
ACCIDENT

Aircraft Type and Registration:	AS355F1, G-XCEL
No & Type of Engines:	2 Rolls-Royce (Allison) 250-C20F turboshaft engines
Year of Manufacture:	1985
Date & Time (UTC):	2 December 2003 at 1438 hrs
Location:	Hurstbourne Tarrant, near Andover, Hampshire
Type of Flight:	Private
Persons on Board:	Crew - 1 Passengers - 2
Injuries:	Crew - 1 (Fatal) Passengers - 2 (Fatal)
Nature of Damage:	Helicopter destroyed
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	51 years
Commander's Flying Experience:	7,800 hours (of which 1,322 were on type) Last 90 days - 81 hours Last 28 days - 18 hours
Information Source:	AAIB Field Investigation

Synopsis

The helicopter was engaged on a post-maintenance test-flight following the fitment of a newly-overhauled main rotor gearbox and combining gearbox. Eyewitnesses heard unusual noises coming from the helicopter before the tail boom apparently folded forward around the cabin. The helicopter then fell to the ground, catching fire on impact. All three occupants received fatal injuries. Examination showed that the two gearboxes and the main rotor had detached before impact. Subsequent investigation showed that the left freewheel showed clear evidence of slippage under load; the right freewheel also showed signs of slippage but not to the same extent.

It is concluded that a series of freewheel slippages followed by aggressive re-engagements led to the structural failure. The reasons for the slippage however, cannot be proven conclusively. Although it was found that the rollers forming part of the freewheel mechanism had come from a manufactured batch that had been coated using an incorrect process, no laboratory testing could reproduce any greater tendency for such a coating to cause slippage. The helicopter manufacturer recorded five incidents of slippage under load, coinciding with the introduction of rollers from this batch. Satisfactory performance of the freewheels resumed following the removal from service of the incorrectly coated batch of rollers.

History of the flight

Maintenance work had been conducted on the helicopter requiring the pilot to spend two days completing engine ground run tests with the two engineers who had carried out the work. On the morning of the accident the pilot carried out a short flight to check that the helicopter's handling was satisfactory and to examine the extent of a torque difference between the engines that had been identified during the previous ground runs. The two engineers were on board for the uneventful 17 minute flight.

Adjustments were made to the helicopter, by one of the engineers, to rectify the difference in torque. About an hour after landing the helicopter, with the same pilot and engineers on board, departed for a further airtest. The purpose of the flight was to confirm that the adjustments to balance the engine torques had been successful.

The air traffic controller's log recorded that the helicopter departed Runway 07 at Thrupton at 1430 hrs. At the time there was a light easterly wind, with good visibility and a cloudbase about 1,200 ft above the airfield. The helicopter was seen to take off and appeared to be flying normally as it departed to the north-east.

Recorded radar data, between 1431 hrs and 1433 hrs, indicated that the helicopter maintained a steady track to the north-east flying at an altitude of approximately 2,000 ft amsl and at a speed of approximately 120 kt. Witnesses, 8 nm from the airfield, saw the helicopter fly overhead and heard it making a loud, and unusual noise, described by one as "a loud screeching mechanical noise". Another witness described seeing the whole helicopter shake. Witnesses then described seeing the tail of the helicopter fold forward against the side of the cabin, without fully separating, and the helicopter fall to the ground. There were variations in the witness

accounts; some describing the tail folding to the right and others describing it folding to the left. One witness described seeing one of the main rotors "flip upwards" just before the tail folded.

The helicopter fell to the ground on the ridge of a small hill and caught fire. The emergency services were quickly on the scene; however, all three occupants had been fatally injured in the impact.

Helicopter description

The Eurocopter (Aerospatiale) AS355 series of helicopters were derived from the AS350 Ecureuil (Squirrel) helicopter but were fitted with two turboshaft engines in place of the single engine fitted to the latter. Known in the UK as the 'Twin Squirrel', the first models were equipped with Rolls-Royce (Allison) Model 250-C20 engines whilst later versions (AS355N) were fitted with Turbomeca Arrius engines. G-XCEL was fitted with Rolls-Royce engines. Of particular relevance to this accident is that fuel control in the Arrius engine is achieved by a full authority digital engine control unit (FADEC), whilst the Rolls-Royce engine uses a conventional hydro-mechanical system. Apart from the necessary changes to accommodate the different engine installations, the two helicopter models are essentially the same, particularly with respect to the main rotor transmission. The engines are mounted on the left and right sides of the main transmission deck and are referred to as left and right or No 1 and No 2 respectively.

The power output from each engine, in both helicopter variants, can be trimmed so that the total torque required for flight can be shared equally between the engines. This is commonly known as 'beep trim' and is adjusted by the pilot using a rocker switch on the collective lever. On the AS355N models (fitted with Arrius engines) this is purely an electrical signal working through the two

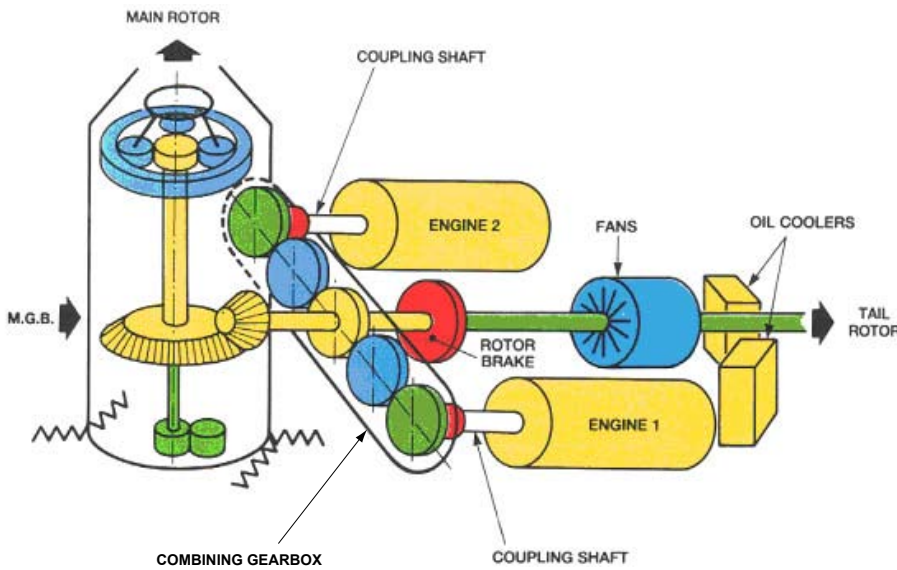


Figure 1

Schematic of AS355 engine/transmission layout

The MRGB/Combining Gearbox assembly is mounted on the helicopter structure by four rigid struts which react lift loads. All other loads and moments are reacted by a flexible mounting plate attached to the bottom of the MRGB.

Main rotor head description

The AS350/AS355 series of helicopters employ a 3-bladed main rotor constructed entirely of glass-reinforced composite materials. Similar material is also

In the case of the AS355, the freewheels are effectively part of the input shafts to the Combining Gearbox and are of a type known as ‘ramp and roller’. Referring to Figure 2, it can be seen that the driven shaft (coloured green) rotating clockwise, has a series of angled steps, called ‘ramps’, machined into it. Fourteen steel rollers (coloured red) engage in the ramps, enclosed by an outer race (coloured blue) which directly transmits torque to the transmission. A spring arrangement keeps the rollers pressed lightly against the outer race, when torque is not being transmitted, to ensure smooth engagement of the freewheel, particularly during start-up. During engagement, the rollers ride up the ramps and bear upon the outer race, allowing torque to be transmitted from each engine to the transmission. In cases where the transmission attempts to back-drive the engines, the rollers ride down the ramps and, spinning under the light spring pressure, no torque should be transmitted from the transmission to the engines. It should be noted that, in normal operation, drive from the engines to the transmission relies on a minimum level of friction between the rollers, the ramps and the outer race.

used in the main structural members of the main rotor hub which are referred to as the blade sleeves and the ‘Starfex’. The ‘Starfex’ (see Figure 3) is the main hub component, since all loads pass through it. In addition to reacting the centrifugal and lift loads, it also transmits torque to the blades and acts as a spring in the blade

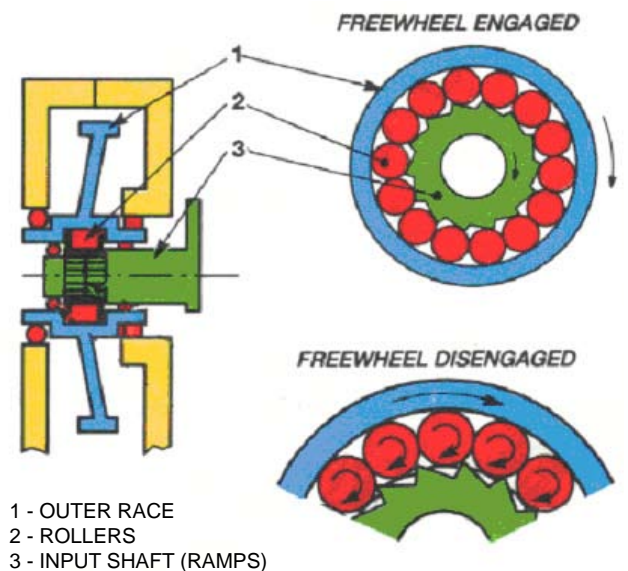


Figure 2

Principle of operation of ‘Ramp and Roller’ freewheel mechanism

fapping sense. Thus it is rigid in all axes except fapping, when it acts as a flexible beam outboard of the laminated spherical bearing.

Maintenance history

G-XCEL had flown a total of 3,296 hours at the time of the accident. On 17 September 2003 it was presented for maintenance at a JAR-145 organisation based at Thruyton Aerodrome. The organisation was tasked with carrying-out a routine 100-hour check but, in addition, there was a requirement to change the Main and Combining gearboxes, which had reached their statutory overhaul life. The MRGB was overhauled by the UK agent for Eurocopter but the Combining gearbox had to be exchanged for an overhauled unit supplied by Eurocopter, Marignane. The two units were mated and fitted to G-XCEL.

The day before the accident, the work was effectively complete and the helicopter engines were ground run; there was then a short test flight. This resulted in the following entry on the worksheet:

'Insufficient TQ (torque) crossover on ground governor beep test (Number one set too low)'

The rectification action, entered by the same engineer, was:

'3 Turns shortened on outer Ng (gas generator speed) cable at ball joint (below rotor brake) locked and torque sealed orange'

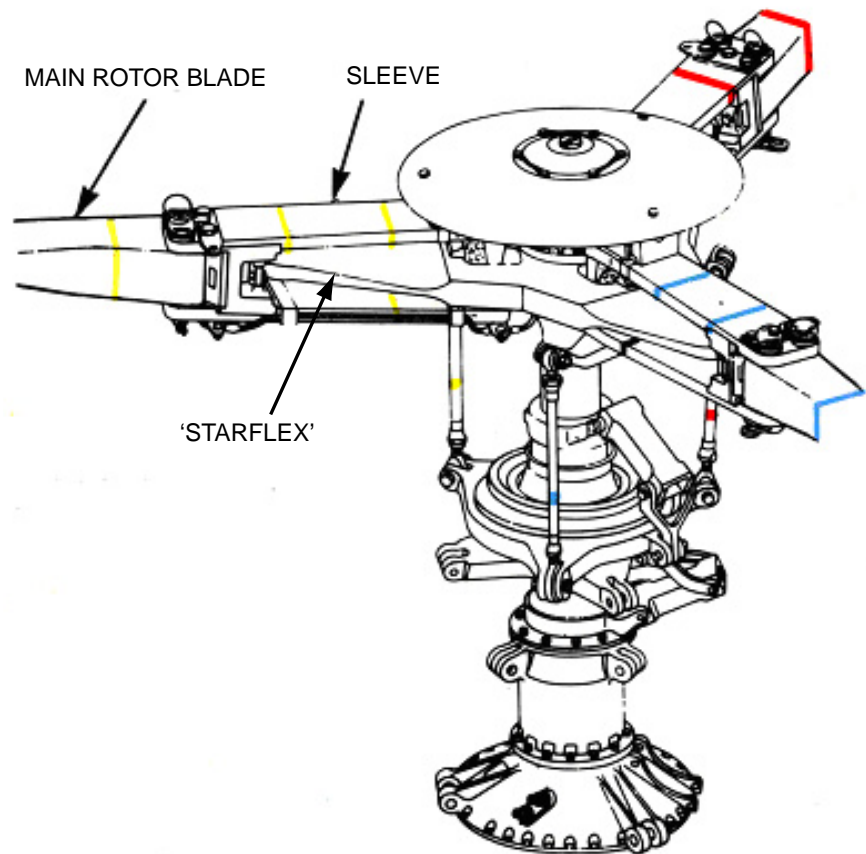


Figure 3
AS355 main rotor head

Although both engineers involved in the maintenance of G-XCEL and the pilot sadly perished in the accident and so could not confirm it, one of the purposes of the accident investigation was almost certainly to check that this adjustment had achieved the required effect. It was also possible that the pilot may have taken the opportunity to perform an in-flight power assurance check, which his company specified on a regular basis.

Examination of the accident site

The main wreckage was in a copse at the edge of a grass field near the village of Hurstbourne Tarrant, near Andover, Hampshire. The fuselage had landed inverted and there had been considerable burning on the ground. The entire primary structure was present at this location, excluding the MRGB, the Combining Gearbox and the

main rotor. These were found, in an unburnt condition, 20 m south-west of the fuselage. All three rotor blades were attached to the hub, although the blade sleeves had become delaminated. None bore evidence of significant leading edge damage indicating very little or no rotation at impact with the trees and ground. It was clear that the MRGB had detached shortly before the fuselage hit the ground due to failure of the four support struts. Both the fuselage and MRGB appeared to have cut vertical paths through the trees indicating little, if any, forward speed. The outboard, flexible, parts of two of the 'Starfex' arms were missing from the main rotor, whilst the third, although present, had also fractured.

The two missing portions of 'Starfex' were found in a relatively compact debris field which lay immediately before the main wreckage. Approximately 100 items were found to have detached from the helicopter prior to impact; these were recovered from an area measuring some 100 m long by 140 m wide. In addition to the 'Starfex' pieces, the debris generally comprised pieces of engine and transmission fairings, contents of the cabin, including a seat cushion, and a 'chin' window transparency. The largest piece was the complete under-fuselage fairing immediately aft of the transparency.

Site examination conclusions

The helicopter had clearly suffered a structural break-up in the air. There was no doubt that the main rotor transmission had detached, probably fairly late in the break-up sequence. Surprisingly, the distribution of wreckage was unable to confirm eyewitness reports that the tail boom had folded, since components such as the empennage and the tail rotor were found with the main fuselage in roughly their correct orientation. It was concluded that the tail boom had not completely detached and had followed the fuselage down, perhaps

even resuming its normal position as the two components fell to earth. Certainly, the manufacturing joint of the tail boom was found separated from the fuselage, with compressive buckling on the left side and shear failure of the rivets on the right side, suggesting that the tail boom had failed by bending to the left.

Information from Eurocopter suggested that the release of the under-fuselage fairings, window and cabin contents were consistent with very high vibration levels. The remaining debris comprised what would have been expected as a consequence of 'tearing-out' of the main transmission. At the time, no explanation was forthcoming for the in-flight failure of the 'Starfex' arms, since it was reported that, even with extreme main rotor coning due to low rotor rpm, the 'Starfex' had never been found to fail.

Detailed examination of the wreckage

The wreckage was transported to the AAIB facility at Farnborough. In order to determine the reason for the MRGB detachment, attention focussed on this component and it, together with the combining gearbox, were shipped to Eurocopter in France for strip examination under strict supervision by the AAIB and BEA (the French equivalent of the AAIB). In addition, the remains of the MRGB mounting structure were removed from the fuselage deck and also despatched. Metallurgical examination quickly discounted any anomalies with these latter components, such as missing fasteners or material defects, as having contributed to the detachment.

The 'beep trim' actuator was recovered and it was found that the left engine had been trimmed fully back and the right consequently trimmed fully to maximum.

The first component to be stripped was the combining

gearbox. After the casing was split, it could be seen that it was in good condition internally. However, when the two freewheels were extracted, it was obvious that the ramps associated with the left unit were in a highly distressed state, consistent with slippage under load (see Figure 4). There was evidence of wear, overheating and material build-up on the ramps. The rollers too, whilst not showing significant wear, were discoloured due to overheating. The outer race, under moderate magnification, appeared to be normal. The right freewheel bore none of these signs and was, at first, thought to be completely normal. Subsequent comparison with in-service units however, later suggested that the slight polished band on the ramps was not normal for an almost new assembly and that this had probably also slipped, but not to the same extent as the left freewheel. Subsequent strip examination of the MRGB revealed no anomalies with the rest of the transmission.

The broken 'Starfex' was also examined. Eurocopter advised that the fracture faces, which ran roughly at 45° to the axis of the arm across half the section and at 90° across the other half, were indicative of a mixture of torque and vertical bending being involved in their failure. No further explanation of the reason for failure could be offered at that stage.

Metallurgical examination of the freewheels

The AAIB employed the services of a consultant in tribology (the study of friction, wear and lubrication of bearings) to assist in the laboratory examination of the freewheels. There was no doubt that the left unit distress had been caused by slippage under load. Indeed, it was possible to discern impact marks from rollers on adjacent ramps caused by the rollers being violently 'spat out' of engagement and striking the face of the ramp behind them. The depth of the wear on each ramp was in the order of



Figure 4

Left input shaft showing wear and overheat damage to ramps of the freewheel

40-50 microns. Although an attempt was made, it was not possible to determine categorically the severity of any re-engagement by examination of the indentations. However, the remains of the 'Thomas coupling' bolts, which were still retained in the combining gearbox input fange, bore signs of deformation suggesting that at least a 250% over-torque had occurred on both sides. This figure was arrived at through tests and calculations carried out by Eurocopter, early in the helicopter's service life, and is normally used for assessing damage caused by events such as main or tail rotor strikes.

Further consideration of the marks on the right freewheel also concluded that this had slipped, but to a much lesser degree than the left.

The consultant tribologist calculated that, given the profile of the ramps and other dimensions, a minimum friction coefficient of 0.062 is required to prevent slippage. In his opinion, a minimum coefficient of 0.1 would therefore be desirable to allow for a reasonable margin of safety. At any value less than 0.062, slippage will occur. Such slippage could be inherently unstable inasmuch as lubrication could actually be improved for

perhaps a few seconds due to oil entrainment velocity. This reduction in friction would allow the power turbine to accelerate. However, after this, friction could build again to the critical value due to heating and scoring of the surfaces, causing re-engagement which could potentially be quite aggressive.

Some concern was raised that graphite grease was used when assembling the gearbox, mainly to lubricate bolt threads, and that this could alter the friction coefficient of the freewheel components if the grease were to contaminate them. Analysis of the oil samples taken during the strip examination subsequently revealed no evidence of grease contamination of the oil.

Metallurgical examination did not, at this stage, reveal any material or dimensional abnormalities with the freewheel components.

Previous instances of freewheel slippage and remedial actions

Following the discovery of the distressed left freewheel, Eurocopter provided the investigation with details of five instances of freewheel slippage, all occurring within a period of about 18 months prior to the accident to G-XCEL. All these incidents had occurred to the AS355N model fitted with Arrius engines. Four of the helicopters were new whilst the other had been fitted with a new MRGB and combining gearbox two operating hours prior to the incident. It is apparent that Eurocopter had linked these with freewheel slippage only after the fourth incident (on 10 November 2003). The first three incidents, commencing in April 2002, had simply been recorded as overspeed shutdowns. With no physical signs of distress of the freewheels, and having verified that there were no dimensional anomalies, problems with the FADEC or wiring were suspected and therefore it was these that became the focus for investigation.

However, after the fourth incident, in which an overspeed shutdown of one engine was followed by an overspeed burst of the other, resulting in a heavy landing, a problem with freewheel-slippage under load was suspected. Even then, no physical evidence was noted on the freewheels themselves.

Eurocopter examined their records to see whether any changes had been made in the previous 18 months to any of the processes affecting the friction environment of the freewheels. They found that, in November 2001, they had changed the supplier of the preservative fluid used when delivering new or overhauled gearboxes from their factory in Marignane. Although the fluid was to the same specification as before, and no chemical differences were identified, it was considered that it could have affected, in some unexplained way, the friction coefficient between the rollers and the ramps or outer race. In normal use some preservative fluid remains in the MRGB and Combining Gearboxes, becoming progressively diluted with the normal running lubricant. It was therefore reasoned that only gearboxes with very low running times were vulnerable, explaining why gearboxes with higher service times, although delivered with the same preservative fluid, had not experienced problems. The fifth incident (on 19 November 2003) was a tethered ground test to evaluate a newly-developed flushing procedure for the gearboxes to hasten dilution of the preservative oil into the lubricant. It also apparently demonstrated that the procedure was not effective, since an engine still suffered an overspeed shutdown.

Accordingly, Eurocopter prepared an 'Alert Telex' No 63-00-21 for distribution to all operators of the AS355E/F/F1/F2 and N as well as military variants. This communication which, according to Eurocopter, had first been drafted on 19 November 2003, eventually grounded any MRGB or Combining Gearboxes which

were new or newly-overhauled ex-Marignane and which had run less than 10 hours. Again, according to Eurocopter, identifying the affected units and routine delays with DGAC (the French equivalent of the Civil Aviation Authority) approval, translation etc meant that this was not issued until 8 December 2003, six days after the accident to G-XCEL but some three days prior to the discovery of the damage to the freewheel described above. The combining gearbox fitted to G-XCEL would have been grounded under the instructions in the Alert Telex. On 11 December 2003 the DGAC, on behalf of the European Aviation Safety Agency (EASA), issued Emergency Airworthiness Directive (AD) UF-2003-464, making the requirements of the Eurocopter Alert Telex mandatory.

The Alert Telex was soon revised to Revision 1 on 19 December 2003 to include cleaning instructions for the bevel gear module of the MRGB (after which they could be returned to service). It is therefore clear that Eurocopter were still convinced at that time that the root cause of the slippage problem lay with the change of preservative fluid. They still felt however, unable to develop a flushing procedure for the combining gearbox. This followed a further test on 3 December 2003, on the combining gearbox from the 19 November 2003 slippage event which had been stripped-down and cleaned before being re-assembled without preservative fluid. When this experienced a freewheel slippage, yet another test was performed on the same gearbox, this time with grease contamination of the freewheel deliberately introduced. When this test, which took place on 18 December 2003, did not result in a slippage event, Eurocopter concluded that lubricant contamination was not responsible and started further investigation of the freewheel components themselves.

At a meeting with the AAIB and BEA (and later promulgated to operators by Revision 2 to the Alert Telex dated 4 February 2004) Eurocopter advised that they had discovered another change to the manufacturing process that had occurred before the first recorded overspeed incident. This concerned the freewheel rollers themselves which had historically been manufactured by a large German company specialising in bearings and precision machining. Between approximately 1980-1983 they had supplied a large number of rollers to Eurocopter and these were used for subsequent production and overhaul. The rollers were supplied in an uncoated, 'as-ground' surface finish.

In 1995, Eurocopter's stock of the rollers became depleted and they entered into dialogue with their German supplier to manufacture a new batch. It is apparent that Eurocopter asked that these rollers should be supplied with a thin surface coating of zinc phosphate (also known as the 'Bonderite' process). The purpose of this was to impart an increased surface roughness to the rollers during the early hours of operation. The high quality surface finish, as delivered, had been found to be prone to occasional slippage under low torque conditions, apparently during first engine start using a new freewheel in cold conditions. They also requested a quotation from the German company to rework the remaining rollers from the original batch with this process. Later, the German company also requested a very minor change to the angle of the chamfer at the ends of each roller for ease of production and this was agreed by Eurocopter.

The subsequent quotation acknowledged that the purpose of the process was to increase the surface roughness of the rollers. However it appears that, whilst the order for new rollers was accepted by Eurocopter, the quotation

to rework the existing stock was not since, in 1997, Eurocopter sent the remaining rollers from the initial batch to a local metal finishing company to have the Bonderite process applied. The change was introduced by Eurocopter modification 077159 and all subsequent new and overhauled freewheels used rollers to this standard until 2001, when rollers from the new batch, delivered with a phosphate coating already applied were used instead. An initial consignment of 5,000 of the new rollers was delivered to Eurocopter in July 2000 followed by a second, in two batches, delivered in November and December 2003.

Roller coating anomaly

In January 2004, as part of the investigative work described earlier, it was found that, with the new batches, the roller drawing instructions had not been followed and that a coating of manganese phosphate had been applied. Under its proprietary name of 'Parco Lubrite', and others, this process claims to reduce wear during running-in of machinery, particularly since its large grain size (compared with zinc phosphate) and relative softness can trap oil, which can be squeezed out under high contact pressures – sometimes called the 'sponge theory'. No such properties are claimed for zinc phosphate, which is mainly used as a surface preparation prior to painting but can also bring benefits when forming sheet metal components under high pressures. The unauthorised change in process would not have been detectable by simple visual comparison between correct and incorrect applications.

Eurocopter have also advised the AAIB that, in addition to the coating being of an incorrect chemical composition, it was also thicker than the dimension specified on the drawing (2-5 microns) by a factor of 3 or 4. The German company dispute this, saying that the term 'thickness' is ambiguous and open to interpretation. They define

'thickness' as the increase in overall roller diameter after coating divided by 2 whereas Eurocopter define it by sectioning the specimen and microscopically examining the surface coating as well as the parent material which has been chemically altered. Because either phosphating process etches material *into* the surface as well as depositing it on the surface, the latter approach will give a coating thickness reading greater for two otherwise dimensionally identical items. The German company assert that their coating met drawing thickness requirements and furthermore that rollers coated by Eurocopter's process suppliers did not. Tests on bare rollers manufactured by them and subjected to zinc phosphating, by the same suppliers used by Eurocopter, have suggested that the process was achieving almost no deposition of zinc phosphate on the surface; only a slight etching, effectively roughening the parent steel, was achieved.

Since Eurocopter are the sole supplier of rollers to overhaul and repair shops, limiting affected gearboxes to those overhauled at Marignane was no longer valid, as defective rollers would have been supplied to agencies worldwide. Accordingly, Revision 2 of the Alert Telex grounded any overhauled, repaired or newly-manufactured Combining Gearboxes from *any* source, which had run less than 10 hours. It also mentioned a modification number (077212) which introduced rollers subsequently produced correctly to the drawing requirements. Gearboxes with this modification embodied were permitted to return to service and this was the only action deemed necessary by Eurocopter to 'unground' combining gearboxes affected by Alert Telex 63-00-21.

Testing of freewheel rollers

The reason for retaining the 10 hours threshold, even though its original technical justification had been

based on a rationale involving dilution of preservative fluid, was questioned. To this end, Eurocopter embarked on a series of tests in which a MRGB and combining gearbox were connected to a rig capable of driving both input shafts in a manner similar to the two engines. The purpose of the tests was to examine the different behaviour of zinc and manganese phosphate coatings with time of operation in freewheel mode. One freewheel was equipped with manganese-phosphated rollers and the other with zinc-phosphated rollers. The assembly was then subjected to a typical engine start sequence (one freewheel engaged and the other disengaged) followed by the second 'engine start' with both engaged. This was followed by a simulated shutdown sequence. The selection of which 'engine' was started and shutdown first was alternated between the two. After a period of time the test was interrupted and the freewheels disassembled to measure the surface roughness and percentage of coating/iron visible on the surface. The freewheels were then re-assembled and the test resumed, followed by another examination.

Accomplishing this many times enabled a graph to be produced showing how the ratio of the surface coating to the amount of base metal (Iron) on each type of roller varied with a number of typical duty cycles, translated into time for which the freewheels had rotated. This graph is reproduced in Figure 5. From this it can be seen that the zinc phosphate coating wears away very rapidly, reaching a figure of 35% visible iron after about 3 minutes of rotation time. The manganese phosphate coating wears much more slowly, reaching the same ratio after about 19 minutes.

It is Eurocopter's considered view that this figure of about 35% of base metal visible, *for either type*, is critical; above that figure, slippage under load is unlikely whilst below that figure it is possible. This percentage was reached after about 3.5 minutes of rotation time for the zinc-phosphated rollers but the manganese-phosphated rollers did not reach the 'critical percentage' until about 19 minutes. They also related these figures to the known history of slippage events, for which the precise operating times and sequences were recorded since the majority took place under their own flight test operations. This comparison enabled a chart to be plotted, relating slippage occurrences to time of freewheel operation since new. From this it was determined that the slippage events all took place within the range of about 100-700 seconds of freewheel rotation time once fitted in the helicopter.

A new set of rollers using both types of coating was then subjected to the normal bench running regime that all gearboxes are subjected to prior to release from the

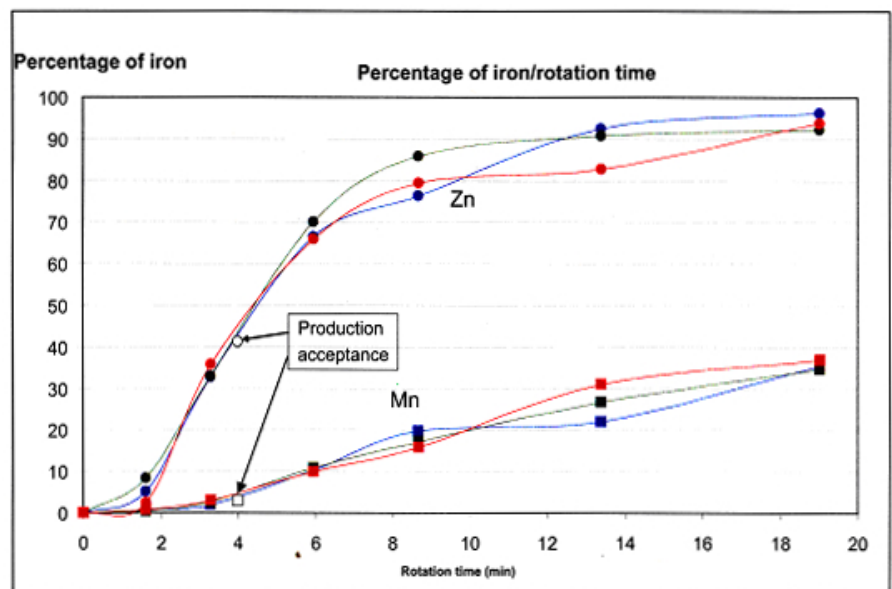


Figure 5

Graph of results from rollers with Manganese and Zinc Phosphate coatings showing percentage of base metal (Iron) visible on the surface plotted against freewheel rotation time

Eurocopter factory. This was found to equate to four minutes of freewheel rotation time, at which time the percentage of Iron visible on the zinc-phosphated roller surface was measured to be about 40%; only some 4% was visible on manganese-phosphated items. From this it was concluded that, when the bench running time is added to the normal post-installation ground running before fight torques are applied, the surface iron/zinc phosphate ratio is comfortably above 35% and slippage will not occur. With manganese phosphate, however, slippage under load is possible for another 10 minutes or so of freewheel rotation time. Eurocopter calculations showed that this equated to about 3 hours of helicopter operation and that, after applying a safety factor of roughly 3, manganese-phosphated rollers, which had run for more than 10 fight hours, could remain in service.

The tests run contrary to the observations made by the German company described earlier, in which they assert that rollers processed by Eurocopter's supplier had almost zero percentage of zinc phosphate visible on the surface before any wear process took place. As discussed later, it remains Eurocopter's position that the percentage of zinc on the surface is not relevant, and that rollers coated to their specification had been proven, by experience, to perform satisfactorily.

Roller manufacture

The German company which manufactured the rollers is a long-established specialist in bearing design and manufacture. Indeed, they are regarded as a 'supplier' to Eurocopter, since the roller production drawing belonged to them (they would technically be a 'subcontractor' if they were working to a Eurocopter drawing). The drawing clearly stated the requirement for 'Bonderite 880 phosphating using the Eurocopter process'. The company was not, however, involved in

any of the design processes of other components of the freewheel. As an experienced and capable manufacturer of freewheels for other applications (including automotive), they have expressed the opinion that they would normally prefer to at least be fully consulted on the overall design of the assembly and at best be given responsibility for the design.

After the final grinding process, the rollers, accompanied by a routing card which specified the process, were shipped to the company's process shop for phosphating. The person preparing the card had annotated it with the letters PHS, indicating that the parts required phosphating and included the word 'Bonderite' in a remarks section to indicate that it was to be zinc phosphate. Unfortunately, the operator responsible for applying the coating, who was familiar with the manganese phosphate process, since his company produced many components finished in this manner, did not recognise the significance of the word 'Bonderite' and applied the process with which he was familiar. Indeed, it would appear that the company had seldom, if ever, used zinc phosphate before and that their phosphating bath would have required draining of the manganese and re-filling with zinc phosphate solution to fulfil the requirement. This however, did not happen.

The German company supplied a full and frank description of the circumstances which led to the error however, they strongly refute that the incorrect coating could have been responsible for freewheel slippage. In support of this assertion, they provided the AAIB with the results of a series of friction coefficient tests they had conducted (post discovery of the error) in which uncoated specimens, manganese, and zinc phosphate coated specimens were compared. The tests, which measured conventional dynamic friction coefficients of

the specimens in lubricated and un-lubricated conditions, were combined with a special static test in which rollers finished in the different ways were loaded between two metal blocks. This attempted to simulate the contact conditions between the freewheel ramps and the outer race. Neither type of test revealed any large differences between the various finishes and the dynamic friction coefficient remained comfortably above the minimum 0.1 value in each case. The company also disputed the theoretical claims made for manganese phosphate in reference works and advertisements for the process, including the 'sponge theory' described above.

In support of their assertion, that some factor other than the incorrect chemical composition of the coating was involved in the freewheel malfunction, they commissioned a wide-ranging report from two German tribological engineering consultants. This report looked at both the theoretical merits and demerits of the 'ramp-and-roller' type of freewheel in helicopter applications as well as a critique of the AS355 design based on 'reverse-engineering' a particular specimen they had acquired. The report had several conclusions, but in particular, the observation was made that the 14-roller design resulted in close-packing of the rollers such that, if one were to be transiently 'spat-out' of engagement (an event acknowledged to be possible or even probable), it could collide with its neighbour. It could then cause this to disengage and so forth around the group, resulting in complete disengagement of the freewheel. In addition, the report concluded that, because of the high contact pressures when the freewheel is engaged, *any* coating could increase the tendency to slip under load.

It is clear, however, that Eurocopter are satisfied that the erroneous coating was responsible for the onset of freewheel slippage under load problems which started

in April 2002. This equates to no serious cases of freewheel slippage experienced over a period of some 22 years with some 690 helicopters delivered plus at least 800 overhauled combining gearboxes using replacement rollers. The only problems, according to Eurocopter, were the isolated cases of slippage on first start-up in cold conditions which led to the introduction of Bonderite coating of rollers in 1997. During the next 5 years, no problems were reported. Furthermore, since the issue of Revision 2 of Alert Telex 63-00-21, in February 2004, which allowed operators to return to service gearboxes which had been previously grounded on the proviso that they replace rollers with less than 10 hours flying time with correctly coated items, the AAIB are not aware of any more in-flight cases of freewheel slippage. This equates to some 28 new helicopters delivered and 112 overhauled combining gearboxes. Thus it would appear that, over a period of approximately 18 months, five cases of single engine overspeed shutdowns, an uncontained engine failure leading to an accident, a further non-fatal accident (see below) and, finally, the accident to G-XCEL all occurred. This coincided with the introduction of rollers coated with manganese phosphate.

Quality Assurance issues

The German company has an excellent reputation and Eurocopter had experienced a long and satisfactory working relationship with them in dealing with many other components as well as freewheel rollers. This clearly influenced the Eurocopter's approach to quality assurance.

There were minimal physical checks carried out on the delivered rollers because it seemed inconceivable to Eurocopter that such a relatively simple component could have been defective. Quality assurance procedures and requirements, contained in various documents, are used

when obtaining relevant approvals, both for aviation and non-aviation-specific tasks. However, these tend to be written in general terms.

For example, EASA regulation 1702/2003 Part 21 para 21A requires that:

'an approved organisation, its partners, suppliers and subcontractors must demonstrate that it has, and is able to maintain, a quality system which ensures that each product or part conforms to the applicable design data and is in a condition for safe operation'.

It does not prescribe in detail how the organisation should construct such a system. Organisations may choose to audit suppliers (who themselves should also conduct internal audits) or physically inspect a sample or 100% of the components supplied. The latter, theoretically, should guarantee that defective components do not enter service and is known as 'quality control'.

Manufacturing industry however, has generally been moving away from 'quality control' in favour of auditing their own, or a supplier's, production process. Such an approach would thus be termed a 'total quality assurance' philosophy. The problem is that, under a 'total quality assurance' system, isolated human error, such as occurred in this occasion, may not be picked up until a component malfunctions in service. In aviation this can have catastrophic results.

A further contributory factor could have been the time that elapsed between the first discussions about the possibility of producing the new batch of rollers (including the zinc phosphate coating requirement) and the actual delivery. As stated earlier, documentary evidence has been supplied showing that, in 1995,

the purpose of zinc-phosphating was understood by the German company to be 'to induce surface roughening of their roller finish'. Verbal evidence has also been given suggesting that, at that time, the German company queried the requirement because the capability to apply zinc phosphate was not available at their premises. They were assured by Eurocopter however, that it was necessary. Had manufacturing commenced shortly after this dialogue, the 'unusual' nature of the process may have alerted the German company to the possibility that they needed to acquire new equipment and certainly a different phosphating solution from their usual manganese process and the error would not have been made. However, it appears that a further five years elapsed before production actually commenced. During that time personnel aware of earlier discussions may have left the company or been moved elsewhere, and the significance of the coating was overlooked. By the time the rollers were manufactured the German company had not acquired the capability for zinc-phosphating.

Eurocopter were evidently operating under a 'total quality assurance' philosophy regarding the rollers. There seems to have been little verification that the product they were receiving conformed to drawing. Additionally, no auditing of the actual roller production process was carried out as they had an expectation that their supplier, by virtue of their reputation, would produce a quality product.

AAIB has received comments from both parties as to where, in their opinion, the other has failed to follow quality assurance procedures. It is felt that to explore these in greater depth in this report however, could be judged as inappropriate and not immediately relevant to flight safety.

However, the observation is made that, given the very long period of time and the changes made between the two production runs of the rollers, both parties would have been well advised to have physically checked samples in greater depth before releasing and accepting the items, regardless of whether such inspection was strictly required or not. To have completely verified all aspects of the manufacturing process (eg material specification, hardness, dimensions, coating thickness and composition) would have required destructive laboratory work on a sample. Tests on such a low-cost item would almost certainly have revealed the incorrect coating.

Additional case of freewheel slippage

Another accident had occurred to an Austrian-registered AS355F1 helicopter, which was damaged beyond economic repair on 3 December 2002, following an autorotative landing. An investigator from Eurocopter assisted the Austrian investigation, on which no report has subsequently been published. The Austrian pilot reported that, whilst performing a routine power assurance check, the crew heard a 'metallic bang' followed by a hammering noise and vibration was felt through the flight controls. Thinking that the noise appeared to have come from the rear of the helicopter, he rapidly closed both power levers and entered autorotation. Because of the nature of the terrain however, the helicopter rolled to the right on touchdown and the main rotor blades hit the ground; nobody was injured.

Examination of the helicopter revealed that an engine oil cooler heat exchanger was loose; all eight nuts mounting it to the airframe were loose and one was missing. Rocking the assembly by hand produced a hammering noise and it was believed, at the time, that this had been responsible for the noise. It was therefore concluded

that failure to tighten the nuts during the 1,000-hour check, which the helicopter had just undergone, was the cause of the accident. Although the transmission was not strip-inspected as part of the investigation, both freewheels were turned by hand and found to operate smoothly. After being pronounced an economic total loss, the helicopter was presented to a museum in Vienna and prepared for display.

After the accident to G-XCEL, the Eurocopter Air Safety Investigator, being aware of the eyewitness reports of loud unusual noises, and also recalling that the Austrian helicopter had had a recent replacement of the combining gearbox, endeavoured to re-visit the helicopter in the museum and enquired about running time of the gearbox since overhaul. After some delay, he was advised that it had run less than one hour and he was allowed to remove the combining gearbox for examination. Although not as severe as the damage found on the left freewheel of G-XCEL, sufficient evidence was found on one freewheel to show that slippage had occurred and the rollers were coated with manganese phosphate from the batch supplied by the German company.

Discussion and Conclusions

Structural break-up of the helicopter

Although the precise forces and moments involved in failing the helicopter structure have not been quantified, calculation has shown that, if the engine affected is neither automatically nor (rapidly) manually shutdown, rapid re-engagement of a slipping freewheel has the potential to cause structural failure of the tail boom. Defining such forces is difficult because the exact timeframe over which the re-engagement occurs has a significant effect on the torque felt through the transmission and by the airframe; an instantaneous re-engagement would theoretically generate an infinite load. Physical examination of the components could

not refine the time parameter, but calculations suggested that a re-engagement occurring over a fraction of a second could cause structural airframe damage. Moreover, if there were multiple re-engagements, at a frequency approaching the natural frequency of the tail boom, then the time period could be even longer than that needed for a single event.

No signs of roller imprints were found on the freewheel outer race. Additionally, other components such as the engine drive shafts, had not failed. It was therefore concluded that over-torque values generated by the shock of re-engagement could not have approached the very high figure necessary to fail the tail boom in a purely static manner. The deformation of the Thomas coupling input fange bolts, however, did suggest that the over-torque was at least 250% for both engines. It is therefore considered that the interaction of the two freewheels, alternately engaging and disengaging, may have created a dynamic situation of alternating applications of high torques (effectively a severe vibration) which compromised the structure of the tail boom.

Another possibility, suggested by Eurocopter, is that the over-torque, caused by re-engagement of the freewheels, could interact with a transient loading of the 'Starfex', caused by rapid lowering of the collective lever by the pilot attempting to enter autorotation. Calculations suggest that the 'Starfex', normally carries a safety factor of 7 (ie would require 7 times the torque output available from the engines to fail it). For a very brief moment during rapid lowering of the collective lever, this is reduced to a factor of 2.7 - fairly close to the over-torque value witnessed by the fange bolts. In other words, the combination of over-torque and fight stresses interacted for an instant and caused failure of the 'Starfex'. The severe vibration could then have failed the tail boom.

Although it has not proved possible to establish the precise sequence of break-up, this could be regarded as largely academic, since it appears that, on Rolls-Royce-engined AS355 helicopters, at least, in-flight slippage of freewheels must be avoided because of the potential to result in catastrophic failure of the helicopter's structure, howsoever that occurs.

There is little doubt that structural damage due directly to freewheel re-engagement was avoided, in the five cases of freewheel slippage under load known by Eurocopter that occurred prior to the G-XCEL accident, by the fact that the helicopters involved were all powered by Arrius engines. This engine reacts to overspeed of the power turbine (resulting from freewheel slippage) by immediately shutting-down the engine. The Rolls-Royce (Allison) engines of G-XCEL continued to run, albeit with the gas generator effectively at an idle condition, but with the power turbine spinning at the 114% while the off-load condition persisted. The kinetic energy in the system was therefore high when the re-engagements occurred. This is also probably the reason why the accident to the Austrian helicopter, although powered by the same engines as G-XCEL, did not have the same tragic outcome. It appears that the Austrian pilot, alarmed by the noise of what was probably a malfunctioning freewheel, rapidly closed both throttles and entered autorotation. There may also have been an element of good fortune, as such events probably have a random element in relation to the severity and timing of the re-engagement. There is little information concerning precisely how the pilot of G-XCEL reacted to what may have been similar cues to those presented to the Austrian pilot, although the radar trace suggests he initiated a descent, possibly with a view to performing a forced landing. There is no pilot drill for such an eventuality and, bearing

in mind how quickly the situation can develop from onset to catastrophic failure, there appears to be little scope for devising one.

It was noted that in both the Austrian accident, and at least some of the five previous incidents of freewheel slippage, the pilots were flying with deliberate torque difference between the two engines. It is also evident that the pilot of G-XCEL was doing the same, probably as a power assurance check. Perhaps, contrary to expectations, it was the engine freewheel carrying the *least* torque which bore most evidence of slippage and re-engagement. However, tribological opinion suggests that this is likely - the lower engagement forces of the freewheel transmitting the lower torque could be more prone to the stimuli, such as vibration and transient rpm variations, which tend to momentarily unload the freewheel and could trigger slippage. Alternatively, Eurocopter believe that the right freewheel, carrying the majority of the flight torque, was the first to slip and transferred the load to the left freewheel which in turn also slipped. As stated previously, it is then possible that both freewheels entered a cycle of slippage/re-engagement creating an oscillation in yaw at a frequency which compromised the tailboom structure.

The effects of the manganese phosphate coating

It has not yet been possible to reproduce, under test conditions, any greater tendency for manganese phosphate coated rollers to slip out of engagement compared with those zinc-phosphated. Indeed, conventional friction measuring tests suggest that there is little significant difference between not only the two different coatings but also uncoated rollers. Against this is the practical experience that serious slippage problems were only encountered when a batch of manganese-phosphated rollers were inadvertently used in AS355 freewheels. Eurocopter are of the opinion

that the environment (eg vibration and transient torque levels) within the freewheel may be too complex to be replicated by standard test methods.

Eurocopter have accepted that the Bonderite process, as applied to their specification, was in practice achieving almost no deposition of zinc phosphate on the roller surface. They believed it was achieving a thin, but 100% coating, since their testing of freewheels equipped with rollers of the two different types was predicated on both phosphate coatings having 100% coverage at the start of the tests. The German manufacturer asserts, therefore, that it was the presence of a coating *of any type*, irrespective of chemical composition, which caused the problem; that is to say it was purely fortuitous that problems were not encountered with the zinc-phosphated rollers because the Bonderite process specification was actually achieving only a slight etching of the surface, not a coating.

In response, it remains Eurocopter's position that if the German company had correctly followed the drawing instructions they too would have arrived at the same finish which was proven to be effective. The same process had been applied to freewheels used in Gazelle helicopters and reportedly given satisfactory performance - this represents decades of flying and millions of hours of service.

The satisfactory performance of rollers both uncoated and coated with zinc phosphate over many years must be acknowledged. However, the freewheel has demonstrated that it is very sensitive to changes in tribological conditions which are not fully understood or measurable by conventional techniques. Its performance may also be compromised by small variations in dimensional tolerances. The following Safety Recommendation is therefore made:

Safety Recommendation 2006-070

It is recommended that the European Aviation Safety Agency, together with Eurocopter, review the design of the AS355 helicopter freewheel to ascertain whether it can be made more tolerant of variations in dimension or tribological performance of its components.

Although Eurocopter have indicated that they do not intend to perform any further tests in support of this investigation, it is possible that they, or their German supplier, may do further work to resolve the inevitable dispute resulting from the errant batch of rollers. If such work results in significant new information, the AAIB will publish it in a future issue of the AAIB Bulletin.

Manufacturer's response to air safety incidents

There was a time interval of some 18 months between the first incident, of what is now considered to be a number of incidents associated with freewheel slippage, and issuance of the first Alert Telex and associated Airworthiness Directive which grounded gearboxes at risk. The unit fitted to G-XCEL would have been one of the latter. The explanation of events offered by Eurocopter for this interval is not untypical of the way industry operates generally, with the major period of time being consumed by an incomplete understanding of the true nature of the problem (which was not thought to be a high-risk event) followed by partial recognition of the basic underlying cause coupled with experience of its potential to result in (non-catastrophic) damage.

After the 10 November 2003 accident at their own premises, it was clear that not only was there a problem with freewheel slippage but also a potential for a double engine failure occurring. The manufacturer realised the need to consider urgently what appropriate safety actions should be taken.

Firstly, they needed to establish which helicopters were at risk and this, in itself, required a connection to be made between the earlier incidents of engine overspeed shutdown with the accident. This led them to conclude that only new or newly-overhauled gearboxes with less than 2 hours running time seemed to be affected by the problem. Presumably, a check on the worldwide experience then indicated that it was only components from their own facility which were affected. Eurocopter were then faced with the decision of whether to ground all such units pending identification of the problem and a solution to return them to service. They chose not to do this, still believing that a slipping freewheel would most likely result in an engine overspeed shutdown (all the incidents, they believed at the time, were to Arrius-engined helicopters) or at worst a double engine failure followed by an autorotative landing.

It is clear that there was the intention that, when the appropriate safety action was communicated, it would also contain the remedy to return affected components to service. Eurocopter were initially focussed on the theory that tribological alteration brought about by the change in supplier of the gearbox preservative fluid was responsible. Even though no chemical or other causes were identified with this change, it was decided that this must have been a factor and therefore an experiment was conducted in which a new 'flushing' procedure was developed to remove as much of the preservative as possible before filling with lubricant. This unsuccessful test resulted in another overspeed shutdown during the tethered ground test on 19 November 2003. It was only with the 18 December 2003 test, with grease deliberately introduced into the freewheel, that Eurocopter finally concluded that lubricant contamination was not responsible and looked in greater depth at the freewheel components themselves.

At any stage the decision could have been made to urgently ground all affected gearboxes, but it was not until 8 December 2003 when the first issue of Alert Telex 63-00-21 effectively did this, stating that Eurocopter were trying to develop an improved flushing procedure to disperse the preservative. It was obviously not deemed to warrant immediate action, for it took 19 days from the unsuccessful tethered test to issue of the Alert Telex.

The manufacturer has to make a judgement, balancing risk against economic factors and also his reputation. Sometimes that judgement can be flawed or based on incorrect information. Eurocopter had notified the 10 November 2003 accident to the BEA (the French equivalent of the AAIB), who did not become involved, primarily because the helicopter was destined for a military customer and was operating under the manufacturer's temporary flight test registration. Thus investigation rested with Eurocopter and the DGAC and the former provided AAIB with a copy of a presentation given to DGAC on 26 November 2003. This largely summarised the history of engine overspeed events leading up to the accident, gave details of the action plan they intended to follow, which has been described above and culminated in the 18 December test which finally convinced them that lubricant contamination was not responsible for the slippage events.

There is no indication from the presentation that a discussion or risk assessment was conducted to consider all the potential consequences of freewheel slippage. Presumably it was assumed that the 'worst case' scenario was the 10 November 2003 accident, which involved no personal injury. The effects of aggressive freewheel re-engagement and different behaviour of the Allison engine, which had no overspeed shut-down protection, were apparently not explored. Since no minutes were kept, or at least available, there is no record of the

DGAC reaction to the presentation and no discussion about the timescale for possible airworthiness action. Therefore, it must be assumed that they were content with Eurocopter's proposals.

Were manufacturers and regulatory authorities to approach the issue of identification of technical problems through to airworthiness actions on a more formal basis, this might, apart from subsequently providing firm evidence should such actions prove to be flawed, result in a more robust exploration of potential consequences at the time. Therefore the following Safety Recommendation is made:

Safety Recommendation 2006-071

It is recommended that the European Aviation Safety Agency ensure that manufacturers and those responsible for regulatory oversight of manufacturers, document the decision-making process resulting from identification of an in-service problem through to issuing airworthiness action.

Conduct of the Investigation

This report will be published more than two years after the accident to which it refers. It has been necessary to exceed the nominal target time to publication, however, because of the extremely complex nature of the technical investigation and the requirement to prepare and assess a wealth of test and theoretical evidence presented by the two principal manufacturing companies involved. It had been hoped that this might resolve the conflicting conclusions reached by each company's evidence but this ultimately was not possible. With no immediate prospect of resolution, it was decided that the facts and opinions of both parties should be described without a conclusion as to whose is correct. The AAIB wish to thank both companies for undertaking this work and sharing their results with the investigation team.