT. He then electrically isolated the aircraft by pulling the battery circuit breakers before leaving the cockpit to assist in the cabin.

The Air Traffic Control Officer (ATCO), located in the visual control room of the tower to the north of the runway, saw the right propeller strike the runway as the gear collapsed. This was also seen by the airport fire-fighter on duty at the Airport Fire and Rescue Service (AFRS) watch office, located to the south of the runway. Both pressed their respective crash alarms while the aircraft was still moving and the AFRS arrived at the aircraft less than two minutes after it had come to a stop.

While the commander shut down the aircraft the co-pilot entered the passenger cabin. He instructed the passengers to remain seated while he ascertained that there were no significant injuries and that the cabin situation was stable. He visually checked the right wing area before opening the passenger door located on the left side of the fuselage at the rear of the cabin. The passengers seated near the single overwing exit, located on the right side of the aircraft, had considered opening it. However, they could see the damage to the right engine and steam or thin smoke rising from the engine area and elected not to do so. The co-pilot assisted other passengers off the aircraft before he returned to the cabin and, along with the AFRS, assisted two passengers of reduced mobility from the aircraft.

Post-accident actions by ATC

After the controller on duty pressed the crash alarm there was no confirmation in the tower that the alarm had functioned and the controller attempted to call the AFRS by direct line telephone to confirm they were aware of the accident. The AFRS did not answer this call as they were in the process of deploying and the controller terminated the call when he saw, on the opposite side of the aerodrome, the fire station doors open.

The air traffic assistant called the Emergency Services Joint Control Room (ESJCR) located in Douglas to initiate the deployment of off-site rescue services. The ATCO had categorised the accident as an Aircraft Ground Incident (AGI) and this message was relayed to the ESJCR. At the time of the accident the pre-planned deployment of off-site assets was identical for both AGI and Aircraft Accident, and consisted of deploying five

Footnote

[1] The feather lever shuts off fuel to its engine and feathers the propeller.

appliances from a variety of fire stations. The AAIB has been informed that future planning is to have a varied level of response to different incident categories.

The AFRS deployed three appliances and were in position to commence fire fighting 100 seconds after the aircraft stopped moving. While the Watch Commander was driving towards the aircraft he could see passengers disembarking and, using UHF radio, asked the ATCO to have the airport bus deployed to the runway to act as a shelter and transport. He was also in direct radio communications with the ESJCR.

The ESJCR had attempted to initiate its automated pre-planned deployment but a computer failure resulted in a delay of about two minutes while a manual override was initiated. This delay was sufficient for the Watch Commander to establish two-way communications with the ESJCR and confirm to them the level of assistance that he required. As a result the ESJCR stood down the majority of their response, leading some observers to comment on the apparently limited off-site response of a single fire vehicle.

The AFRS conducted visual and thermal imaging surveys of the aircraft, which revealed no signs of fire or fuel leaks. A small area of foam was laid around the right wing and engine as a precaution.

Runway marks and debris

The aircraft left a number of marks on the runway surface starting approximately 90 m from the start of the threshold markings. The first marks were made by the right engine propeller blades cutting into the runway surface. Sections of the right landing gear yoke pintle were found at 150 m and 180 m from the runway threshold, near the right landing gear door.

Recorded information

The aircraft was equipped with a 30-minute Cockpit Voice Recorder (CVR) and a continuous loop Digital Flight Data Recorder (DFDR). The DFDR recorded just over 26 hours of operation with five parameters which were time, pressure altitude, indicated airspeed, normal acceleration and heading.

Additionally, a Terrain Awareness and Warning System (TAWS) installed in the aircraft recorded 30 separate parameters including aircraft rate of descent, radio altitude and pressure altitude, at a higher sampling rate than the DFDR. These data sources were combined to present a more detailed picture of the aircraft's operation.

The rate of descent recorded by the TAWS, just prior to touchdown, was 463 ft / min (7.7 ft/sec) and is shown in Figure 1. This was within the landing gear limit load defined for a touchdown which was a rate of descent of 10 ft/sec at a maximum landing weight of 14,900 lb (6,758 kg). The normal acceleration at touchdown, after correcting for a maximum accelerometer drift of 0.04 g, was established as 1.72 g which was the highest recorded normal acceleration at touchdown from the 20 flights recorded on the DFDR.

System description

Main landing gear

The main landing gear was designed to meet the structural requirements of BCAR Section D with a limit load that equates to a maximum landing weight of 14,900 lb (6,758 kg) at a descent rate of 10 ft / sec. The landing gear legs are overhauled every 10,000 cycles or six calendar years after the previous overhaul.

Each main landing gear leg consists of a cylinder, manufactured from DTD 5094 aluminium alloy, and an inner sliding tube assembly on which the single wheel

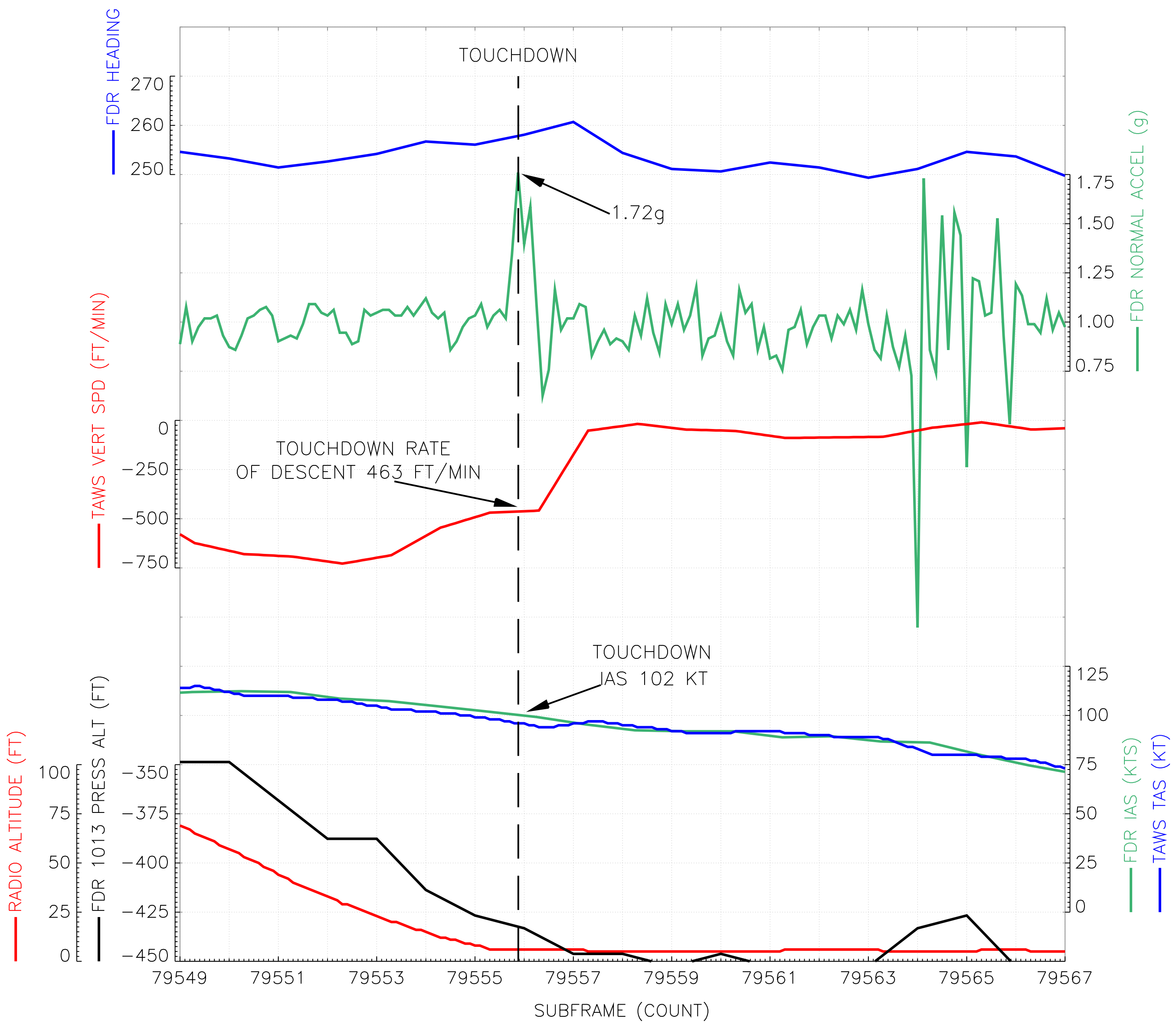

Figure 1

Flight data recorded during the landing

and brake assembly are mounted. The landing gear radius arm (retraction jack) is connected to the cylinder and incorporates the down-lock microswitch.

The landing gear is attached to the airframe by trunnions that fit into steel spigots bolted to the inside of the cylinder yoke pintles which form part of the cylinder. The upper surface of the forward yoke pintle is machined to introduce a weak link that, in the event of the landing gear being subjected to a force outside its design limits, will fail and allow the landing gear to detach from the aircraft without damaging the fuel tanks. With the exception of the machined area, which is 9 mm thick, the wall thickness of the pintle is 17 mm. A sketch of the yoke pintle is shown in Figure 2.

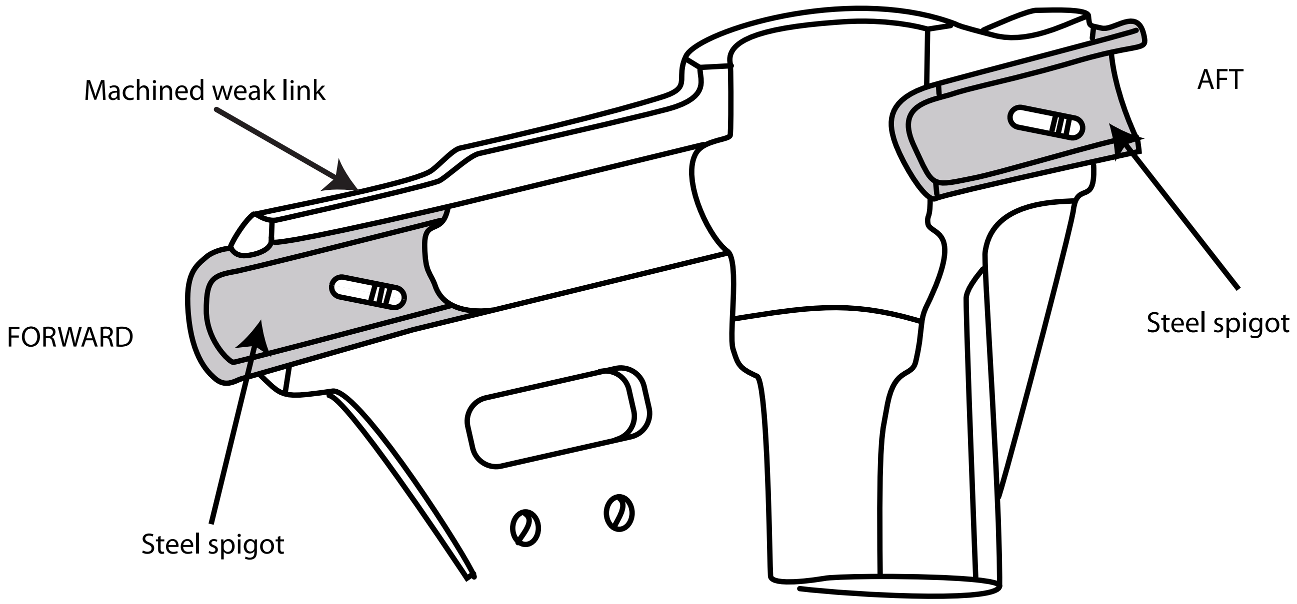

Figure 2

Sketch of yoke pintle

Stress Corrosion Cracking (SCC) had been identified in the forward yoke pintle housing of a main landing gear in 1985, following which an Airworthiness Directive (EASA AD G-003-01-86) and Mandatory Service Bulletin (SB A-JA851226) were introduced requiring an eddy current and visual inspection of this area. This inspection is required every 1,200 cycles or within one calendar year of the last eddy current inspection. The visual inspection is required every 300 cycles or within three calendar months of the last visual inspection. The SB also requires the inspections to be carried out following a heavy or abnormal landing.

Whilst the Jetstream 32 landing gear is of the same design as the Jetstream 31, it is manufactured from Aluminium Alloy L161 which is not as susceptible to intergranular corrosion and SCC.

Feather / emergency shut off levers

Two feather / emergency shut-off levers are situated towards the rear of the centre console and provide a rapid means of shutting off the fuel to the engines, feathering the propellers and inhibiting the engine starting system. The feather levers are operated by turning the handle clockwise by 90° such that a key on the shaft of the feather lever aligns with a slot in the hole in the console through which the lever passes. The lever can then be extended to the FEATHER position. The feather lever is spring-loaded counter-clockwise, such that when it is released the key will lock on the edge of the hole in the console. In the aircraft manuals this action is described as '*locking the lever in the detent.*' This feather lever and locking arrangement is also used on the Jetstream 32 aircraft.

Pulling the feather lever from the NORMAL to the FEATHER position performs the following actions:

- Manually, through a system of cables and control rods, closes the HP fuel cock
- Manually, through a system of cables and control rods, operates the propeller Feather Valve
- A microswitch on the lever operates and the LP fuel cock is electrically closed (the crew can also close the LP and hydraulic cocks using switches on the overhead panel)
- A microswitch on the lever operates and the LP hydraulic cock is electrically closed
- A microswitch on the lever operates and inhibits the engine starting systems

When the feather valve opens, it stops the flow of oil from the propeller governor to the propeller pitch control sleeve and allows the oil in the propeller cylinder to drain into the engine case. The propeller will then feather under the action of the spring and counterweights.

If, after the propeller has feathered and the engine has been shut down, the feather lever is moved to the NORMAL position the propeller will not unfeather unless the unfeather pump is operated. The HP fuel cock will also stay in the CLOSED position until the engine start sequence is initiated. However, the LP fuel cock, which is controlled by a microswitch, will move to the OPEN position and fuel can then flow from the aircraft fuel tanks to the engines.

The inadvertent opening of the LP fuel cock could present a significant safety risk during an emergency such as a forced landing or engine fire.

Aircraft damage

During the accident sequence the right main landing gear forward yoke pintle failed with three large segments breaking away.

The right landing gear broke away from its trunnions as a result of the failure of the forward yoke pintle housing (see Figure 3). However, the landing gear remained attached to the aircraft by the radius arm and hydraulic pipelines. The down-lock microswitch fitted to the radius arm remained intact and, when electrical power was selected ON, all three green landing gear position lights illuminated.

The blades on the right propeller had been badly damaged and the right engine appeared to be distorted in its engine mounts. The right propeller feathering mechanism had been damaged when the propeller blades contacted the runway. The right aileron balance horn, wingtip and a section of the pannier had abraded away. There was some distortion to the right wheel well and flaps where the landing gear had broken away but was no evidence of a leak from the wing fuel tanks. The main cabin door and over-wing emergency exit both opened freely. Apart

Figure 3

Damage to right forward yoke pintle

from the failure of the forward yoke pintle on the right main landing gear, there was no visible evidence that the aircraft had sustained a heavy landing.

Aircraft weight

The landing weight of the aircraft was estimated to be 6,067 kg (13,375 lb). This was below the maximum landing weight of 6,745 kg (14,870 lbs).

Corrosion

Galvanic corrosion

Galvanic corrosion, which is also known as dissimilar metal corrosion, is the process by which two dissimilar metals, or alloys, come into contact with an electrolyte and oxidise or corrode. In this situation one of the metals acts as an anode and the other a cathode with the anode dissolving in the electrolyte. On the Jetstream 31 landing gear the aluminium alloy pintle would act as the anode and the steel spigot the cathode. Anodising aluminium components and cadmium coating steel components can help to prevent galvanic corrosion.

Stress Corrosion Cracking (SCC)

Stress corrosion cracking occurs when susceptible metals, or alloys, are subject to a continuing tensile stress above a threshold level in a corrosive environment. The initiation phase normally occurs when the surface protective finish has been compromised and the crack will then travel along the grain boundaries. Unless the stress is relieved, the crack will continue to grow over time until it reaches the critical crack length when the remaining metal will fail in sudden overload.

Intergranular corrosion

Like stress corrosion cracking, intergranular corrosion can initiate when the surface finish has been compromised. The grain boundaries often contain small particles of dissimilar alloying metals which are less corrosion resistant than the grains. So the corrosion occurs along the grain boundaries. Unlike stress corrosion cracking, intergranular corrosion does not require the presence of a tensile load.

Exfoliation Corrosion is a form of intergranular corrosion.

Metallurgy

As part of the investigation into the failure of the forward yoke pintle on G-CCPW, metallurgy examinations of the failed parts were carried out by QinetiQ and the Royal Navy's 1710 Naval Air Squadron, Materials Integrity Group.

The examinations established that the crack initiated at the top outer edge of the forward yoke pintle and extended along the top of the pintle for approximately 120 mm before final failure occurred. (See Figure 4.) The first 10 mm of the crack was heavily corroded and lighter deposits of corrosion were found along the remainder of the crack. Scanning Electron Microscopy (SEM) of the first 10 mm of the crack showed evidence of intergranular failure consistent with SCC. A microsection taken through the outer 35 mm of the pintle identified branching crack growth which is also characteristic of SCC. Beyond the first 10 mm the crack failed as a result of overload.

The anodised layer on the end of the pintle had been disrupted, possibly as a result of rubbing against the bearing cap that secures the leg to the aircraft, leaving the end grain of the metal exposed. A dark stain approximately 60 mm long and 2 mm deep ran along the inside face of the failed section of the pintle. A section taken along the stain, approximately 12 mm from the end of the pintle identified the presence of intergranular corrosion which extended 0.13 mm into the pintle. It

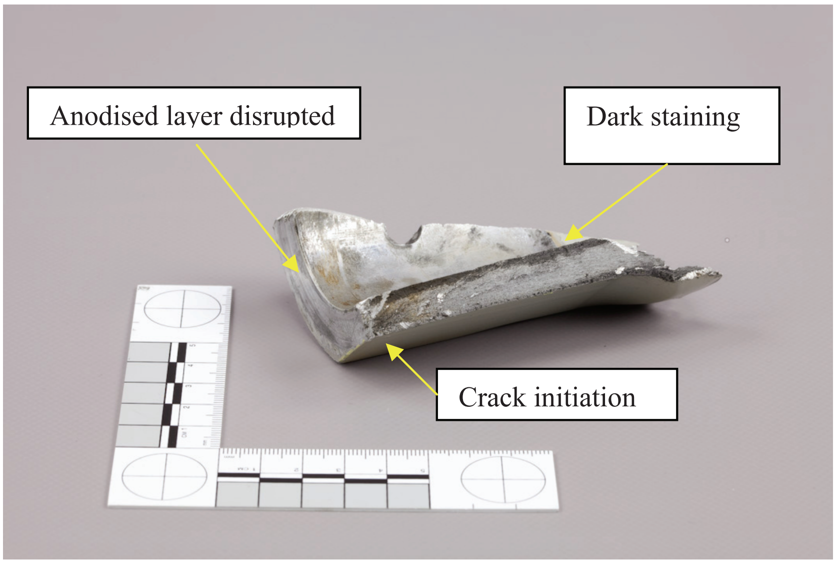

Figure 4

Failed section of forward yoke pintle

was also noted that the metal grain at this position flowed from the inner to the outer surface shown in Figure 5. This is probably due to the 'flash line' which is formed when the metal is forced out of the die during the manufacturing process.

Corrosion was also found on the steel spigot, (see Figure 6), and there was visible staining on the inner face of the yoke pintle that was in contact with the corroded areas of the steel spigot. Dye penetrant and visual examination of the stained area, using high magnification devices, revealed the presence of numerous defects, the majority of which were less than 0.5 mm across. Microsections taken from this area determined that these defects were not stress-driven, but were consistent with intergranular corrosion. A smaller number of these

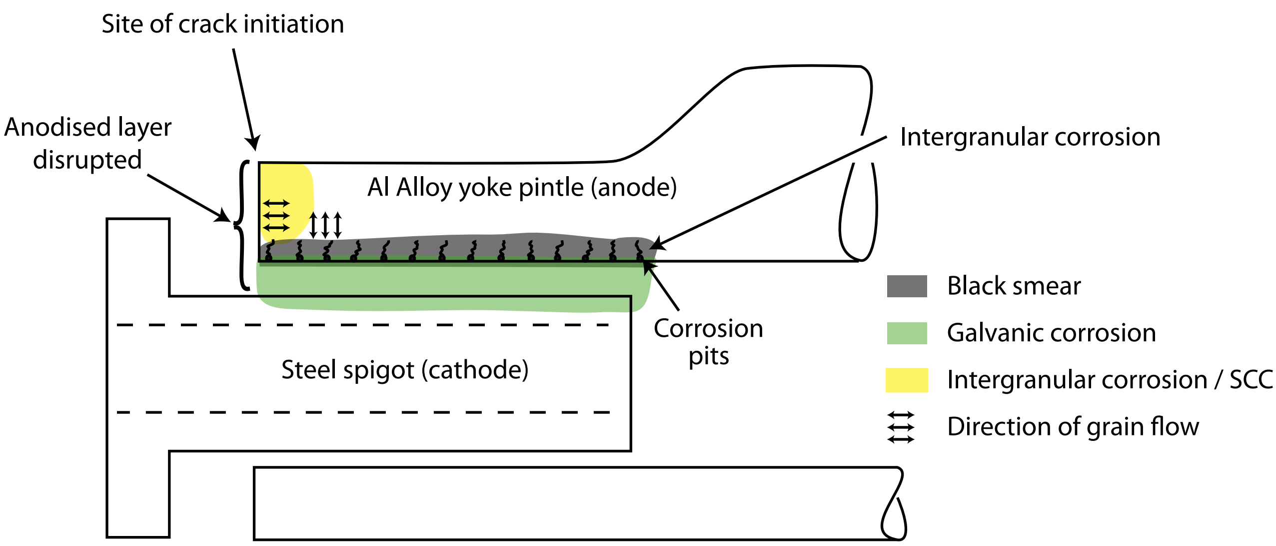

Figure 5

Defects found on forward yoke pintle

defects were also identified on the inner surface of the forward yoke pintle on the left landing gear. Energy-dispersive X-ray spectroscopy (EDX) of the fracture surface of the crack in the yoke pintle identified the presence of cadmium that had leached into the crack from the corroded steel spigot. It was determined that the dark stain along the inner face of the pintle was the result of fretting debris and dirt that had been drawn into the crack. This indicates that this section of the crack must have existed prior to the final failure of the yoke pintle.

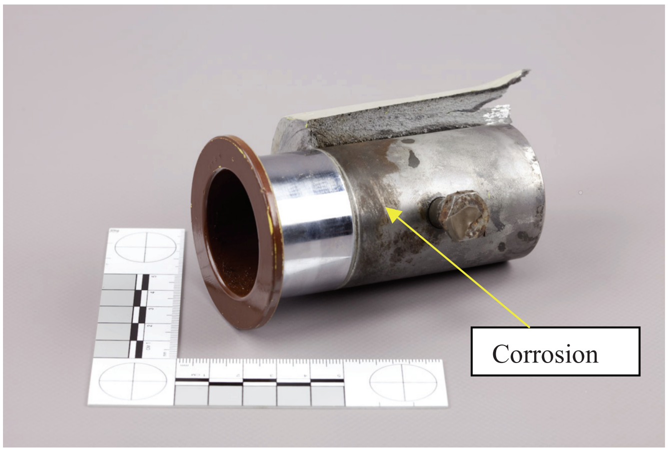

Figure 6

Corroded areas on steel spigot

Maintenance history

Main landing cylinders

Both landing gear cylinders had last been overhauled in July 2009 and fitted to G-CCPW in August 2009. The maintenance organisation that carried out the overhaul advised the investigation that the paint had been removed prior to the NDT inspections. No damage had been found and no repairs had been carried out to either cylinder. At the time of the accident they had been subjected to 1,445 cycles.

Since being fitted to G-CCPW, eddy current inspections of the pintle on both landing gear legs had been carried out on 30 March 2010 and on 13 May 2011, 743 cycles prior to the accident. The last visual inspection was carried out on 26 February 2012, 29 cycles prior to the accident. There was no record of any damage having been found during these inspections. The aircraft operator also advised the investigation that they had no reports of the aircraft having sustained a heavy landing.

Feather levers

A 200-hour maintenance check, which included a functional check of the feather levers, was carried out on 21 November 2011, 173 hours and 269 cycles prior to the accident.

Other reports of cracking in the yoke pintle

Royal Air Force (RAF)

The RAF discovered cracks in the forward yoke pintles of landing gears fitted to their Jetstream T Mk 1 aircraft on three occasions between 1980 and 1987. Although not identical, the landing gear is of a similar design, is made from the same material and has the same overall dimensions as that fitted to the Jetstream 31.

Registration XX493

In 1980, a crack 127 mm long was discovered on XX493 during other work. The crack appeared to have originated from a number of intergranular corrosion cracks growing from the outer edge of the pintle. Fatigue banding was found at the end of these cracks. Photographs of the crack, after it had been opened, show evidence of dark staining similar to that seen on the failed yoke pintle fitted to G-CCPW. Two years prior to the discovery of the crack, the aircraft had been used for crosswind landing trials.

Registration XX491

In 1985 a crack approximately 160 mm long was found in the yoke pintle on the left main landing gear fitted to XX491; the aircraft had had a runway excursion five months and 478 landings earlier. The crack initiated on the outer edge of the face of the forward pintle and extended along the upper machined face for 130 mm when it then split into two branches that were 25 and 30 mm long. There was no evidence of fatigue and the failure did not appear to have been caused by overstress produced by a heavy landing. Examination of the crack found evidence of intergranular cracking and exfoliation along the inside of the bore, halfway along the crack. In addition, there was a 'dried mud' feature at the start of the fracture. There were also reports of a 'black' deposit on the surface of the crack, predominately at the outer edge and along the inner face of the pintle. The deposit was identified as hydraulic fluid containing particles of aluminium alloy and nitrile rubber – no corrosion ions were detected. SEM examination indicated the presence of stress corrosion cracking that the investigation concluded was driven by residual stresses introduced during the manufacturing process.

In 1987 a crack approximately 120 mm long was found in the forward yoke pintle in the landing gear that was fitted following the discovery of the crack in 1985. The investigation determined that crack was caused by SCC and the crack originated at the outer corner of the end face of the pintle. There was no evidence of the 'dried-mud' feature that had been observed during the previous occurrence. It was believed that the SCC most probably extended for no more than 5 mm, which then resulted in a subsequent rapid failure from a dynamically applied load. The investigation also concluded that a breakdown of the corrosion protection allowed inter-crystalline corrosion to propagate with subsequent crack propagation by SCC. The leg had flown a total of 10,289 landings and had last been overhauled 9 months and 2,622 landings prior to the discovery of the crack. During overhaul, corrosion had been removed from the end face of the pintle. The last eddy current inspection had been carried out 31 flights previously.

Registration XX494

As a result of the findings on XX493 and XX491 in 1984, the RAF inspected the yoke pintles on XX494 using an eddy current technique. The examination revealed small defects on the end face of the forward yoke pintles on both landing gear cylinders that had resulted from 'end grain' corrosion. They also identified that the protective treatment (anodised layer) on the end face of the pintle housing had been worn away.

Civilian Jetstream 31, registration SX-SKY

On the 12 February 2009 the forward yoke pintle on the right main landing gear fitted to SX-SKY failed on landing. The landing gear had flown 23,940 cycles since new and had been overhauled 148 landings prior to the accident. The aircraft landing weight was calculated to be 14,870 lb, which was within the maximum limit of 14,900 lb, and the FDR recorded a normal acceleration on landing of 1.79 g. A review of the data on the FDR identified two possible heavy landings of 2.5 g and 2.87 g that had occurred 5 and 27 landings prior to the accident.

The pintle on SX-SKY had failed in the same location as on G-CCPW. Although the final failure was due to ductile overload, a crack appeared to have originated from a region of intergranular corrosion on the outer end face of the pintle. A dark stain was also evident along the inner edge of the fracture surface, similar in size to the stain on XX493 and G-CCPW. There was no evidence of SCC on any of the fracture faces.

Overhaul organisation

The two organisations that overhauled the landing gears fitted to G-CCPW and SX-SKY advised the investigation that they had never rejected a landing gear as a result of discovering cracks in the yoke pintle. However, the organisation that overhauled the legs from G-CCPW was aware of one operator who had discovered cracks during the mandatory inspection of the pintle.

Findings reported to the aircraft manufacturer

The aircraft manufacturer and the landing gear design authority have advised the investigation that they have received no reports of cracking found during the mandated inspections detailed in SB A-JA851226. This is possibly due to the fact there is no repair scheme for cracks in the pintle, or requirement to report any findings to the aircraft manufacturer.

Use of eddy current inspection to detect cracks in the yoke pintle

Principle of crack detection using eddy current examination

Eddy current inspection uses a probe that generates an electromagnetic field that causes eddy currents to develop in the material being inspected. The strength of the eddy currents is sensed by the probe and can be presented to the operator on a display, or used to drive a needle on a gauge. Surface and near-surface cracks will alter the flow of the eddy current and produce a change on the operator's display. However, the operator is required to calibrate the equipment for the size of the crack being inspected and to compensate for the 'edge effect', which occurs when the probe is positioned close to the edge of the material. While the presence of a surface crack is seen as a change in the display, intergranular and SCC, which has not broken through the surface, can give a more subtle change which the operator might mistake as a change in the material properties. Even if the crack is surface-breaking, the branching nature of intergranular and SCC, and the possibility of numerous adjacent cracks, may give a more subtle, diffuse response than that of a sharp crack. Such a situation may occur on the end face of the pintle.

Following the discovery of cracks in the forward yoke pintles on RAF Jetstream 31 aircraft, the aircraft manufacturer established that a minimum crack length of 1.57 mm was required to initiate steady crack growth. Once the crack reached 1.57 mm it would then grow steadily to 6 mm in approximately 120 days at which point it would become critical and fast fracture would occur[2]. Once the crack had developed beyond 6 mm the pintle could fail under normal operating loads. The RAF determined that, due to edge effects, an eddy current technique would not be suitable for detecting cracks of less than 2.5 mm as the crack would be approaching its critical crack length before it was likely to be discovered.

Minimum detectable crack length

As part of this investigation, QinetiQ undertook a review of the eddy current technique called up in SB A-JA851226 to detect cracks in the pintle housing. The review considered a United States Air Force (USAF) assessment[3] of a high frequency eddy current technique

Footnote

[2] The nominal 6 mm is based on the manufacturer's assumed residual stress in the forging. Different forgings may result in different residual stresses.

[3] "Nondestructive inspection capability guidelines for United States Air Force aircraft structures." Structures Bulletin EN-SB-08-012, Rev B.

of up to 2 MHz. The USAF assessment determined that, using this technique, a reasonable minimum size for a detectable crack is 6 mm in length and 3 mm deep on a machined flat surface, and 13 mm by 6 mm respectively on a radius. Moreover, the crack should be detected 90% of the time with 95% confidence. QinetiQ also advised that, using this technique, SCC may be more difficult to detect than fatigue-initiated cracks. This is because of reduced local conductivity in the corroded region, due to the presence of a layer of non-conducting corrosion product, and the resulting rough surface of the parent material. Of more significance is that the eddy current response from surface-breaking corrosion pits could desensitise the operator to actual crack indications.

Detection of SCC and intergranular corrosion

During the investigation into the cause of the cracks on G-CCPW, a Level 3 NDT technician was tasked with inspecting both landing gear forward yoke pintles using an eddy current and dye penetrant technique. The operator was initially unable to detect the SCC, intergranular corrosion and pits on the inner bore of the yoke pintle until the metallurgists had advised him of the location and nature of the damage.

Feather levers

Following the accident, and before the aircraft had been moved, the propeller feather levers were found in the positions shown in Figure 7. The left engine feather lever was in the fully extended FEATHER position (63 mm) and the key on the lever was locked in the hole in the console; the right engine feather lever was found in a partially extended position (32 mm).

Examination of the right engine HP and LP fuel cocks established that they were both closed. The left engine propeller blades were visually established as being in the feathered position. The pitch mechanism on the right engine propeller blades had been damaged when the blades repeatedly struck the ground and all the blades were found in a non-feathered position. After the aircraft had been moved to a hangar, the aircraft battery power was selected ON; the left LP fuel cock indicator on the roof panel illuminated SHUT and the right indicator illuminated OPEN. The microswitch at the base of the lever was heard to operate when the right lever was pulled out by 33 mm and at the same time the right LP cock indicator changed to SHUT.

The dimensions of the holes in the console, through which the feather levers pass, are specified in the aircraft drawing as 0.500” +.01” (12.7 mm +0.25 mm), which gives an upper tolerance of 12.95 mm. On G-CCPW the left hole was found to be 13.35 mm and the right hole was found to be 14.61 mm. The detents on both feather levers were found to be 13.97 mm, as specified in the aircraft drawings.

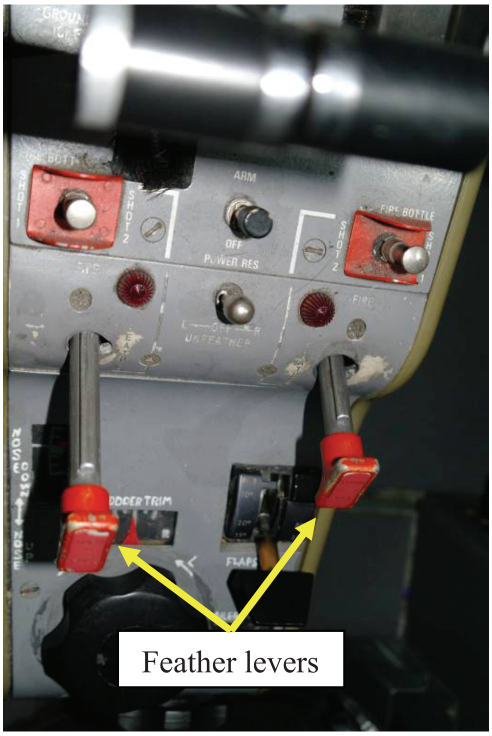

Figure 7

Position of feather leavers after accident

While the hole for the left feathering lever was found to be worn, and outside the drawing tolerance, it was still sufficient to ensure that the left feathering lever could be locked in the extended position. However, at 14.61 mm the hole for the right feathering lever was 0.64 mm larger than the key; consequently the right lever would not lock in either the feathered (extended) or non-feathered (fully in) position and could be easily moved in and out without having to first rotate it clockwise by 90 degrees. The wear around the hole suggested that it had been in this condition for some time.

With regard to the feather levers, the Jetstream 31 Flight Manual requires that they are checked at the start of the first flight of the day to ensure that they engage the detent:

> *'Verify Feather Levers are fully down.*
>
> *## IF ……..first flight of the day:-*
>
> *Observe LEFT and RIGHT HYD and FUEL LP COCKS indicators show OPEN.*
>
> *Turn and pull FEATHER levers to engage detent and observe LEFT and RIGHT HYD and FUEL LP COCKS indicators show SHUT.*
>
> *Push stop and feather levers fully down and observe LEFT and RIGHT HYD and FUEL LP COCKS indicators show OPEN.'*

The aircraft and engine maintenance manuals require the airframe emergency feather / fuel shut off systems to be operated every 200 hours and, at the 'A' check, *'to determine if the engine feathering valve and fuel shut off valve have actuated'*. However, the procedure[4] does not require personnel to check that the key on the feather lever locks in the hole in the console.

Footnote

[4] Maintenance Manual TPE331-10 (Report No 72-00-42).

The first flight of the day checks were discussed with the aircraft commander. He believed that the primary purpose of the check was to ensure that the LP Fuel and hydraulic cocks closed when commanded and that there were no control restrictions. The technique used to conduct the checks began with the crewmember looking at the overhead panel to note the valve indications. While continuing to observe the overhead panel, the lever was turned and pulled, the valve position indicator change noted before the lever was restored to its starting, flush position. Although individual techniques would vary, it appears likely that flight crew do not remove their hand from the lever whilst it is in the extended position.

Analysis

General

Audio analysis of the CVR, witness marks on the runway and the location of the debris indicates that the right forward yoke pintle failed when the aircraft touched down. The available evidence indicates that the aircraft was being operated within its maximum landing weight and the rate of descent was within the certification standard for the main landing gear.

Failure of the forward yoke pintle

From the available information on the cracks found in the forward yoke pintles on five different main landing gear cylinders, and the defects found on the end face of the yoke pintles on both landing gear fitted to XX494, it would appear that the cracks probably initiated as a result of disruption of the anodised layer on the end face of the forward yoke pintle as a result of it rubbing against the bearing cap. The end grain of the metal would then be exposed to the elements and cracks would start to grow as a result of intergranular corrosion. However, the dark (black) stain reported on the inner surface of a number of occurrences indicates that the rapid crack growth, due to overload, was arrested for a sufficient period of time for capillary action to draw debris into the crack before it then rapidly grew to failure. The investigation determined that there are probably two failure mechanisms that could have resulted in the failure of the yoke pintles:

Stress corrosion cracking. The crack is initiated as a result of intergranular corrosion growing from the exposed end grains. Internal residual stresses from the manufacturing process would cause SCC to develop and the crack would continue to grow to a nominal 6 mm. The stress resulting from the normal landing loads would then be sufficient to cause the crack to grow rapidly in overload, until either the yoke pintle fails or the crack is arrested by the increased wall thickness. If the crack is arrested, then debris would be drawn into it, creating the dark stain, until the stress resulting from normal landing loads is sufficient to drive the crack to failure. It should be noted that once the crack exceeds a nominal length of 1.57 mm, the residual stresses will be sufficient to cause the crack to grow; the aircraft manufacturer estimated that it would take 120 days for the crack to grow from 1.57 mm to 6 mm. The cracks could become critical at a shorter length if subjected to a high load such as may occur in a heavy landing. This failure mechanism is dependent on the materials susceptibility to SCC. The failures of the three yoke pintles on XX491 and G-CCPW appear to have been caused by this failure mechanism.

Intergranular corrosion followed by overload. The crack is initiated as a result of intergranular corrosion and grows to approximately 1.57 mm. The crack then propagates in overload. The lack of any evidence of SCC in some previous accidents suggests that the cracks in these pintles had grown to less than 1.57 mm before failing in overload as a result of being subject to a large load, such as might occur in a heavy landing. The lack of any evidence of SCC suggests that this was the failure mechanism that occurred on XX493 and SX-SKY.

Defects in the bore of the yoke pintle

The corrosion on the steel spigot and staining of the walls in the bore of the yoke pintle was most probably caused by surface corrosion that compromised their cadmium and anodising layers. Galvanic action might then have accelerated the corrosion. It is not known how the electrolyte entered the space between the two components, but it might have been drawn in through a crack in the yoke pintle or as a result of wear between the spigot and pintle.

It is believed that the manufacturing process resulted in the end grains in the area of staining being oriented towards the inner surface. The pitting from the surface corrosion would have compromised the anodised layer and exposed these grains allowing the onset of intergranular corrosion. During the investigation, the depth of the intergranular corrosion on the walls of the bore was only measured at one location and found to be around 0.130 mm deep. While this defect was unlikely to have significantly affected the strength of the yoke pintle on G-CCPW, the investigation was not able to determine how fast the intergranular corrosion would propagate and the effect it would have on the structural integrity of the pintle. The report of exfoliation corrosion having been found on the bore of the yoke pintle fitted to XX491, and the defects found on the left cylinder fitted to G-CCPW, indicates that intergranular corrosion has occurred in this area before.

Currently there is no requirement to remove the steel spigot and examine the bore of the yoke pintle between overhaul periods on the landing gears fitted to Jetstream 31 aircraft. To conduct an effective inspection of this area, it is likely that the spigot would have to be removed. However, such a maintenance activity could damage the cadmium coating on the spigot and the anodised layer on the pintle thereby initiating corrosion by another mechanism and the relative risks of this process would need to be considered. However, the following Safety Recommendation is made:

Safety Recommendation 2012-024

It is recommended that BAE Systems Regional Aircraft consider the introduction of a routine inspection on the main landing gear fitted to Jetstream 31 aircraft to detect and monitor the presence of intergranular corrosion in the bores of the yoke pintles.

Detection of cracks in the bore

EASA AD G-003-01-86 mandates non-destructive testing and visual inspections to identify cracking in the forward yoke pintle housing on landing gears fitted to Jetstream 31 aircraft, with eddy current examinations carried out annually and visual examinations every three months. The heavy corrosion deposits at the start of the crack and previous reports of a 'dried mud' appearance indicate that intergranular corrosion can be be present for some time before the crack starts to grow beyond the first few millimetres.

Previous work undertaken by the aircraft manufacturer established that once the crack reaches 1.57 mm in length it could then grow, as a result of internal stresses, to 6 mm within 120 days. Once it reaches a length of 6 mm it could then fail in overload as a result of normal landing loads. The RAF previously advised that eddy current examination was not suitable for detecting cracks of less than 2.5 mm and the USAF assessment was that a 'reasonable' minimum detectable crack length was 6 mm with a 90% probability of detection. The visual inspection of the yoke pintle is undertaken every three months with the landing gear still fitted to the aircraft. However, given the restricted access, and modern flexible paint finishes, it is not certain that a crack in the yoke pintle would be detected before it reached the critical length of 1.57 mm.

As the current inspection requirements did not detect the crack in the forward yoke pintle before it failed on G-CCPW, the following Safety Recommendation was made to the European Aviation Safety Agency on 23 March 2012:

Safety Recommendation 2012-008

It is recommended that the European Aviation Safety Agency review the effectiveness of Airworthiness Directive G-003-01-86 in identifying cracks in the yoke pintle housing on landing gears fitted to Jetstream 31 aircraft.

Feather lever

The worn state of both feather lever detents played no part in the outcome of this accident. However, the inability to lock the lever in the FEATHER position has a safety implication in that it might inadvertently move towards the normal position and open the LP fuel cock.

The check at the start of the first flight of the day required the lever to be pulled to '*engage detent*' but did not make it clear that the lever should lock fully out. The commander believed that the primary purpose of this check was to ensure that the LP Fuel and hydraulic cocks closed when commanded and that there were no control restrictions. The check required the crew to monitor the overhead panel and operate the lever by feel; consequently they may not have noted that the detent was ineffective. Similarly the maintenance checks did not specifically require the functioning of the detent to be checked. Therefore the following Safety Recommendation is made:

Safety Recommendation 2012-025

It is recommended that BAE Systems Regional Aircraft review the functional checks of the feather lever detailed in the Flight Manual and Maintenance Manuals for Jetstream 31 and Jetstream 32 aircraft to ensure that a routine check on the positive locking of the lever in the detent is conducted.

As an interim measure, the manufacturer issued a Notice To Aircrew (NTA J31 007-1) on 30 May 2012, reminding crews of the correct operation of the feather levers.

AFRS response

The AFRS response was immediate, effective and proportionate. However, the ATCO was unsure if the crash alarm had worked and, as is common during high workload periods, the short delay between the crash alarm being pressed and the AFRS deploying was perceived by the ATCO as being much longer than it actually was. The lack of a feedback mechanism resulted in the ATCO attempting to phone the AFRS to confirm activation of the alarm. The AFRS, understandably, did not stop their deployment to answer the phone call and the ATCO was only satisfied when he saw the fire station doors opening. The period following an accident is one of very high workload and this uncertainty could be a distraction. In low visibility the ATCO would not have been able to see the fire station and so a mechanism to provide feedback that the crash alarm had activated would be essential. Therefore the following Safety Recommendation is made:

Safety Recommendation 2012-026

It is recommended that the Isle of Man Airport provide a feedback system to allow the Air Traffic Control Officer to be certain that the Airport Fire and Rescue Service have received and are responding to a crash alarm from the tower.

Shut down and evacuation

The commander's radio call, that he thought a tyre had burst, did not reflect the circumstances of the accident but, with all three landing gear green lights still illuminated his diagnosis was understandable. He was aware that the visibility was good and that the aircraft was in direct line of sight of the control tower. This led him to decide there was no need to provide further information and to concentrate on shutting down and disembarking the aircraft. As both ATC and the AFRS had witnessed the accident, the commander's radio call had no effect on their response to the event.

Once the aircraft stopped the commander instructed the co-pilot to "GET THEM OUT". The operator's *'on ground emergency'* or *'emergency evacuation'* checklist would have been appropriate but were not used. The shut down and disembarkation that followed did not follow any scripted procedure precisely but were accomplished safely and effectively.

After being instructed to do so by the commander, the co-pilot took responsibility for the cabin. When interviewed, more than one passenger commented that the co-pilot's control of the evacuation ensured that everyone de-planed in an orderly fashion and sustained no additional injuries.