AIRCRAFT ACCIDENT REPORT 2/88

Air Accidents Investigation Branch

Department of Transport

Report on the accident to Boeing Vertol 234 LR, G-BWFC 2.5 Miles east of Sumburgh, Shetland Isles on 6 November 1986

Including the Review before
Sheriff P G B McNeill QC (Chairman)
and
Professor P Hancock
and
Mr K V Kellaway (Assessors)

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List of Aircraft Accidents Reports issued by AAIB in 1988/9

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Department of Transport

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Department of Transport
Air Accidents Investigation Branch
Royal Aerospace Establishment
Farnborough
Hants GU14 6TD

28 January 1988

The Right Honourable Paul Channon
Secretary of State for Transport

Sir,

I have the honour to submit the report by Mr D F King an Inspector of Accidents, on the circumstances of the accident to Boeing Vertol BV 234 LR, G-BWFC, which occurred 2.5 miles east of Sumburgh Airport, Shetland Isles, on 6 November 1986.

I have the honour to be
Sir
Your obedient servant

D A COOPER
Chief Inspector of Accidents

Contents

Air Accidents Investigation Branch

Aircraft Accident Report No: 2/88
(EW/C992)

Operator:		British International Helicopters Limited
Aircraft:	*Type:*	Boeing Vertol 234 LR (BV 234)
	Nationality:	British
	Registration:	G-BWFC
Place of Accident:		2.5 nautical miles east of Sumburgh Airport, Shetland Isles. Latitude: 59° 53.5' North Longitude: 001° 12' West
Date and time:		6 November 1986 at 1131hrs
		All times in this report are UTC

Synopsis

The accident was notified to the Department of Transport Air Accidents Investigation Branch (AAIB) at 1215 hrs on 6 November 1986. An investigation began the same day and the team included inspectors experienced in the location and recovery of wreckage from the sea bed.

The accident happened when the helicopter was approaching to land at Sumburgh Airport, Shetland Islands on returning from the Brent oilfield in the East Shetland Basin. Whilst descending from a height of 1,000 feet and at a range of about 2.5 miles from the helicopter runway at Sumburgh,the helicopter suffered a catastrophic failure of the forward transmission which in turn led to de-synchronisation of the twin rotors such that the forward and aft rotor blades collided. As a result the aft pylon, complete with the aft transmission and rotor system, detached from the fuselage. The aircraft struck the sea in a tail down attitude with considerable force,broke up and sank.

A Sikorsky S61N operated by HM Coastguard was in the immediate area and the crew sighted wreckage floating in the water. Two survivors were spotted and winched aboard. During this operation further pieces of wreckage and a number of bodies were sighted. Further searching by surface vessels and aircraft failed to locate any more survivors.

The report concludes that the immediate cause of the accident was the failure of the modified spiral bevel ring gear in the forward transmission which allowed the twin rotors to collide when synchronisation was lost. Underlying causes were the inadequacy of the hitherto accepted aircraft industry standard of test programme carried out by the manufacturers and the insufficiently stringent inspection programmes required by the Federal Aviation Administration (FAA) and the Civil Aviation Authority (CAA). Three safety recommendations are made.

1. Factual Information

1.1 History of the flight

The helicopter and crew were detached from their normal base at Aberdeen to Sumburgh, Shetland Islands. They had been stationed at Sumburgh since Monday 3 November 1986 and had operated shuttles to and from the Brent Field in the East Shetland Basin. On Thursday 6 November 1986 the aircraft was prepared for flight in the morning and, since an oil leak from the left engine gearbox had been discovered the previous evening, a breather pipe was replaced. After the crew had ground run the engines and rotors the oil leak was found to have been rectified. The aircraft left Sumburgh at 0858 hrs with 40 passengers for the Brent Field. The outward flight proceeded without incident and three platforms in the field were visited with passengers and freight being exchanged. No fuel was uplifted since sufficient was carried for the return trip to Sumburgh.

The helicopter left Brent Platform \`C' at 1022 hrs with a full complement of 44 passengers on board. It climbed to 2,500 feet and proceeded towards Sumburgh along track 'M' of the Helicopter Main Routes. At 1108 hrs when 40 miles from Sumburgh VHF omni range, the crew reported their position to the Sumburgh approach controller. They were identified on radar and given permission to route from the boundary of the Sumburgh Special Rules Zone towards the airfield, descending to an altitude of 1,000 feet and at a speed of about 100 knots. At 1122 hrs the flight was handed over to the Sumburgh aerodrome controller.

At 1130 hrs the Sumburgh based HM Coastguard Sikorsky S61N helicopter departed to the east of the airfield for a routine training flight. The helicopter was fully equipped and crewed for Search and Rescue (SAR) operations. Information about this helicopter was radioed to the commander of \`FC' who had just informed the controller that he was "four and a half miles" from the airfield. The controller gave him clearance to land on helicopter runway 24. No further radio communication was heard from \`FC'.

Evidence from the Cockpit Voice Recorder (CVR) showed that at the same time the crew remarked on a noticeable increase in the noise level on the flight deck. One of them described it as a "roaring noise". This was followed by a "bang" and the aircraft went out of control as the tail dropped to a near vertical attitude. The commander immediately applied full forward cyclic pitch control but the aircraft did not respond although he remembered the helicopter nose diving towards the sea from a height of about 150 feet.

The descent was witnessed by a man who was working outside at the summit of Compass Head, which is 1,000 metres south east of the helicopter runway at Sumburgh. On looking out to sea he observed, at a height of about 300-400 feet, a falling orange coloured object which was weaving from side to side. He saw the lower set of rotor blades fly off to the right. It then hit the sea making a large splash which was also observed from the airport and by the crew of some fishing boats in the immediate vicinity of the crash.

The aerodrome controller had lost visual and radio contact with the aircraft when indications that it had crashed into the sea came from the crew of the Coastguard helicopter who had noticed two inflated liferafts floating in the sea to the east of Sumburgh Airport. Shortly afterwards, aircraft wreckage was observed floating on the sea and a survivor was seen clinging to a substantial piece of wreckage. Whilst he was being winched aboard the Coastguard helicopter other bodies were observed floating in the sea, all apparently lifeless, except for one man who was clinging to the side of one of the inflated liferafts. He was winched aboard the Coastguard helicopter and further searching continued. With no other sign of survivors, the commander of the Coastguard helicopter decided that, in view of their deteriorating condition, he would fly the survivors to Lerwick (18 miles north of Sumburgh) for transfer to Lerwick hospital.

An intensive air and sea search, involving Service and civilian aircraft and vessels, failed to find any more survivors but the bodies that remained afloat were recovered to the airport at Sumburgh.

1.2 Injuries to persons

Injuries	Crew	Passengers	Others
Fatal	2	43	-
Serious	1	1	-
Minor/none	-	-	

1.3 Damage to aircraft

The aircraft was destroyed

1.4 Other damage

None

1.5 Personnel information

1.5.1	*Commander:*	Male, aged 45 years
	Licence:	Airline Transport Pilot's Licence (Helicopters) valid until 9 March 1990
	Helicopter type ratings:	Bell 47, Hiller 360 UH 12 series, Sikorsky S61N, Sikorsky S76A, Boeing Vertol 234 LR
	Instrument rating:	Renewed 26 September 1986
	Medical certificate:	Valid until 28 February 1987 No limitations
	Certificate of test:	BV 234, 26 September 1986
	Flying experience:	Total helicopter 10,130 hours Total BV 234 2,550 hours Total last 28 days 47 hours Total last 7 days 15 hours
	Duty time:	Off duty at 1230 hrs on 5 November 1986 On duty at 0800 hrs on 6 November 1986
1.5.2	*Co-pilot:*	Male, aged 43 years
	Licence:	Airline Transport Pilot's Licence (Helicopters) valid until 28 November 1987
	Helicopter type ratings:	Bell 47, 206, 212, BV 234 LR
	Instrument rating:	Renewed 3 July 1986
	Medical certificate:	Valid until 30 November 1986 No limitations
	Certificate of test:	BV 234, 7 July 1986

Flying experience:	Total helicopter	4,995 hours
	Total BV 234	185 hours
	Total last 28 days	55 hours
	Total last 7 days	25 hours

Duty time: Off duty at 1530 hrs on 5 November 1986
On duty at 0800 hrs on 6 November 1986

1.5.3 Cabin attendant Male, aged 38 years

Last competency check:	16 December 1985
Dinghy drill:	17 March 1986
Medical certificate:	24 March 1986

1.6. Aircraft information

1.6.1 Description

The BV 234 LR, which is a development of the CH47C Chinook helicopter has tandem three bladed rotors of 60 feet diameter which overlap by about 80% of the disc radius over the fuselage centreline. Power is provided by two engines, one located either side of the tail pylon, via right angle gearboxes, to the combining transmission. Synchronising shafts then transmit the drive from the combining transmission to the forward and aft transmissions and maintain the correct phase relationship between the rotors. According to the manufacturers, the two rotor discs, which are vertically separated, intermesh at low airspeeds and when certain control inputs are made at higher speeds.

Diagrams of the general transmission layout and components of the forward transmission are at Appendix 1a-d.

1.6.2 Main particulars

Manufacturer:	Boeing Vertol Company Philadelphia, USA
Aircraft type:	BV 234 LR
Date of manufacture:	1981

Manufacturer's serial No:	MJ 004
Registered owner since September 1986:	British International Helicopters Limited
Registered owner from May 1981 to September 1986:	British Airways Helicopters Limited
Certificate of Registration:	G-BWFC/R1
Certificate of Airworthiness:	Transport Category (Passenger) No SR-844-2 valid until 28 May 1987
Configuration:	Passenger, 44 seats
Total airframe hours:	7,690 hours
Last check:	`A' check at 7,680 hours on 4 November 1986
Engines:	Two Avco Lycoming AL 5512 turboshaft engines
Maximum permitted take-off weight:	48,500 lb
Calculated take-off weight:	42,837 lb
Estimated weight at accident:	39,917 lb
Centre of gravity :	Calculated within limits for the duration of the flight

1.6.3 *Description of the forward transmission*

The forward transmission is driven from the combining transmission via the synchronising shafting which runs at a nominal 6,912 rpm. It angles the drive through 81° and reduces the speed to 225 rpm which is 100% rotor rpm in three stages within the transmission. The first stage uses a spiral bevel set (input pinion and ring gear) to angle the drive and reduce the speed. The other two stages are speed reducing only, using planetary gear systems. The spiral bevel ring gear is attached to the first stage sun gear shaft by a bolted joint. Flanges on the two components are clamped together by 24 bolts and between the flange faces is a shim. This is used to improve the working characteristics of the joint and position the gear axially on the shaft for correct meshing with the input pinion. The shim is made of steel with a thin coating of anti fretting material on both faces.

The joint is designed to transmit the drive from the gear to the shaft by friction through the shim. The primary function of the bolts, therefore, is to generate pressure between the mating surfaces. The greater the clamping force so produced the greater will be the torque transmission capability of the joint.

1.6.3.1 Service history of the forward transmission

Forward transmission Serial No.A7-1625 was originally supplied to the operator (British Airways Helicopters Ltd) in 1982 installed in BV234, G-BISP. The spiral bevel ring gear fitted at this time (Serial No M 5197) conformed to the then current -5 modification standard and remained with the transmission up to the time of the accident. The transmission, which had an overhaul life of 2,150 hours before modification, was removed on 18 October 1985, at 4,019 running hours, for scheduled overhaul. The manufacturer's Service Bulletin 234-63-1014 of 1 August 1985 which modified the spiral bevel ring gear to the -6 standard was incorporated at the same time.

After modification, the transmission was installed in BV234, G-BISR on 15 February 1986 and operated satisfactorily for 60 hours until the main rotor shaft had achieved its service life. This was replaced and the transmission returned to service installed in G–BWFC.

It had to be removed again after only 10 hours running because of a reduction of oil pressure and the discovery of metal particles in the oil filter. Examination of the transmission showed that the main oil pump was failing and producing metallic debris. The transmission was rectified according to the manufacturer's repair and overhaul manual and, although inspection was not required for a further 430 hours, the opportunity was taken to perform a torque check on the bolts which attach the spiral bevel ring gear to the first stage sun gear shaft. The transmission was then re-installed into G-BWFC.

It ran for a further 477 hours, when a scheduled torque check on the ring gear attachment bolts was performed. No evidence of loss of torque was recorded at either check. Following this second torque check, the transmission performed apparently unremarkably for a further 120 hours until the time of the accident.

At the time of the accident the forward transmission, A7-1625, had run a total time of 4,687 hours, 668 since the time of modification of the spiral bevel ring gear.

1.6.4 Relevant transmission Service Bulletins (SB)

1.6.4.1 SB 234-63-1009 (initial issue 29 June 1984)

This SB called for inspection at 35 hour intervals or retirement of forward rotor shafts (Part No 114D1245-7) after the accumulation of 1,600 flight hours.

1.6.4.2 SB A34-63-1010 ('Alert' bulletin - initial issue 20 August 1984)

This SB called for a torque check on the bolts which clamped the ring gear to the sun gear shaft in both forward and aft transmissions. The requirement for this arose when disassembly of an aft transmission, removed after a chip detector indication, revealed a nut and washer in the sump. The nut was from the bolted connection of the first stage sun gear and spiral bevel ring gear. Subsequent inspection indicated looseness in many of the bevel gear/sun gear shaft bolts.

The torque check was performed by applying an unopposed tightening torque to the ring gear joint nuts through the sump aperture. The requirements stated that:-

a) If no nuts rotated with 350 pound inches (lb.in.) applied, the joint was acceptable.

b) If no more than two nuts rotated below 350 lb.in., but above 275 lb.in., the joint must be reinspected at 100 flying hour intervals thereafter.

c) If three or more nuts rotated below 350 lb.in., or any nut rotated at or below 275 lb.in., the transmission was to be replaced.

This inspection requirement was incorporated into the Maintenance Manual. A similar check appropriate to the -6 standard joint was incorporated into the manual after the introduction of the modification specified in SB 234-63-1014/1015. This was identical in all respects except that the 350 lb.in. requirement was raised to 400 lb.in. and the 275 lb.in requirement to 325 lb.in..

1.6.4.3 SB 234-63-1014/1015 (initial issue 1 August 1985)

These SBs detailed the modifications to the bolted joint between first stage sun gear shaft and the spiral bevel ring gear. The manufacturer redesigned the joint as a product improvement with the intention of effecting a long term solution to the bolt looseness problems which gave rise to SB A234-63-1010. The redesign was justified by calculation, extrapolation of service data and a 150 hour test rig run of an aft transmission. The requirements for justifying the redesign were agreed with the FAA, as the primary certificating authority. The CAA were fully involved in the approval of the modification for embodiment.

The SB was approved for embodiment by the FAA, with the stipulation that the torque of the clamping bolts in one forward and one aft transmission were to be checked at 500 flying hours and two of each at 1,000 hours in a similar way to that detailed in SB A234-63-1010 (see 1.6.4.2). Additionally, one forward and one aft transmission was to be stripped and the condition of the bolted joint examined after 1,500 running hours. The CAA also approved the modification but required that two examples of each transmission be torque checked at 500 running hours. The manufacturer recommended compliance with the SB as soon as practicable after the parts became available.

1.6.5 *Embodiment of SB 234-63-1014*

The attachment of the spiral bevel ring gear to the first stage sun gear shaft was modified to the standard laid down in SB 234-63-1014 concurrently with a scheduled overhaul which was performed by the operator at 4,019 transmission running hours. This modification changed the parts affected from the original standard, denoted in this report as -5, to the new standard, here denoted as -6. The required reworking of the existing ring gear and sun gear shaft was subcontracted.

Although the final condition of the reworked components was as intended by the aircraft manufacturer, the subcontractor had changed the order in which the stipulated operations were performed, eliminating duplication of two of the processes. The Bulletin also called for protection of the reworked surfaces. This was done by the subcontractor using Presto Black rather than the specified Instant Gun Blue 44/40, which was similar, both having selenious acid as an active ingredient. The use of Presto Black had been approved by the operator, using his delegated design authority and was applied in accordance with the subcontractors process specification which they had been using for the previous 8 years. The aircraft manufacturer's representative had been aware of the use of Presto Black and its use has since been approved by the aircraft manufacturer if applied in strict accordance with the treatment manufacturer's instructions.

The work-sheets used when the reworked components were assembled into the forward transmission by the operator were hand amended examples of those which had been in use when the earlier -5 spiral bevel ring gear had been fitted. They still specified the lower torque that was appropriate to the -5 gear rather than that required by SB 234-63-1014. Although the header cards attached to the worksheets indicated that the SB had been introduced, the section in which the bolt torque was certificated remained unamended and did not indicate that the required higher torque had been used. However, the operator stated that the correct torque as specified in the SB had been used. The overhauled transmission was run on a test bed and released to service.

1.6.6 Spectrographic oil analysis programme (SOAP) (see 1.17.3)

BV 234 transmissions were the subject of SOAP monitoring. The forward transmission had been monitored in accordance with the limits specified by the operator, which were developed in consultation with the CAA and the appropriate actions taken at all times. After the modified transmission was reintroduced into service and until the partial oil pump failure, after 70 running hours, the SOAP results had given no cause for alarm. Post rectification, the concentrations of iron and copper particles increased rapidly to the first sample, but then remained steady, at an acceptable level for about 150 running hours. The concentrations then rose steadily, at a rate close to, but not exceeding the specified critical simultaneous rates for about 100 further hours, and then became erratic at raised concentrations over the next 50 hours. During this 50 hour period there was an isolated sample which indicated an exceedence of the critical simultaneous rates, but this was not confirmed by subsequent sampling. At no time did the absolute concentrations reach the next critical level, but the operator, as required, increased the sampling rate and considered replacing the transmission. However, at 370 hours post rectification, the concentrations settled again at a moderate level, and remained steady for a further 150 hours until the scheduled bolted joint torque check. The oil was changed and the concentrations of iron and copper again built up rapidly, but at less than the critical simultaneous rate. The operator had been running a programme of filter and magnetic plug wipe inspections in parallel with the SOAP. Although critical criteria were not exceeded in any of the monitoring techniques, a serviceability check on the transmission, in accordance with the Maintenance Manual and involving ground running and inspection, had been planned for the weekend following the accident and the possibility of changing the transmission was again being considered.

1.7 Meteorological information

A cold unstable west northwesterly airstream covered Shetland and the East Shetland Basin. At noon a warm front lay some 500 miles to the west and was moving eastwards at 40 knots. The surface wind at Sumburgh was 290° at 25 knots gusting to 38 knots. Visibility was 20 kilometers and the lowest cloud consisted of one okta of cumulus at 1,500 feet. The aircraft had encountered showers of rain and solid precipitation en route from the Brent field. The sea state at the accident scene was a heavy swell with mean wave heights between 0.6 and 1.2 metres.

1.8 Aids to navigation

Not relevant

1.9 Communications

The aircraft was in contact with the control tower at Sumburgh on the tower frequency of 118.25 MHz. The tape recording which was made of this frequency showed that at 1129.21 hrs the commander reported his distance from the airport as 4.5 miles. Twenty five seconds later the commander reported to his company operations room "FC is just coming in" and this was the last transmission made by the aircraft. Communications throughout the flight had been satisfactory.

1.10 Aerodrome information

Not relevant

1.11 Flight recorders

1.11.1 Cockpit Voice Recorder (CVR)

G-BWFC was fitted with a Fairchild A100 (CVR) which made a continous recording of conversation and sounds from the commander's, co-pilot's and area microphone stations. The duration of the recording was 30 minutes and covered the final period of the flight. The rear cabin area microphone was not fitted. The fourth channel was wired to record the main rotor rpm but due to an unserviceability only the carrier signal was present.

At 1129.56 hrs the co-pilot remarked "Seems to have got very noisy in here all of a sudden". The cabin attendant, who was making his pre-landing report to the commander agreed, saying, "it's in the cabin as well just behind this bloody box". The co-pilot then said "It's quite a loud noise, a roaring noise". Nine seconds later at 1130.21 hrs the CVR recording stopped.

1.11.2 Engine health monitoring system

The helicopter had been fitted with a Novatech TSR-16 engine health monitoring system. This was a trial installation and was not a mandatory airworthiness requirement. It recorded some 10 separate parameters from each engine on a solid state recorder. It proved impossible to recover any data from the device. However, the cassette had not been changed pre-flight and so any data would not have been relevant to the accident flight.

1.11.3 Frequency analysis

The frequency spectrum from the cockpit area microphone track of the CVR from `FC' was analysed over the whole length of the tape and compared with spectra previously obtained from other BV 234s. The comparison showed that, throughout the last 30 minutes of the accident flight, the audio signature generated by `FC' was different from that obtained from normal aircraft.

An abnormal feature of the signature of `FC' was the presence of a large number of harmonics of a fundamental frequency of 64.7 Hz. Some 62 seconds before the end of the recording, the 12th harmonic, which until then had been present as an infrequent and transient feature, suddenly became a permanent feature of the signature. At 0.6 seconds before the end of the recording the general noise increased dramatically and was clearly audible.

Analysis showed that, although the rotor speed track of the CVR was not working, it was possible to establish from rotor noise picked up on the area microphone, that the aircraft was operating at the normal rotor speed of 98% (221 rpm). In light of this, it was possible to relate the frequency of 64.7 Hz to the once per revolution of the spiral bevel ring gears in both forward and aft transmissions.

1.12 Wreckage and impact information

1.12.1 Recovery

A three man AAIB team embarked on MSV `Deepwater 1', a 98 metre long diving support ship with a dynamic positioning capability, on the evening of 6 November at Peterhead. A search for the sunken wreckage was started at 0900 hrs 7 November on the day following the accident. The helicopter had been fitted with two Dukane underwater locator beacons which facilitated its location on the sea bed. Search operations were assisted by high accuracy navigation and positioning systems, a saturation diving system, sonar beacon location equipment, a remotely operated submersible vehicle capable of providing seabed television pictures and a scanning sonar imaging system. Water depth in the area of the crash site was approximately 90 metres. Sea conditions were rough.
Wreckage was soon located and by late afternoon the CVR and the cockpit section of fuselage with the forward transmission and rotor still in place had been brought on deck. It was agreed that `Stadive', a semi-submersible oil exploration vessel on charter to Shell Expro Limited should join in seeking and recovering seabed wreckage. She remained on station until late on 14 November 1986 to clear the seabed of remaining wreckage.

By the evening of 10 November 1986 the major portion of the aircraft wreckage, including most of the transmission system, had been recovered. The forward transmission was removed from the cockpit section and transferred to `Stadive' on 8 November 1986 for detailed investigation in a more stable environment by another specialist team under the control of AAIB. It was transferred for further examination to a hangar at Aberdeen Airport and subsequently to AAIB at Farnborough.

1.12.2 *Wreckage distribution*

The wreckage lay generally within a 900 x 300 metre area, the longer axis of this area being orientated approximately east-west. Some of the items of wreckage had experienced an eastward tidal drift from their initial surface impact positions. With allowance made for this effect, the wreckage trail consisted mainly of a wide distribution of small fragments of rotor blade. The aft pylon with its transmission and rotor was located on its own and was the first substantial item of wreckage along the flight path direction. The main area of concentrated wreckage was located some 340 metres west of the aft pylon.

1.12.3 *General examination of the wreckage*

When the wreckage had been laid out, it was estimated that approximately 85-90% of the aircraft had been recovered. Structural disintegration was extensive, particularly of the rear and upper portions of the fuselage. The only large portions of the fuselage found relatively intact comprised the cockpit section, with the forward transmission and rotor, the aft pylon, with the aft transmission and rotor and a five metre long section of the forward cabin minus its roof and upper sidewalls.

The forward left pair of passenger seats, which faced aft, remained generally intact, including their seat belts. All the other passenger seats, which faced forwards, had suffered severe damage, consistent with gross overloading in a mainly rearwards direction. Most seat remains had detached from the aircraft floor. The flight crew seats, together with their harnesses, were found intact and still attached. Structure immediately adjacent to the cockpit was generally intact on the right side, but some disruption was present on the left.

There were marks which indicated that rotor blade contact with the cockpit section had occurred, but with relatively little velocity. No other evidence was found that any rotor blades had struck the fuselage, but structural disintegration of the cabin was such that this possibility could not be dismissed.

1.12.4 *Transmission and rotors*

Nearly all the transmission and rotor systems were recovered. Rotor blade damage was characterised by severe localised disruption in the case of two blades from each rotor and by gross disruption of the third blade from each rotor. Damage and markings were consistent with the effects of an initial substantial glancing contact between the forward and aft yellow blades in a manner that would have imposed an acceleration load on the forward rotor and a deceleration load on the aft rotor, followed by a collision between the forward and aft red blades that would have imposed the opposite loads on each rotor. The evidence also indicated that further minor collisions had occurred between forward and aft blades when they were in a highly abnormal relative orientation.

The synchronisation shafting had been damaged in a manner consistent with the effects of aircraft disintegration on impact with the sea. In addition, the No 2 shaft (part of the shafting between the combining transmission and the forward transmission), had suffered torsional failure consistent with overload in the normal direction of drive. Also, synchronisation shafting between the combining and aft transmissions exhibited marking that suggested the shafts had been displaced from their normal positions while rotating at high speed.

All five transmissions were recovered and were mainly intact externally. However, slight anomalous damage to the input pinion oil seal of the forward transmission was noted during initial inspection and further examination revealed the presence of a large quantity of metal fragments within the transmission. Both features were inconsistent with the effects of water impact, but indicative of pre-impact failure within the transmission.

1.12.5 *Forward transmission*

Preliminary inspection, aboard `Stadive', confirmed that, apart from the minor damage to the input pinion oil seal, the transmission appeared to be virtually undamaged but seemed to be seized. Initial internal inspection through the sump apperture showed that the teeth of both the input pinion and the spiral bevel ring gear had been severely damaged. The attachment bolts for the auxiliary oil pump and sun gear shaft thrust anchor plate had been broken free. Also, the input pinion bearing retaining plate studs had been stripped out of the bearing housing and the pinion itself appeared to have moved in towards the centre of the sun gear shaft.

When the upper half of the transmission had been removed it was possible to see a gap in the rim of the main spiral bevel ring gear about 3/4 inch wide. There was also evidence of contact between the top of the ring gear and the underside of the sun gear shaft upper bearing support. Following removal of the upper bearing support, it could be seen that the rim of the spiral bevel ring gear had fractured radially and had been distorted outwards in the plane of the gear. There was evidence that the outer edge of the ring gear had touched the inside of the transmission case whilst rotating, although it was not possible for this to occur without the rim being distorted outwards beyond its static position.

The transmission casing was cut away to allow the first stage sun gear shaft and spiral bevel ring gear to be removed as an assembly. Besides the radial crack, the ring gear had a circumferential failure around the outer radius of its flange which appeared to exist round at least 60% of the circumference (Appendix 2a). The gear and shaft were then taken as an assembly for further examination at the materials laboratory of RAE Farnborough. (Appendix 2b)

1.12.6 *General examination of bolted joint components* *

Before dismantling the bolted joint, the existing torque of the clamping bolts was checked. It was found that, on applying the torque check appropriate to a -6 standard joint (see 1.6.4.2) as specified in the Maintenance Manual, only one nut rotated with less than 400 lb.in. applied and that required 384 lb.in.. Sixteen of the 24 nuts required a torque above 700 lb.in. (the specified maximum -5 assembly torque) before turning although none required the minimum -6 assembly torque. There was a group of five nuts located almost diametrically opposite the radial fracture of the gear rim and one adjacent to the radial fracture which required significantly lower torque values than the remainder.

When the joint was dismantled, the circumferential crack was observed to run all round the flange of the ring gear on the face which mates with the shim. It had completely penetrated the flange for some 240°, running anticlockwise from the radial split (Appendix 2b). There was a rough surfaced groove in this flange face which had formed just inside the radius of the outer rim of the shim as it lay against the flange. The width of this groove varied regularly from about 3mm where it passed outside a bolt hole to about 5mm mid way between the holes. The circumferential crack ran mainly in this groove but ran outside the circle of the groove in three inter-bolt hole sites (1-2, 4-5, 7-8), the direction and plan shape of the crack being almost identical at all three sites.

The main circumferential crack had apparently been formed by a coalescence of smaller cracks which appeared to lie at an angle across the main crack and within the groove. The angle of these small cracks varied regularly from about 35° to the radial at one hole to almost circumferential at the next anticlockwise one, with an abrupt reversion towards radial as it passed each bolt hole (Appendix 2c). The metal surface in the groove showed corrosion which differed from that resulting from the gear's immersion in sea water. Where the circumferential crack had been opened up, it was noticed that the face of the crack through the flange had a fatigue like appearance. The fracture surface of the radial crack also appeared fatigue like over most of its length.

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*Unless specified, directions are given as if looking down on the ring gear or shaft, *ie* onto the plain face of the gear and the mating surface of the ring gear flange. Thus viewed, the spiral bevel ring gear and shaft are driven in an anticlockwise direction. The clamping bolts and their associated holes in the two flanges are numbered 1 to 24 anticlockwise from the radial crack.

On the side of the shim which had been against the gear there was a build up of sticky dark coloured material over the area which matched the groove in the flange (Appendix 2d). The outer rim of the shim was damaged where the free edge of the circumferential crack had struck it after the gear had been distorted. The flange of the sun gear shaft had light polishing wear in the same pattern as the plan shape of the groove in the gear flange. This was reflected in similar light wear on the shaft flange face of the shim.

All the teeth of the ring gear were badly damaged. The first tooth anticlockwise from the radial fracture, when looking from the underside of the gear, had particularly severe damage to its crown (Appendix 2e). The width of the gap in the gear rim, as a result of the separation of the radial fracture, was of the order of one tooth pitch. Some teeth carried a heavy impression of the pinion teeth on their overrun side and these impressions indicated that the pinion had moved in towards the sungear shaft. There was no evidence that the teeth of the pinion had slipped out of engagement with the bevel in the the region where the rim had separated from the flange whilst significant power was being transmitted.

1.12.7 Examination of failure of the gear flange and rim

The fracture surfaces of the radial and circumferential cracks on segments of the spiral bevel ring gear were microscopically examined. The latter had originated at a large number of sites which all lay in the worn groove on the mating face. There was at least one origin in every visible inter-bolt hole sector. Where the crack had not completely penetrated the flange thickness by fatigue, the shape of the fatigued portion indicated that the earliest initiating cracks had been between the bolt holes and had not initiated from them. The proportion of the flange thickness penetrated by fatigue varied from 100% between holes 24 and 8 to about 25% between holes 13 and 15. (Appendix 2f shows the main features of the flange fracture).

In the zone between holes 8 and 16 the non fatigue part of the fracture was by overload failure but its appearance suggested a series of short tearing actions rather than a single event (Appendix 2g). In the zone from hole 16 to 24, where visible, the fatigue fracture had penetrated more than 80% of the thickness of the flange. Although the circumferential crack had diverted into most of the bolt holes, no fatigue origins were found in any of them. The radial fracture of the gear rim was also predominantly fatigue, having its origin in the circumferential fracture face close to the lower surface of the gear flange. The final portion of the radial crack at the outer rim had failed as a single overload.

The fatigue generated surfaces of the circumferential crack had corrosion staining which was different in appearance to the general corrosion on other parts of the bevel gear, including the radial crack surfaces, which had probably occurred as the result of its being immersed in sea water. This suggested that some corrosion activity was present as the crack was progressing.

1.12.8 *Examination of the shim*

The black sticky deposit on the face of the shim was analysed and found to consist of a mixture of the Al-Br-Ek shim coating with iron oxides and other constituents of the gear steel. A section through the shim revealed that, in the deposit, the shim coating material had intermixed with debris from the groove in several layers. The surface of the steel core of the shim had corroded under this area of intermixing and the shim coating had lost adherence to the core.

1.12.9 *Examination of the groove in the gear flange*

A section through the groove in the flange showed it to be 'bath-tub' shaped with steep sides at both the inner and outer edges. The whole groove surface was overlaid by a corrosion like product and many small fatigue cracks had grown down from 'V' shaped notches in the base of the groove. Ghost cracks running through the corrosion like product, which extended into these notches, indicated that the 'V'–notches had been formed by corroding away the sides of the fatigue cracks as they grew (Appendix 2h), an indication of a corrosion fatigue mechanism. Analysis of the product revealed it to be composed of a mixture of Al-Br-Ek shim coating material with iron oxides which was consistent with the product expected from a fretting corrosion mechanism under wet conditions or corrosion under anaerobic conditions. There were traces of chloride indicative of the ingress of the maritime environment and this suggested that the joint interface could have acted as a crevice, producing the anaerobic acidified conditions consistent with the observations. The degeneration of steel by fretting or corrosion can produce similar results, such that fretting is often referred to as 'fretting corrosion'.

1.13 Medical and pathological information

Post-mortem examination of the recovered bodies indicated that all the fatalities had, without exception, resulted from impact forces. There was no evidence that the co-pilot, who was the handling pilot, was in other than good health at the time of the accident.

1.14 Fire

There was no fire

1.15 Survival aspects

1.15.1 Personnel

High impact forces were experienced on striking the sea, as evidenced by the degree of structural disintegration of the aircraft. The two survivors occupied two of only four seats on the aircraft that remained essentially undamaged. These four seats were in, or immediately adjacent to the cockpit section which was the only part of the aircraft to remain substantially intact.

The presence of the Coastguard helicopter, which was on a training flight in the immediate vicinity of the impact, was fortuitous. Furthermore, some local fishing vessels were on hand to render assistance. In the event they were able to recover some of the bodies which remained floating on the surface. Other bodies were recovered by the lifeboat and SAR helicopters. All the remaining bodies except one were recovered during the search of the sea bed.

Both survivors, having been in the water for about 10 minutes, suffered from hypothermia. They were wearing respectively an aircrew survival suit and a passenger survival suit but in both cases water had entered their suits by the neck opening. The crew of the Coastguard helicopter reported that it was necessary to pierce the ankle area of the suits to release water once the survivors had been recovered. The commander was not wearing his personal life jacket at the time of the accident but he was able to cling to a large piece of wreckage. He had made his escape by swimming towards a patch of light as the aircraft sank. He did not remember releasing his safety harness and estimated his submersion at some 10 feet. The surviving passenger stated that, on being awoken from dozing, he had time to move his survival suit zip fastener from a midway position to higher up but that it did not completely seal the neck opening. He found himself in the water and was entangled with one of the inflated life rafts. He clung to it until he was winched aboard the Coastguard helicopter.

1.15.2 Search and rescue

The subsequent search and rescue operation was co-ordinated by the Maritime Rescue Sub Centre of HM Coastguard at Lerwick, Shetland and later by the Rescue Co-ordination Centre Edinburgh. The immediate "on scene command" role was performed by a CP 140 Aurora aircraft of the Canadian Armed Forces which was on exercise in the area. This aircraft was later relieved by a Nimrod Maritime Patrol aircraft from RAF Lossiemouth. Two Sea King helicopters were made available from the fleet tanker RFA Olwen which was on exercise in the area and a further Sea King SAR helicopter was despatched from RAF Lossiemouth. Two Bell 212 helicopters from

Bristow Helicopters Limited's base at Unst (53 miles north of Sumburgh) were despatched to assist in the search. The Maritime Rescue Coordination Centre at Aberdeen monitored the operation throughout. Its search planning computer was used to assist the (SAR) planning officer in determining the optimum search areas based on tidal currents and leeway calculations. In the event this information was largely confirmatory since the actual search datum had been marked by the Coastguard helicopter. The search was suspended during the hours of darkness and resumed at first light on 7 November. All except the sea bed operations ceased later that day.

1.15.3 Equipment

The aircraft was fitted with an automatically deployable emergency location transmitter (ADELT) mounted externally in the left rear side of the fuselage and incorporating a VHF/UHF emergency transmitter and an X band radar transponder. Release could be initiated by pilot selection or automatically either by frangible or water sensing switches. Impact damage to the aft part of the aircraft was particularly severe and the ADELT was found broken up and rendered inoperative.

The aircraft carried four RFD life rafts. Two Type 18R 18 person rafts were mounted externally in the sponsons and inflated automatically on impact. The other two, Type 14R 14 person rafts, were carried in the cabin and were recovered from the seabed uninflated and still in their valises.

1.16 Tests and research

1.16.1 Tests on forward transmissions

Up to the time of the accident the manufacturer had not tested a forward transmission with a -6 standard spiral bevel ring gear. The justification for the modification was performed on an aft transmission. After the accident, the manufacturer performed a series of tests of forward transmissions fitted with -6 gears, in an attempt to discover the mechanism by which the groove in the ring gear flange was being formed. The first two tests, referred to as 'dry', were performed using an oil of similar composition, although not the one used in service by the operator and no attempt was made to simulate the operating environment.

The first test was of a transmission containing a ring gear modified by the manufacturer. This was subjected to four 50 hour test runs of 40 hours at 100% dual engine torque followed by 10 hours of 110% dual engine torque. The transmission was stripped for inspection of the ring gear flange face after the first 50 hours and then reassembled for the remaining test period. Inspection of the flange of the ring gear, at the end of the test, did not reveal any wear of significant depth but both the flange and shim showed the same pattern of wear as had been observed on the parts from the failed transmission.

The second test was of a transmission containing a ring gear modified by the same subcontractor, and in the same way as the gear which had failed in G-BWFC. This was subjected to six 50 hour test runs, each comprising 40 hours at 100% torque and 10 hours at 110% torque. The ring gear bolted joint was not disturbed throughout the test series.

When the flange of this gear was inspected at the end of the test, it was again noted that the depth of wear was small although the wear pattern was similar to that of the accident gear. It was seen, however, that on this gear flange, there were places where the wear had produced a shallow but sharp sided depression in the flange. Although this feature was shallow and exhibited no evidence of a corrosive attack, its form was similar to that seen on the accident gear and more sharply defined than any seen on typical service worn aft gears. The depth of the depression was insufficient to have penetrated the shot peened layer and there was no evidence of any embryonic fatigue cracking within it. Examination showed that although it was possible to detect selenium from the Presto Black treatment on the unworn flange surface, there was no trace of it in the bottom of the shallow depression. This suggested that the Presto Black treatment was not involved in the groove formation.

The third test was an attempt to reproduce the operating conditions specific to the North Sea environment and used a representative oil. Throughout the test, a salt laden mist was produced and directed at the transmission breather. The running cycle represented a typical out and back mission and simulated the torque requirements for an initial rotors running warm-up period, a typical climb, a protracted period of cruising followed by a descent to a rotors running turn-round on a platform before another flight cycle to a landing and shut-down. The shut-down condition was held overnight. This cycle was repeated until 300 hours flying had been simulated. The examination of the flange of this gear showed a similar wear pattern to the previous tests, but was significantly different in that there was evidence of corrosive attack within a well developed groove as noted on the accident gear, although shallower. After removal of the corrosion products it was also possible to see embryonic open mouthed cracks in the groove which were orientated in the same directions as those seen on the accident gear and other service -6 forward gears.

1.16.2 *Examination of other ring gear flanges*

A large number of ring gears, of both -5 and -6 standard from forward and aft transmissions, was examined to establish whether or not there was a consistent difference in the way the -6 forward gears had worn. All types displayed evidence of some wear of the flange mating face and of electro chemical action between the flange and the shim in the form of redeposited copper. However whilst all the -5 gears were generally worn under the shim contact area in a broad annulus from the rim to the bolt-hole pitch circle, the -6 gears were worn in a narrow annulus outside the bolt holes, albeit aft gears always having wider annuli. A further difference was seen in the depth and form of the wear. The wear depth of all -5 and -6 aft gears increased gradually from 0 at the inner radius of wear to up to about 0.007 inch near the rim of the shim in the worst cases, the worn surface being generally free of abrupt troughs; that in -6 forward gears was up to 0.05 inch deep, having a 'bath tub' shaped cross section with steep sides. All the -6 forward gears seen had the same wear pattern, the depth of which was approximately related to the length of time that they had been in service. The shims of the -6 forward gears had a dark sticky build up, in the same pattern as the groove, on the face which had been in contact with the gear flange. This was similar to that found on the shim from the accident transmission, but, as on the accident shim, very little build up was present on the shaft flange side.

The groove in the gear involved in the accident, which had been immersed in the sea, was severely corroded over its entire surface and it was found that corrosion was also generally present in the grooves of all other service worn -6 forward gears. It was noted, however, that in these other service gears there were bright, corrosion-free spots within the grooves and that the metal surface within these bright spots showed evidence of mechanical wear. The form of this wear appeared to be consistent with fairly small relative movements having occurred between the gear flange and the shim. These bright spots were at a depth where contact between the shim face and the bottom of the groove should have been impossible, but it appeared that the debris which had built up within the groove and also adhered to the shim coating had extended the reach of the shim surface down into the groove. This same effect had happened to a slight degree on the gear flange from the 'dry' test where the shallow but steep sided wear had occurred.

One of the service -6 forward gears, which had been in use for longer than the accident gear, was found to have developed the circumferential cracking observed in the accident gear. Examination showed that its formation had followed the same pattern with a large number of cracklets, at the same characteristic angles seen on the accident gear, coalescing to form a continuous circumferential crack. The cracklets were, as on the accident gear, seen to have the same open mouthed appearance indicating that the same corrosion fatigue mechanism was present in the groove. Another -6 gear, which had been in use for a total time of 324 hrs since modification, was also found to have developed some embrionic open mouthed fatigue cracks within a groove, but these had not yet coalesced. This gear had been separated from its shaft 105 hrs after modification and refitted with a new shim to correct a backlash error found during investigation of a seal defect. In the transmission strip report made at that time, no remark was made on the condition of the flange face.

1.17 Additional information

1.17.1 The ring gear and sun shaft joint used in the forward and aft transmissions of the BV 234 LR

1.17.1.1 The necessity of the bolted joint

Spiral bevel ring gear sets are a means of achieving an angular change of direction in a transmission. In the case of the CH47 Chinook, or its civil derivative the BV 234, spiral bevel sets are used in all 6 angular changes in the whole of the main transmission. The particular sets under consideration in this report are in the main forward and aft transmission assemblies.

When the CH47 was designed, the technology which would allow the spiral bevel gear to be machined integrally with the sun gear shaft did not exist. Due to physical difficulties in machining, it was necessary for the two components to be formed separately with flanges to allow them to be bolted together. This arrangement was common to most helicopter types but more recent technology now permits the machining of integral spiral bevel gears and shafts.

1.17.1.2 The development of the joint

The design of the bolted joint in the forward and aft transmissions of the CH 47 series aircraft (including the BV 234 LR) has remained fundamentally unchanged up to the introduction of the `D' model.

There had been, however, a continuous development programme to resolve problems found in service and to ensure the continued suitability of the joint as the maximum permitted weight of the aircraft and the available engine power was increased.

Original CH 47 models had bolts which were torqued to 400-500 lb inches and the flanges of the ring gear and shaft were 0.312 inch thick. The shim used was faced evenly with tinplate and this was referred to as a solid shim Appendix 1d). It was found that severe fretting was occurring between the gear flange and the shim close to the bolt holes, particularly on the gears of those aircraft which were cleared to a higher gross weight. This fretting was seen to be accompanied in some cases by small cracks close to the holes and in others by cracks between adjacent holes.

To alleviate this problem a modified shim was introduced in 1970 which had the tinplate coating relieved around the bolt holes with slots from this relief to the inner and outer edges (Appendix 1d). This was referred to as a scalloped shim. At the same time higher strength bolts were substituted and the torque applied was increased to 650-700 lb inches. The general intent of the modification was to increase the clamping force so as to reduce the relative movement between the flange face and the shim and to eliminate the possibility of fretting close to the bolt holes. This standard of joint was satisfactory in the forward and aft transmissions but the need for product improvement in the combining transmission had led to the adoption of a different surface coating for the shim. The new coating was Aluminium-Bronze-Ekonal (Al-Br-Ek) and it was scalloped like the tinplate shim. This type of shim was introduced in 1977 when the thickness of the flanges on the ring gear and shaft was increased to 0.375 inch.

The joint was at this state of development when the BV 234 was introduced into civilian service in about 1980 and is referred to in this report as being the -5 standard which was the modification state of the ring gear at that time.

In 1982, the manufacturer issued an instruction to apply `Loctite' (a binding agent) to the bolt threads at overhaul with the intention of increasing the security of the clamping bolt nuts. Following operation of this standard of joint for about two years, it was noticed, during transmission overhauls, that the joint bolts were becoming loose and in one extreme case a detached clamping nut was found free in the transmission sump. The manufacturer immediately issued an Alert Service Bulletin, instituting a check on the torque of the ring gear attachment bolts every 300 flying hours.

Investigations conducted by the manufacturer showed that the `Loctite' increased the running friction between the nut and the bolt thus leading to lower than expected clamping forces from the specified torque loading. They also found that the nuts being used were not meeting the required run-on torque and, therefore, were not working satisfactorily as self retainers. Accordingly, they amended the maintenance procedures, requiring all nuts to be checked for run-on torque before assembly and rescinding the use of `Loctite'. The requirement to check the bolt torque was, however, continued.

This last requirement imposed a considerable operating penalty on civil operators who demand higher usage rates from their machines than military operators normally do. In order to improve the joint, and so reduce the frequency of inspection, the manufacturers introduced a modification, by Service Bulletin 234-63-1014 for the forward transmission and -1015 for the aft transmission, in which the clamping force was increased by introducing larger diameter bolts which were installed at a higher torque. This in turn had necessitated a return to the solid type shim to avoid bearing overload of the Al-Br-Ek coating.

The ring gear joint was at this modification standard (referred to as -6) at the time of the accident to G-BWFC.

1.17.2 *Factors affecting the failure mechanism*

During the course of the examination of the gears and attempting to explain the process of the failure of the flange, the following factors, which were relevant to the failure mechanism, were identified:

(a) *Presence of moisture in transmissions*

The lubricant used in the transmissions was an ester based synthetic oil which is, to an extent, hygroscopic. In service it normally contained a water concentration of around 300 parts per million, although considerably higher concentrations had been recorded. It was noted that, in general, the water content reduced from its storeage value with use and achieved a substantially stable concentration. This water would have the potential to create 'wet' conditions suitable for corrosion related activity to occur. Post failure analysis also showed traces of chlorine in the oil indicating a possible contamination from the maritime environment.

(b) *Acceleration of fretting by 'wet' conditions*

A paper on research into the reaction of the materials present in the bolted joint suggests that moisture alone would increase the rate of production of fretting debris by a corrosion mechanism. It shows that, in the presence of moisture, the wear rate of steel against Al-Br-Ek is increased by a factor of 2 and that of steel against steel, wet, is about 25 times that which would occur at a dry steel / Al-Br-Ek contact. The observed differences in the degree of groove formation in the service gears (and to some extent the 'wet' test gear) compared with that on the 'dry' test gears, appear to support this finding as the contact between the shim and the gear would tend.towards the steel to steel type as the shim coating became progressively loaded with the iron products of fretting and corrosion.

Reference:- R.C.Bill - Fretting of AISI 9310 Steel and selected fretting-resistant surface treatments. ASLE Transactions Vol 21

(c) *Reduction of fatigue resistance in 'wet' conditions*

The possibility of fatigue crack initiation is greatly enhanced by surface damage produced by corrosion and also by the corrosion process itself, such that the stress level at which cracking can start may be drastically reduced in steel materials. Furthermore, the presence of a wet atmosphere can increase fatigue crack growth rates by an order of magnitude. The presence of water is the dominant factor in creating this corrosive environment, and the additional effect of salt in solution may further accelerate the process. Cracks growing in such conditions typically have corrosion widened mouths caused by corrosion of the fatigue crack as it grows. Examples of this action were observed on the -6 forward transmission gear flanges from service transmissions and on the 'wet' test gear.

(d) *Shot peening*

Shot peening is a process in which the surface of a metal is bombarded with small spherical particles. The purpose of this is to introduce a layer in which there are residual compressive stresses. This increases the resistance of the material to the initiation and growth of fatigue cracks which is primarily caused by fluctuations in tensile stress. The depth and compressive stress of the layer is controlled by the duration and intensity of bombardment to which it is subjected but over-use of the technique can give rise to mechanical defects on the surface which may then act as fatigue nucleation sites. The specification of the peening to be applied to the ring gear flanges was intended to produce a layer between 0.006 and 0.008 inch deep. The examination of the failed gear and others revealed that this depth of layer was achieved without producing any surface defects.

1.17.3 Spectrographic oil analysis programme (SOAP)

SOAP is a technique used for health monitoring of oil lubricated mechanisms. The philosophy adopted is that, as components wear within the mechanism, the minute particles produced by the wear processes become suspended in the oil. Thus, by determining the proportion of selected elements in the oil, usually measured in parts per million, it is possible to get an indication of the extent to which components containing particular elements are wearing.

The quantity of any element that can be expected to be present in suspension will be, in some way, proportional to the amount of that element which is in a location where wear can take place and the relative proportions, normal concentrations and acceptable rates of change of concentration of each monitored element have to be established from experience of a particular mechanism. Thus, the normal and acceptable SOAP signature of a particular monitored mechanism is determined as the total use accumulates. During this learning process, any abnormal signatures which are noted have to be related to failures or abnormal wear discovered as a result of physical examination of the mechanism. In this way a dossier of failure and impending failure signatures can be accumulated. In some cases where particular elements are present in unique or a limited number of locations within the mechanism, it may be possible to deduce the part which is wearing; but confirmation should be established by physical examination. Account must also be taken of the way in which the addition of fresh oil will dilute the concentrations of elements.

The technique, whilst useful in the monitoring of known wear problems, has limitations in the case of multiple failures, where several signatures may be overlaid, and in the diagnosis of novel failures which produce a hitherto unseen signature. It is also recognised that the technique is unsuited to the detection of fatigue in components, since, unless the fatigue creates a marked increase of wear rates due to increased flexibility of the affected part, the fracture process itself will be unlikely to produce sufficient wear particles to create a significant change in the overall signature of the mechanism.

In the case of the forward transmission of the BV 234, considerable experience had been obtained and threshholds for the concentrations of the elements within it had been long established. As a result of the problem of the loosening of the bolts in the spiral bevel ring gear to sun gear shaft joint, a signature involving rates of increase of iron and copper concentrations had also been established. The operator was monitoring the transmissions in accordance with the guidelines laid down by the manufacturer for these elements and to more stringent requirements for others.

1.17.4 The Helicopter Airworthiness Review Panel

In June 1984 the CAA published CAP 491 which was a report of the Helicopter Airworthiness Review Panel (HARP) of the Airworthiness Requirements Board (ARB). The panel's principal terms of reference were:

1. To review the existing airworthiness requirements for public transport helicopters, taking into account associated operational practice.

2. To recommend in principle such changes as are considered necessary and practicable to ensure the safety standards of these aircraft match more closely those of comparable fixed wing aircraft.

The panel made 15 recommendations and submitted its report to the ARB. Of all the recommendations, three of them dealt with the subject of condition monitoring. The relevant section of the report and recommendations are reproduced at Appendix 3.

The HARP report also identified the problems associated with the remedy of defects which are discovered during the early stages of service by a new type of helicopter. HARP Section 7.9 - Service Development and Product Support- includes the following statements and recommendation:

> "It is a fact of engineering life that no matter how great the effort put into developing any complex product such as an aeroplane or helicopter not all residual problems or defects will have been eliminated when it first enters service. The proper procedure has been and should be for the manufacturer and the initial operators to co-operate fully to eliminate early defects.
>
> This is often easier to say than to achieve. To remedy defects means change, which takes time and money and requires replacement or new parts. But in the case of helicopters safety may well be prejudiced, especially if the problem areas are in the rotor or transmission systems.
>
> RECOMMENDATION 4. We recommend that before a new type of helicopter is introduced on to the British Register the manufacturer and operator should evolve a system, in conjunction with the CAA, the better to review and take action upon service difficulties affecting airworthiness; where more than one operator is involved on a new type, the system should allow for cross feeding of knowledge and experience between operators."

Furthermore, in a section entitled 'Quality control' the panel quoted the conclusion of a senior engineer that '... there is a strong case for introducing a category of 'VITAL' components, where critical parts of the design cannot be made 'damage tolerant'. The quality control for such parts would be handled with the utmost seriousness'. The panel believed that it was important for the CAA to publish a manual of recommended practice to '... assist all concerned in the manufacture, operation, maintenance and overhaul of helicopters to establish and maintain the quality of 'VITAL' components. Appropriate recommendations were made in the HARP report.

1.18 New investigation techniques

Nil

2 Analysis

2.1 General

Operation of the flight up to the accident had been in accordance with normal procedures and, in the short term, could not have contributed to the transmission failure. The crew received virtually no warning of the impending catastrophe. Their recognition of an increased noise level on the flight deck and in the forward fuselage was so shortly before the event that they had no time to analyse the situation or take any action. Indeed, given the nature of the catastrophic failure there was no possible action that they could have taken to prevent or alleviate the accident.

The sudden and dramatic loss of control reported by the commander was totally consistent with the loss of the aft pylon with its rotor. Once the pylon had detached, there followed independent descents of the aircraft and the pylon into the sea. Wreckage characteristics made it clear that initial impact of the main portion of the aircraft with the sea was made in a tail down attitude with considerable vertical velocity, probably followed by an inverted secondary impact of the upper left side of the fuselage with the surface. However, it is conceivable that the cockpit section had hinged downwards at the bulkhead joint just before impact. This would substantiate the commander's statement that he was facing the sea during the final plunge. This hinging open also offers an explanation for the miraculous escape of the passenger who was seated on a rearwards facing seat behind the bulkhead.

The report now considers some aspects of survivability, the disintegration of the aircraft and subsequent loss of control. It then considers the factors which led to the catastrophic failure of the forward transmission and examines the certification and testing which was applied to modified spiral bevel ring gears. The usefulness of condition monitoring techniques is then discussed.

2.2 Survival aspects

The degree of break up of the fuselage on impact with the sea was such that all except two occupants perished as a result. The two occupants who survived the impact did so because they were in, or adjacent to, the cockpit section, which was the only part of the fuselage to remain relatively intact. Their continued survival in the sea was due to prompt rescue since both their survival suits had allowed considerable quantities of water to enter. Fortunately, the Coastguard helicopter was able to rescue them after about 10 minutes in the sea, albeit suffering from hypothermia. Had this aircraft not sighted the wreckage, the chances of rescue arriving in time could have been crucially dependent on the functioning of the ADELT, but this was destroyed by the impact. Since the accident, it has been proposed to modify ADELT installations to include an independent power supply within the fuselage mounted housing so that deployment is not jeopardised by any interuption of the aircraft's power supply. However, in this case the ADELT was located in a position which happened to take the brunt of the impact and it was not considered that any sensible redesign could ensure that the ADELT would survive such an impact. Finally, the availability of the crew's SARBE personal locator beacons is sufficient justification for the crew life saving jackets to be worn at all times irrespective of considerations of personal survival. Company instructions to this effect had been published three months before the accident.

2.3 Disintegration and loss of control

The wreckage distribution and witness evidence made it clear that the aft pylon of the aircraft, complete with the aft transmission and rotor, had detached from the aircraft in flight. Damage characteristics suggested that the cargo loading ramp tongue and the synchronisation shaft covers had probably left the aircraft before it struck the sea. Detachment of the pylon was consistent with the effects of the in-flight collision between the forward and aft rotor blades. Examination of the wreckage confirmed that a major collision between one blade from each rotor had occurred and, as previous cases of such an event have shown, reaction forces and blade imbalance cause the aft pylon to be torn from the aircraft. All control of the helicopter would have been lost following detachment of the rear pylon and rotor.

2.4 Failure of the forward transmission

The analysis of the failure sequence falls into two distinct parts. The first part considers the chain of events resulting from the initiation of corrosion fatigue cracking of the spiral bevel ring gear in the forward transmission; the second is concerned with determining the reasons for the formation of the groove in the attachment flange and the initiation of this cracking.

2.4.1 Primary failure

The evidence indicated that the primary failure was circumferential fatigue cracking of the attachment flange of the spiral bevel ring gear in the forward transmission. The metallurgical evidence showed that this initiated at a large number of sites all round the outer circumference of the flange and was associated with a groove formed by a combination of wear and corrosion in the flange upper face. The stresses in the upper face of the flange due to gear meshing forces are primarily compressive, and shot peening of the surface contributes a further compressive stress. However, a strain survey conducted by the aircraft manufacturer during earlier development of the transmission indicated that gear deflection induced by meshing forces causes the upper surface of the flange to experience tensile stresses at some points remote from the position of mesh. These tensile stresses are relatively low, and the service history of the gear, in its earlier modification states, indicates that, in the absence of serious flange surface deficiencies, they give no cause for concern. However, this level of tensile stress appears to have been critical in the presence of the stress concentration effect of the groove, with the loss of the shot peened layer and the influence of corrosive conditions resulting from water, some possibly from the maritime environment, present in the oil. This led to the initiation of corrosion fatigue cracking which progressed downwards through the flange. Thus the fatigue failure was related to the formation of the groove.

The examination of many forward and aft ring gears showed that only forward transmission gears of the -6 standard suffered concentrated grooving damage to the flange with associated corrosion within the groove. The -6 gears from aft transmissions had suffered much lighter wear and although the mechanical attack on the surface was similar to that seen on forward gears the corrosion element was much less severe. All ring gears examined by AAIB had been reworked from -5 standard gears and metallurgical examinations revealed no deficiencies in the material properties of the flanges of any of them. Particular attention was given to the possible effects of using Presto Black, but no evidence was found to suggest that this treatment had been applied or protected in a manner that had adversely affected the resistance of the surface to mechanical or corrosive attack.

The fatigue cracking associated with the groove had progressed by varying amounts at different parts of the flange, ranging from complete penetration over about one third of the circumference between holes 24 and 8, to about 25% of the flange thickness between holes 13 and 15. The radial crack, which eventually severed the gear rim grew by fatigue from a point on the circumferential crack near the lower surface of the flange, midway between holes 1 and 24, and extended at right angles to the circumferential crack. Its position, in a place where complete circumferential fatigue penetration of the flange had occurred, adjacent to a sector with residual flange strength, is consistent with the way in which the meshing load would have to be carried circumferentially round the rim of the gear rather than radially into the flange. The radial crack would thus appear to have depended, for its initiation, on the existence of the circumferential crack. It was judged to have grown relatively quickly by comparison and been little influenced by corrosion effects.

The evidence indicated that the radial crack progressed by fatigue until the remaining section available to transfer meshing loads circumferentially failed in overload. It would not be until this condition was reached that there would be sufficient in-plane flexibility of the gear rim, then acting as a curved cantilever, to permit progressive overload tearing of the sections of the flange which the fatigue cracking had not fully penetrated.

This sequence was corroborated by analysis of the area microphone track of the CVR. The sudden appearance of a new harmonic of the fundamental ring gear frequency, about one minute before the end of the recording, was indicative of a step change in the physical condition of the gear at that moment. Since the fatigue and tearing failures are both essentially progressive, the only potential for a step change of condition would be the complete radial separation of the gear rim. This would suggest that the tearing of the residual parts of the flange occurred over the space of about one minute, or 4000 revolutions of the ring gear and this postulation appears to be consistent with the number of tearing steps observed.

As the tearing progressed, the length of the cantilevered sector of the rim increased to the point where the moment applied at its root, by meshing forces, caused permanent outward deformation of the sector. This caused a gap to open in the rim, at the radial fracture, and resulted in an apparent increase in the number of teeth on the gear. This would lead to a change of gear ratio in the forward transmission, thereby destroying the synchronization between the two rotors and leading to the aft rotor overtaking the forward. Information from the manufacturer indicates that with an apparent increase of one tooth on the bevel gear, the rotor blades could desynchronize into a potential clashing position within 1.5 seconds.

The damage to the teeth of both the pinion and the bevel indicated that, although the bevel rim was very flexible in the out of plane sense, tooth slip did not occur anywhere but at the gap. The presence of the gap in the rim, which is unlikely to have been equivalent to exact tooth spacing, would have caused the driving pinion to crash back into mesh after crossing the gap. The severe damage to the first gear tooth after the gap was evidence of this. The size of the gap, approximately one tooth width in the static condition, would almost certainly have been greater when pinion drive loads were being imposed, and the evidence of rubbing of the rim on the casing demonstrated that this occurred. Thus, under load, the gap was probably the equivalent of at least two teeth, and this would lead, more quickly, to the possibility of a rotor clash. Further evidence of this was provided by the sudden very loud noise recorded in the last 0.6 seconds of the CVR area microphone track which was consistent with what might be expected from gears in foul mesh. The duration of this noise suggested that a rotor clash occurred in a time consistent with a two to three tooth equivalent gap.

The abnormal axial loads experienced by the forward transmission pinion and sun gear shaft, leading to failure of their thrust retention, and the torsional overload failure of the No.4 synchronizing shaft, resulted from collisions between forward and aft rotor blades. The evidence was consistent with collisions causing a sudden acceleration of the forward rotor, followed by its sudden deceleration. The rotor blade damage was also consistent with this sequence.

Damage to the rotor blades would inevitably lead to loss of rotor balance and, consequently, severe loading of the rotor supports. The evidence shows that the aft pylon structure was unable to sustain the imbalance and collision reaction forces and separated from the rear fuselage, carrying the aft transmission components with it.

2.4.2 *Formation of the groove in the forward ring gear.*

The analysis of the main failure sequence revealed that the fatigue stemmed from the groove that had been formed in the mating face of the flange of the spiral bevel ring gear and the metallurgical examination was directed at trying to establish the conditions which had led to the formation of this groove.

The examination of a large number of -5 and -6 standard ring gears showed that the wear on the flanges of the -6 gears, especially those from forward transmissions, was significantly and consistently different. This showed that the way in which the bolted joint in the transmissions behaved as a result of its being redesigned had changed, leading to a highly localized attack on the flange faces which was much more severe on forward gears.

A major feature of this attack was the evidence of significant corrosion within the worn area which was much less evident on -5 gears and -6 aft gears. This corrosion was present, in varying degrees, on all -6 forward gears examined except the two which had only been run on the test stand without the salt fog atmosphere. These two gears, however, still displayed the characteristically narrow areas of wear, lying well inside the radius of the rim of the shim, unlike the wider, more diffuse pattern seen on the -6 aft and all -5 gears. On the flange of the second `dry' test gear the metal had been eroded in some areas, to a depth below the surrounding flange face. Direct contact between the shim and the flange could not have occurred without the shim face locally acquiring extra material to cut down into the flange. A similar feature had been observed in the grooves of service gears where evidence was found of mechanical wear on the corroding surface inside the groove. It would thus appear that the deposit which was found to have built up on the gear contact face of the shim was continuing the mechanical wear processes within the groove in conjunction with the corrosion.

Comparison of the groove in the flange of the gear from the second `dry' test with that of the `wet' test gear showed a clear similarity of form, implying that the same mechanical wear process had occurred in the two cases. It was seen that, under `wet' test conditions, the damage rate had been greater than in the `dry' test, and that corrosion similar to that seen in the service forward -6 gears had occurred. The most significant difference in the groove from the `wet' test, however, was the occurrence of embryonic open mouthed cracks within a shallow groove (0.003 in.) and within the thickness of the shot peened layer. This feature showed that the corrosive environment within the groove had so dramatically reduced the resistance of the gear material to fatigue that even the beneficial effects of the peening had not prevented it.

Comparison of the `wet' test gear with a 324 hour -6 service gear revealed that the service gear had developed embryonic fatigue cracking and been more deeply grooved. This suggested that the conditions which reduced fatigue resistance and produced mechanical wear in service gears were more severe than in the `wet' test. This gear had been separated from its sun gear shaft 105 hours after modification and refitted with a new shim to correct a backlash error found during a transmission strip to investigate a seal wear problem. As no comment was made on the condition of the gear flange at this strip, its appearance cannot have been obviously degraded at this time.

This comparison of `wet' and `dry' test, and service gears, indicated that the groove was formed by a combination of mechanical wear and corrosion. The formation of the characteristic groove shape by the `dry' test indicates that mechanical wear is a major part of the groove initiation process, but the relative importance of mechanical and corrosive erosion in enlarging it is unclear. The `wet' test, however, would seem to indicate that the presence of a corrosive environment is an essential ingredient for the early formation of fatigue cracks.

The examination of the corrosion products in the groove and embedded in the shim coating did not reveal the presence of the classic products of crevice corrosion but were consistent with the results to be expected from fretting corrosion in an oxygen depleted environment. This is consistent with the fact that similar conditions for the occurrence of crevice corrosion exist in a newly assembled forward -5 joint as in a -6 one. Since, in the absence of this type of damage in -5 gears, only minor corrosion occurs, it would appear that this mechanism is not at work initially. There is no doubt that, with the groove being formed inside the rim of the shim, the conditions for oxygen depletion occur, which will in turn lead to aggressive acidic conditions in the groove if water is present in any quantity. The hygroscopic properties of the ester-based oil being used would ensure that some water is present, part of which may derive from the maritime environment. This may be channelled towards the joint due to the basin like form of the gear and drawn into the joint by capillary action, particularly under working conditions.

So it would appear that the mechanical wear, of the type observed in the `dry' test and the presence of moisture, must occur before the corrosive conditions necessary for the initiation of fatigue cracking at relatively low tensile stresses can exist. The change in the detailed configuration of the joint would appear to have resulted in concentrated wear and the establishment of a groove corrosion cell.

2.5 Certification of the modification

It is evident from the examination of several ring gears that the performance of the -6 gear joint as applied to the forward transmission was consistently unsatisfactory. This was a direct result of the change in the design wrought by the modification from the -5 standard. To assess the procedures by which such a modification could be introduced, without this feature being exposed, it is first neccessary to define the state of knowledge which existed at the time that the modification was certificated.

The certification of the BV 234 as a civil aircraft had taken into consideration the long service history of the CH47 Chinook. Part of that history included the development work that had to be done on the transmission bolted joints to combat the fretting and associated cracking which occurred with the early solid tinplated shim. This early work had shown the neccessity for firm clamping of this joint and the desirability of relieving the shim coating around the clamping bolts to reduce the likelihood of fretting close to the bolt holes.

Service and overhaul records up to the time of the introduction of the -6 modification had indicated that the aft transmission bolted joint had suffered slightly more problems in service than the forward. Also, the service history of the BV234 in North Sea operations had not shown any evidence of corrosion occurring in the bolted joints which would have suggested that this new environment had introduced extra factors to be considered.

Comparison of the observed wear characteristics of the bolted joints on -5 forward and aft transmissions showed there to be no significant difference between the two. This supported what was to be expected as, although the gears and shafts of which the joining flanges were part were different, the two joints were identical. Futhermore, the wear observed was relatively light and had not been seen to penetrate the shot peened layer on the flanges.

All these factors appear to have led to a situation where the important considerations in the design of the joint were the possibility of fretting and the maintenance of clamping force. The possibility of fatigue was assessed as being present only in association with fretting, since the basic design had shown no tendency to fatigue in the absence of flange surface damage.

The requirement to check the torque of the joint bolts at 300 hour intervals, following the discovery of loose ones, was a considerable operating penalty for civil operators. As a result, the manufacturer perceived a need to produce a modification to the joint which would remove this burden. Their approach to this problem was to apply classic joint improvement technique, which essentially involved increasing the clamping of the joint. Since this increase in clamping would have lead to bearing overload of the shim facing material if the scalloped pattern of the -5 shim had been retained, a return to the earlier solid type shim was needed. However, in its tinplated form this had given rise to some fretting associated cracking. Therefore the testing which was felt neccessary to qualify the modification for release was directed at establishing whether, with the increased clamping and Al-Br-Ek shim coating, this problem showed any tendency to return.

Experience of operations in the North Sea had not indicated that the environment produced any significant effects on the joint, and accordingly the manufacturer gave no consideration to introducing environmental inputs to the test. Some justification for this approach can be derived from the fact that the examinations of aft transmission -6 gears have shown only slight evidence of significant corrosion activity in the joint. It is therefore unlikely that, even if such inputs had been made in the testing of an aft gear, significant differences in performance would have resulted.

With this information available, the manufacturers believed that they were making a minor change in the design of the joint, using accepted improvement techniques. Thinking that they were aware of all the possible problem areas, they also believed that a 150 hour test would be sufficient to reveal the first signs of any potential shortcomings of the redesign. Although there had been no obvious difference in performance of forward and aft -5 joints, the manufacturer elected to test an aft transmission to qualify both joints on the basis of the aft having had slightly more problems in the past.

This philosophy was acceptable to the FAA, who agreed the validity of the theoretical work presented and agreed with the manufacturer that a 150 hour test run would be adequate to expose the initial indications of any undesirable characteristics. As the authority concerned with the airworthiness of a number of BV 234 helicopters, the CAA was kept fully informed of the progress of this modification. So once it had been decided that tests on an aft transmission were adequate to qualify the modification in both the forward and aft, the feature which gave rise to the accident was never going to be revealed during the qualification testing. Furthermore, the results of the post-accident testing suggest that even if a forward transmission had been used for a similar 'dry' test, it is unlikely to have revealed this feature.

2.6 The failure of the certification process

That this modification could be released into service, possessing characteristics which made it inherently dangerous when applied to the forward transmission, indicates that the certification process to which it had been subjected had been inadequate.

The consequences of an unpredicted failure depend on where in an aircraft they occur. Clearly there are places where such failures are inevitably disastrous and it is in such places that the most stringent proofs of integrity are required and usually demanded. When the system of checks fails it can usually be traced, either to not perceiving a particular component as vital to the maintenance of flight, or to not demanding sufficient proofs of its durability. In this particular case the whole synchronisation system, of which the ring gear bolted joint was a part, was regarded as vital for continued flight.

The manufacturer appears to have considered that it would be sufficient proof of the integrity of the joint to show that the design changes had had the desired effect on the torque retention characteristics without introducing any undesirable side effects. Their requirements to achieve this proof of integrity were based on their experience of the problems that had been encountered in the bolted joints in three different zones of the transmission system. This included some 15 years of military use and civil operations in a maritime environment over 4 years.

The FAA, as the `Primary Certificating Authority', must have considered that the work done by the manufacturer was sufficient for the modification to be granted full engineering approval, and allowed it to be introduced into service. To monitor in service performance they required periodic torque checks followed by a strip examination of one forward and one aft transmission after 1,500 running hours (about two thirds of the established overhaul life). The FAA believed that this inspection programme was adequate and sufficiently conservative in timescale to ensure that the modification had cured the problem and to expose any unpredicted shortcomings before they became critical. The CAA, as the `Validating Authority' in the UK, accepted the engineering approval given by the FAA but took a more demanding approach to confirming in service behaviour by requiring that two examples of each transmission should be torque checked at 500 hours. The intention was that, after satisfactorily completing this introductory inspection period, checking the torque of the ring gear nuts between overhauls would no longer be necessary or required.

Periodically machines and structures do not work as predicted, even when the prediction uses the most advanced knowledge and analytical techniques available. Such is the amount of engineering data presently available that, even with the most conscientious research it is not possible to take account of the full range of information. The factor, or combination of factors, which made the joint lethal in the forward transmission is so subtle that it has not been possible to determine the critical difference between the forward and aft joints. Methods to expose such differences lie either in more rigorous testing or more cautious introduction into service. Airworthiness requirements should be framed to take account of these factors to reduce the effects of unexpected failures to an acceptable level.

The validity of rig testing must always be slightly suspect as it is virtually impossible to reproduce faithfully the real operating environment, even if all factors have been identified and built into the test procedure. This is doubly true since no two nominally identical components will ever perform exactly the same. It has always been accepted that the only true measure of performance of any mechanism is to be obtained in service use.

The tests on forward transmissions after the accident have shown that, without environmental inputs, a test twice as long as that done for approval produced some evidence of the wear mechanism which is thought to be the start of the failure process. Its significance, however, is unlikely to have been appreciated without the benefit of hindsight. Thus, to have exposed the inherent weakness of the modification in its application to the forward transmission, it would have been necessary to have performed a longer test on a forward transmission than that run on the aft one and to have included environmental conditions.

An alternative approach would have been to be more conservative in the requirements used to introduce the modification into service. Full approval of the modification was dependent on the successful completion of the introductory period, during which the aircraft was being used for revenue flying. This demanded a conservative approach to determining the initial inspection period. It would seem that had strip inspections at say 300 hour intervals been required, the shortcomings of the modification, as applied to the forward transmission, would have been seen before becoming hazardous. Such a frequency of strip inspection would have been hard to justify on the basis of the past history of the transmissions. However, any change to vital components, such as were affected by this modification, must attract a most rigorous inspection programme on introduction. It is acknowledged that interference with components without good reason can unnecessarily introduce dangers and the path between prudence and overscrutiny is difficult to judge.

The certification process to which this modification was subjected failed to expose the unsatisfactory characteristics of the joint in the forward transmission. The manufacturer and airworthiness authorities considered the modification to be a relatively straightforward improvement to the previous design standard. Consequently, they failed to appreciate that there was a real possibility that it might perform in a fundamentally different way to forward and aft transmission joints of earlier modification states, or indeed to a modified aft transmission joint under test. With the benefit of hindsight this might have been avoided if more realistic and rigorous testing had been required. Thus, this accident demonstrated that the performance history of the pre-modified component was an unsound basis for determining its post-modification performance.

2.7 Condition monitoring

Frequency spectral analysis of the area microphone track of the CVR recording after the accident revealed the presence of a signature that on comparison with other BV 234 recordings was clearly anomalous. This signature was present over the whole 30 minutes of the available recording, and assessment of the gear failure progression makes it reasonable to conclude that it was probably present for a considerably longer period, quite possibly for many hours of operation. It is well known that the most telling parameter reflecting the health of any item of high speed rotating equipment, be it turboshaft engine or a helicopter transmission, is likely to be its noise and vibration signature.

Following the accident there was renewed interest in the possibility that warning of such a catastrophic failure could have been achieved by means of in flight monitoring of certain vital components. Such a system is highly desirable for flight safety reasons. The HARP report made three recommendations designed to encourage and promote the development of condition monitoring systems. The report contains a realistic statement of what is required but recognises that much development of suitable systems is necessary. This accident reinforced the need for urgent progress in this field and a substantial sum of public money was made available in support of continued research. It is recommended that the CAA should report on the progress that has been made towards the early incorporation of a specification for suitable condition monitoring systems into airworthiness requirements for helicopters and indicate the time scale and scope of likely future developments.

2.8 Summary

The accident occurred because the spiral bevel ring gear in the forward transmission failed, causing desynchronisation of the helicopter's twin rotors. This allowed the rotors to collide which in turn led to the disintegration of the aircraft. The ring gear failure stemmed from corrosion fatigue which was initiated by the unpredicted wear and corrosion characteristics of the bolted joint attaching the gear to its shaft.

The bolted joint was of an approved modified design and was still under scrutiny in its introductory phase before the operator was permitted to dispense with the requirement to monitor bolt torque between overhaul periods. The manufacturer and airworthiness authorities failed to perceive the possibility that the change in the design of the bolted joint might lead to it performing in a radically different way to that previously experienced. As a result, they did not explore its working characteristics sufficiently to expose its inherent weakness.

3 Conclusions

(a) *Findings*

(i) The crew were correctly licensed and competent to conduct the flight.

(ii) The helicopter had been maintained in accordance with an approved maintenance schedule and its Certificates of Airworthiness and Maintenance were valid at the time of the accident.

(iii) The helicopter was loaded with its full complement of passengers (44) and had been correctly loaded within its permitted centre of gravity range.

(iv) The aircraft crashed out of control into the sea from a height of about 500 feet.

(v) Fatal injuries were sustained by all occupants except the commander and one passenger. Their survival and rescue was entirely fortuitous.

(vi) Spiral bevel ring gears within some BV 234 transmissions, including G-BWFC, had been modified to eliminate a loss of torque which was occurring on the bolts clamping the ring gear to the sun gear shaft. The manufacturer's Service Bulletin detailing the modification had received engineering approval from the FAA and was approved for embodiment into U.K. registered aircraft by the CAA.

(vii) The spiral bevel ring gear in the forward transmission fractured and synchronisation between the rotors was lost. The tip of an aft rotor blade struck the root end of a forward rotor blade and the resultant forces tore the complete aft rotor assembly from the aircraft.

(viii) The Cockpit Voice Recorder tape showed an abnormal frequency signature throughout its duration. It could be identified as emanating from the forward transmission. The relevant harmonics increased in amplitude for the final 60 seconds. There was a general noise increase for the last 0.6 second. The abnormality was only audible to the crew for the final 60 seconds, by which time they were unable to take any action to prevent the accident.

(ix) Modified spiral bevel ring gears which were used in the forward transmissions consistently suffered wear and corrosion which gave rise to conditions in which fatigue could readily initiate in the bolted joint flange.

(x) The assumption made by the manufacturer, and accepted by the FAA and CAA, that the modified bolted joints in the forward and aft transmissions would behave similarly was wrong, although unmodified ones had behaved similarly in the past.

(xi) The hitherto accepted aircraft industry standard of test performed on an aft transmission was inadequate to expose the behaviour of the modified joint in the forward transmission.

(xii) A similar test performed on a forward transmission would also have been unlikely to have exposed this behaviour.

(xiii) The 'in service' inspection programme, which was based on the results of tests on an aft transmission and previous service experience of both transmissions, was not adequate to reveal the impending failure of the forward bolted joint.

(xiv) The hitherto accepted processes of approval by the FAA and CAA were inadequate for the incorporation of a modification to a vital component.

(xv) Condition monitoring of the transmissions might have given indications which could have prevented the accident but suitable systems were not developed to the point where they were approved for operational use at the time of the accident.

(b) *Cause*

The immediate cause of the accident was the failure of the modified spiral bevel ring gear in the forward transmission which allowed the twin rotors to collide when synchronisation was lost.

Underlying causes were the inadequacy of the hitherto accepted aircraft industry standard of test programme carried out by the manufacturers and the insufficiently stringent inspection programmes required by the FAA and the CAA..

4. Safety Recommendations

It has been recommended that:

4.1 Certification procedures be reviewed so that all modifications to vital components are adequately scrutinised and tested before approval and more closely monitored after their introduction into service.

4.2 The CAA should report on the progress that has been made towards the early incorporation of a specification for suitable condition monitoring systems into airworthiness requirements for helicopters and indicate the time scale and scope of likely developments.

4.3 Requirements relating to the ADELT equipment, including location, crashworthiness, protection and power supplies, be reviewed in the light of this accident.

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13 January 1988