SERIOUS INCIDENT

Aircraft Type and Registration:	Boeing 747-436, G-CIVK
No & type of Engines:	4 Rolls-Royce RB211-524G2-19 turbofan engines
Year of Manufacture:	1997
Date & Time (UTC):	23 August 2008 at 2120 hrs
Location:	Heathrow Airport, London
Type of Flight:	Commercial Air Transport (Passenger)
Persons on Board:	Crew - 19 Passengers - 293
Injuries:	Crew - None Passengers - None
Nature of Damage:	Damage to No 7 wheel bearing, hub and axle
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	50 years
Commander's Flying Experience:	8,500 hours (of which 6,000 were on type) Last 90 days - 185 hours Last 28 days - 36 hours
Information Source:	AAIB Field Investigation

Synopsis

During taxi to Runway 27R, a wheel fire on the incident aircraft was seen by the crew of another aircraft who reported it to ATC. The commander of the incident aircraft brought it to a stop and requested the assistance of the fire service. When the fire service arrived, they saw smoke emanating from the No 7 wheel but no fire. The wheel was removed and the aircraft towed to a stand where the passengers were disembarked.

The cause of the fire was attributed to a failure of the outer bearing in the wheel; this resulted in a loss of support and caused the rotating wheel hub to rub against the axle. The cause of the bearing failure could not be conclusively established, but improper wheel installation, or an inadequate bearing inspection during the last tyre change, were possible factors.

History of the flight

The aircraft was pushed back from stand 407 at 2105 hrs for a flight to Bangkok. The aircraft's weight was 370,200 kg, which was 27,000 kg below the aircraft's 396,893 kg maximum takeoff weight. After engine start, the aircraft taxied on a heading of 045° and then made a left turn to 270° onto Link 44. This was followed by a right turn back to 045° onto Link 43, in order to cross Runway 27L for a departure from Runway 27R. After crossing runway 27L at N4E, and taxiing along Link 29, a pilot from a nearby aircraft reported to the ground controller that a Boeing 747 on his right had a wheel fire.

The commander of G-CIVK established that this report was referring to his aircraft so he immediately requested the airfield fire service to attend and inspect the aircraft. The commander brought the aircraft to a stop at Link 23, about 0.7 miles north-east of the N4E Runway 27L intersection, at 2121 hrs. There were no warnings or cautions notifying the crew of a problem but, when the commander examined the EICAS[1] 'gear' synoptic page, he noticed that there was no tyre pressure reading for the No. 7 wheel and that the brake temperature for the wheel was slightly elevated; indicating level '2', where '0' is cold and '9' is hottest. All the other wheels were indicating normal tyre pressures and a brake temperature of level '0'. The cabin crew were briefed for a possible evacuation.

When the fire service arrived at the aircraft, they saw smoke emanating from the rear outboard wheel of the left body landing gear (the No. 7 wheel) but no fire. The wheel was left to cool while one fire-vehicle remained to monitor the situation. Engineers from the operator arrived at the scene and discovered that the No 7 wheel bearings were missing and that there was extensive damage to the wheel hub and axle. The left body landing gear was jacked up and the damaged wheel removed; the aircraft was then towed to a new stand where the passengers disembarked.

A ground surface inspection by the airport operator revealed that the wheel's hub cap and some bearing rollers were located just north of the N4E Runway 27 intersection, with additional roller bearings and swarf being found further along taxiway Link 29, Figure 1. These parts were collected and passed to the aircraft operator. No debris was reportedly found on Runway 27, although a sweeper was used to clean the area and the taxiways after the incident and any debris collected was lost. Approximately six aircraft landed on Runway 27 between the time that it was crossed by G-CIVK and the time that the runway was closed for inspection.

Wheel installation

The main wheels on the Boeing 747-400 are mounted on the axle as shown in Figure 2. The Tyre Pressure Indication Sensor (TPIS) and hub cap are omitted from this diagram. When the wheel is delivered to the operator the bearings, grease seals and retaining rings are already installed inside the wheel. The operator slides the wheel onto the axle and then adds the washer and tightens the axle nut. Both the inner and outer bearings are tapered roller bearings and the outer race or 'cup' of each bearing is a press-fit inside the wheel hub and remains inside the hub when the tyre is replaced by a wheel maintenance organisation. The inner race and roller bearing cage or 'cone' of each bearing is removed during each tyre change, inspected and, if deemed serviceable, re-greased and re-installed in the wheel.

The Aircraft Maintenance Manual (AMM) for the wheel installation specifies that an initial axle nut 'seating torque' of 450 to 525 lb.ft is to be applied with the axle washer properly seated against the axle shoulder, in order to seat the bearing cups and cones into their respective abutments and seats. The wheel should be rotated by hand when applying the seating torque, then stopped and the nut loosened to 10 to 100 lb.ft, before being rotated again while applying the final 'flying nut torque' of 150 to 250 lb.ft. Two lockbolts are then inserted to prevent loosening of the nut and, if necessary, the nut can be tightened to a maximum of 250 lb.ft in order to align the lockbolt holes.

Footnote

[1] Engine Indication and Crew Alerting System (EICAS) is a digital multi-function display.

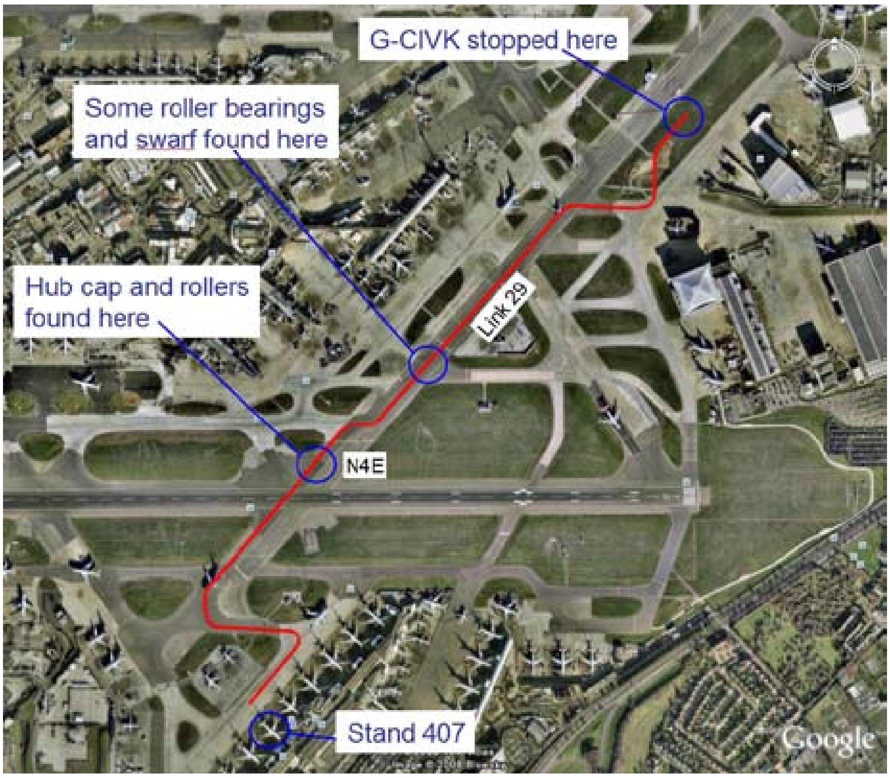

Figure 1

Estimated aircraft ground track based on starting position, the Flight Data Recorder heading parameter and eyewitness reports. The radii of turns are not representative. (Grass is depicted in the area that G-CIVK stopped, but a new taxiway now exists in this area.)

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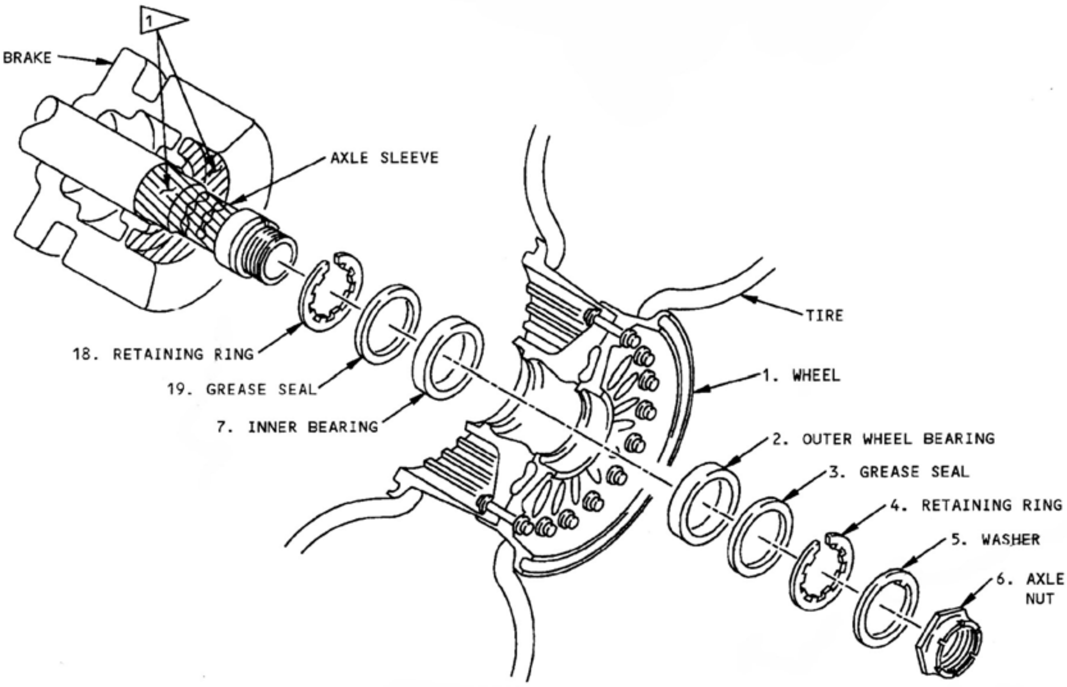

Figure 2

Boeing 747-400 main wheel bearing installation diagram

Examination of the damage

The debris recovered from the taxiways included the hub cap, part of the TPIS in-axle assembly with a severed cable, rollers, parts of the retaining rings and broken pieces of outer bearing cone. The axle nut was found seized to the axle. Both axle nut lockbolts were reportedly in place and were removed by the operator's engineers, although one of these was subsequently lost. The remaining lockbolt was bent with a sheared shank, indicating that it was installed at the time of the failure. The washer was in place but had been flattened, Figure 3. The upper surface of the axle sleeve was in good condition but the lower surface had been partially abraded away; discolouration associated with high temperatures and evidence of molten metal was present, Figure 4. There were large deposits of molten aluminium alloy from the wheel hub inside the brake-liner heat shield, and the wheel hub was extensively damaged with loss of material both inside and around the outside hub circumference, Figure 5. The section of inner wheel hub that would have supported the inner cone had been completely removed. There was no evidence of inner bearing rollers or cage material inside the hub, although the inner bearing cone was found intact around the axle. There were no remains of outboard bearing rollers, roller cage or cone inside the wheel, although the outboard wheel bearing cup was still in place in the outboard hub, and this exhibited significant surface erosion

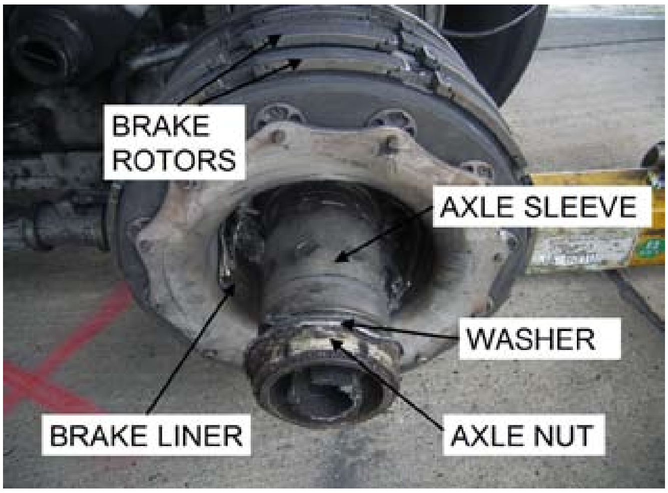

Figure 3

Damage to wheel axle

Figure 4

Damage to wheel axle underside (6 o'clock position)

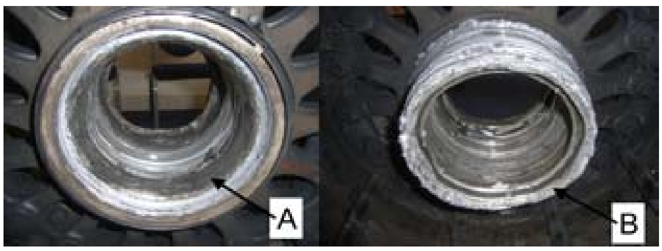

Figure 5

Left: Outer wheel hub showing remains of outer bearing cup (A).
Right: Inner wheel hub showing that at (B) the inner bearing hub support and inner bearing cup are missing.

Recorded data

The Cockpit Voice Recorder (CVR) recording for the incident had been overwritten, but the Flight Data Recorder (FDR) contained data for the incident. The FDR had recorded the aircraft's groundspeed and heading from which the approximate ground track in Figure 1 was established. The data showed that the No 7 wheel tyre pressure was indicating 200 psi (normal) during the pushback, and then the signal was lost about 1 minute and 15 seconds after start of taxi. This loss of signal occurred at the end of the aircraft's first turn from a heading of 045° to a heading of 270°. Since this loss of signal was attributed to the severing of the TPIS cable, it was established that the failure occurred during or prior to the first taxi turn, and therefore prior to the aircraft crossing Runway 27L. The peak lateral acceleration during this turn was recorded at -0.1g at a groundspeed of about 10 kt. Five and a half minutes later, at time 2116:50, the No 7 wheel brake temperature started to rise from level '0' to level '2'. There were no other abnormal indications in the data.

The Quick Access Recorder (QAR) contained data for the aircraft's previous 12 landings. These were analysed by the AAIB and by the aircraft manufacturer. The highest peak normal acceleration at touchdown was 1.31 g, and this occurred during the aircraft's last landing. This corresponded to a sink rate at touchdown of 2.9 ft/sec. The highest peak lateral acceleration at touchdown was 0.24 g, and this occurred during the seventh-last landing during a crosswind. The aircraft manufacturer concluded that all of the landings analysed were within the normal range of touchdown acceleration and sink-rate parameters, and would not have contributed to a wheel bearing failure. The aircraft operator later carried out further analysis, using their stored data system, and were able to study the aircraft's landings dating back to 20 May 2008, when the No 7 wheel was installed. None of these landings exhibited vertical or lateral accelerations at touchdown that were significantly above normal.

Maintenance history

The aircraft had accumulated 53,549 hours and 6,012 cycles at the time of the incident. The subject wheel had been installed on the aircraft in the No 7 position on 20 May 2008, which was 95 days prior to the failure. During this period, the aircraft completed 134 cycles. The only recorded maintenance on the wheel after 20 May 2008 was the replacement of its TPIS sensor, and this would not have involved disturbing the axle nut or any part of the wheel installation.

The maintenance records for the wheel in question revealed that it was removed for the first time since new from aircraft G-CIVO, on 15 April 1998. As this aircraft was first registered on 5 December 1997, the wheel had been in service for about 11 years at the time of the failure. Between 15 April 1998 and the date of the incident, the wheel had been returned to a workshop for a tyre change on 26 occasions. The wheel itself had been overhauled twice, once on 27 November 2000 and again on 12 September 2004. On 26 February 2007, the wheel was returned for an 'IRAN' (Inspect and Repair As Necessary) occurrence, which could have been necessary because of a problem with the tyre, other than normal wear. The last tyre change occurred on 17 May 2008, three days prior to the wheel's installation on G-CIVK. The records did not reveal any history of abnormalities with the wheel, any bearing cup or cone changes, or of any repairs having been carried out in the bearing boss area. Thus, it was apparent that the bearings had probably been in service in the same wheel since 1997. The bearing parts are 'on condition', and therefore do not have a life limit.

Detailed examination of failed bearings

The wheel hub and bearing remains were taken to the aircraft operator's wheel workshop for detailed examination, under the supervision of the AAIB and an investigator from the bearing manufacturer. A total of 37 rollers were recovered and examined out of a total of 73 rollers; 37 are used in the inboard bearing and 36 in the outboard bearing. The rollers for the inboard bearing and the outboard bearing had the same part number, but it was possible to separate the rollers into two groups on the basis of a batch mark indentation (shaped like a house) present on some of their ends. This indentation revealed that the rollers were from a batch manufactured in 1995. The rollers without the indentation mark were blackened, and exhibited evidence of high temperature exposure and some minor plastic deformation (the lower row in Figure 6). Some of the rollers with the indentation mark were relatively undamaged and had not been exposed to high temperatures; others exhibited crushing damage (the upper row in Figure 6). The sliding ends of both sets of rollers were in good condition, which is an indication that lubrication was present. Also, the roller bodies had not elongated, which is an indication that failure occurred rapidly and at relatively low rotational speed.

Figure 6

Some of the recovered rollers from the outer bearing (lower image) and inner bearing (upper image)

Figure 7 shows new rollers installed in their cage and fitted around the cone.

The outer bearing cone had fractured into six large pieces (left image in Figure 8) and its race surface exhibited evidence of elevated temperatures. The inner bearing cone was recovered intact from the axle and did not exhibit evidence of elevated temperature (right image in Figure 8). The original ground surface was visible with

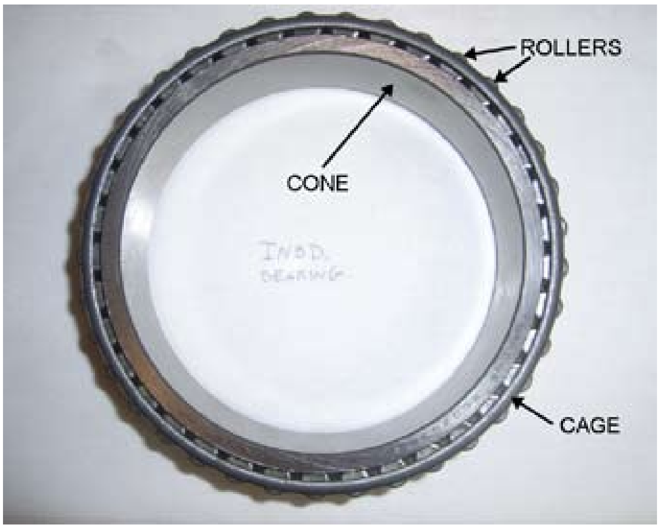

Figure 7

Example of a new inner bearing showing the cone, rollers and cage

deposits of smeared steel, probably originating from the cup, and smeared aluminium from the wheel hub. On the basis of the bearing cone evidence it was established that the rollers with the elevated temperature characteristics were from the outer bearing and the rollers without the elevated temperature signatures were from the inner bearing.

The bearing manufacturer's report concluded that the outer bearing was the first to fail, because the first bearing to fail normally generates the most heat, and that the failure probably occurred due to the outboard bearing cage becoming trapped between rollers and the rotating cup. The report stated that:

Figure 8

Damaged outer bearing cone (left) and inner bearing cone (right)

'This allowed the rollers to be released from the cage at low rotational speed. The absence of the rollers caused the cone to spin on the axle sleeve as the result of friction between the cone, a few trapped rollers and ultimately contact with cup and wheel. This friction generated heat and caused mechanical damage to the cone. The disintegration of the bearing allowed the wheel to collapse onto the brake pack and migrated outward, putting extreme loads onto the inboard wheel hub, subsequent overturning loads on this sliding aluminium to brake pack surface fractured the inboard cup support from the wheel.'

The report further stated that the known causes for a wheel bearing cage to become trapped between rollers and rotating wheel hub/cup were, in order of probability, as follows:

'1. Low axle nut torque – or incorrectly applied nut torque resulting in very small bearing load-zone and abnormal cage stress.

2. A bearing with a severely worn cage being returned to service.

3. Lack of grease causing roller wear and cage wear.

4. Massive radial shock load – very heavy landing.'

Examination of the wheel hub

The wheel hub was examined by the wheel manufacturer's metallurgical laboratory to determine, for example, if a fatigue crack in the inner bearing bore area had contributed to the bearing and hub failure. Following this examination, the manufacturer stated that they could not determine the actual pattern of failure of the structure supporting the inner bearing. However, they had not previously experienced any problems with fatigue cracking in that area and the wheel type had existed virtually unchanged in geometry since 1989. They said that if there had been a likelihood of fatigue cracking, they would have expected to have already witnessed such occurrences in older wheels.

Wheel bearing inspection process

The incident wheel's last two tyre changes had been carried out by a component engineering company that was relatively new to wheel maintenance. The company began maintaining Boeing 737 wheels in November 2007 and, in January 2008, took on maintenance of Boeing 747-400 wheels. The company had carried out the last two tyre changes on the incident wheel on 30 January 2008 and 17 May 2008 respectively.

When a 747-400 wheel arrives at the company for a tyre change, the inner and outer bearing cones are removed for cleaning and inspection, while the cups are cleaned and inspected in-situ. A detailed inspection of the rollers and cage is carried out prior to re-greasing and re-fitting to the wheel. The wheel hub also undergoes an NDT[2] inspection. The company's common practice is to keep the same cups and cones together, even though the component maintenance manual permits 'mix and matching'. The technician who carried out the last inspection of the bearings on the incident wheel had previously been a pneumatics engineer and had started his training on 'wheels and brakes' in October 2007. He completed the required one-day manufacturer's bearing inspection course on 1 November 2007. The

Footnote

[2] Non-Destructive Test (NDT).

bearing was also inspected and then installed in the wheel by a mechanic who had 10 years experience of working with wheel bearings for a previous employer.

The bearing inspection process in the wheel Component Maintenance Manual (CMM) calls for visual inspection of the bearing cup race, cone race, roller surfaces, cage, and inner diameter of the bearing cone. It includes diagrams showing examples of spalled areas on the rollers and race, and score marks on the ends of rollers that would result in a part being rejected. It also requires a check for nicks, dents, scratches, etched surfaces, stains and pitting, with references to what would be considered acceptable and what would require rejection. The CMM does not contain a 'cage shake test', which involves rotating the cage around the cup by hand and checking for play. The bearing manufacturer trains personnel to carry out a 'cage shake test' and, although they consider this to be an important test, it was not included in the CMM. However, the wheel maintenance company said that, despite this, they do conduct the test.

Following this investigation, the wheel manufacturer stated that they would amend their CMM to include the 'cage shake test', but that they did not believe the lack of this inspection would have contributed to the G-CIVK incident.

Wheel installation process

As previously mentioned, the wheel installation process involves first applying a 'seating torque', then loosening the nut and re-tightening to the 'final flying torque'. The aircraft manufacturer's AMM specified that the wheel should be rotated by hand during the tightening process but that the wheel should be stopped before the loosening process. However, the bearing manufacturer stated that it was also important to rotate the wheel during the loosening process. Information received from the bearing manufacturer stated that:

> *'Wheel rotation between the higher seating torque and the lower final torque is important. If this is not done, the bearings could be re-clamped at the higher seating torque value which could lead to roller end scoring and is cause for removal from service.'*

The operator of G-CIVK carried out wheel installations in accordance with the aircraft manufacturer's AMM and therefore did not rotate the wheel during loosening.

The aircraft manufacturer was contacted regarding the bearing manufacturer's recommended wheel installation procedure, but their view was that fleet experience did not justify any immediate revisions to the AMM procedure. They did not believe that the root cause of the G-CIVK incident was related to not having rotated the wheel during loosening. However, they stated that they would remain open to consideration of any further in-service data relating to the perceived advantages of rotating the wheel assembly while relieving the torque.

Previous 747-400 wheel bearing failures

The operator of G-CIVK had no record of any previous wheel bearing failures on their fleet of Boeing 747-400s. One incident occurred on a Boeing 767 in July 2006, where a wheel bearing failed, but this was attributed to the wheel having been installed without the washer. The aircraft manufacturer was contacted regarding previous Boeing 747-400 wheel bearing failures. They reported that they were aware of a few incidents where cracks in bolt holes were discovered during wheel overhaul, but not of any similar incidents to that of G-CIVK. In

July 2006, a main gear wheel separated from a 747-400 in flight, but this was caused by the axle nut lockbolts backing out of the axle nut and allowing the axle nut to loosen. In that case, it was suspected that the lockbolt/nut combination was being reused to the point where the self-locking feature of the nut was compromised.

Analysis

The AAIB investigated this incident as a serious incident due to the possibility of the aircraft having become airborne without the wheel failure being noticed. The flight crew were unaware of the problem during taxi, until the crew of another aircraft reported seeing a wheel fire. Had it been daylight, any flames might not have been as readily noticeable and it was possible that this could have resulted in the aircraft getting airborne with a wheel-well fire. There was an additional potential hazard to ground personnel in that the wheel could have detached after takeoff. Also, had any wheel or bearing debris been deposited on the runway, a further hazard would have been posed from FOD to landing and departing aircraft.

The evidence from the TPIS sensor failure on the FDR indicated that the bearing failure probably occurred during or prior to the first taxi turn, and therefore prior to the aircraft crossing Runway 27L. High landing gear/wheel loads can be imposed during push-back, so it is also possible that the failure initiated at that time. The FDR and QAR evidence from previous landings did not indicate that any abnormal loads had been sustained in its recent history, so operational factors were unlikely to have contributed to the failure of the wheel/bearings.

It was possible that the failure could have been initiated by a crack in the wheel hub, but no evidence or history of such a failure could be found. It was, therefore, most probable that failure initiated at a wheel bearing. The outer wheel bearing cone and rollers had experienced abnormally high temperatures, whereas the inner bearing cone and rollers had not; this suggested that it was probably the outer bearing that failed first. There was insufficient evidence to determine conclusively the cause of the outer bearing failure but, based on previous experience of bearing failure examinations, the bearing manufacturer thought that it was probably initiated by the cage becoming trapped between rollers. Four possible causes for this were cited: (1) low or incorrectly applied axle nut torque, (2) a worn cage being returned to service (inadequate inspection), (3) lack of grease causing roller or cage wear, and (4) a very heavy landing.

The FDR and QAR data discounted a very heavy landing as the cause. A lack of grease was a possibility, although the roller sliding ends were in good condition which is an indication that sufficient lubrication was present. Therefore, the most likely causes were incorrect wheel installation or an inadequate bearing inspection during the last tyre change.

The wheel was installed 95 days prior to the incident, so it was not possible to get an accurate recall of how the wheel was installed. The physical evidence revealed that the washer was correctly installed and the axle nut appeared to be in the correct position. It was also considered that at least one, if not both, lockbolts were installed. If there had been a gross under-torque during wheel installation, the wheel bearings would not have lasted for 134 cycles over the 95 day period; failure would normally have occurred immediately. However, it was considered possible that a bearing with a ‘flying nut torque’ that was slightly below requirements might incur damage and not fail until after a high number of cycles.

The second most likely possibility was that the bearing was returned into service during the last tyre change with a defect that went undetected. The technician who carried out the inspection was relatively new to the job, as was the company he worked for. Nevertheless, he had completed all the required training and there were no indications that there were issues with his workmanship. Furthermore, the mechanic who installed the bearing had significant wheel bearing experience with a previous employer.

The 'cage shake test' was missing from the wheel CMM, but the technician had been trained to carry out this test and it was company policy to carry out this test, so the fact that the procedure was missing from the CMM was probably not a factor in the incident. The wheel bearing manufacturer and aircraft manufacturer disagreed over the wheel installation requirement to rotate the wheel during loosening, and this could be a factor in premature wear of components, but there was insufficient evidence to indicate that it was a factor in this incident.