AIRCRAFT ACCIDENT REPORT 3/88

Air Accidents Investigation Branch

Department of Transport

Report on the accident to Bell Model 222, G-META at Lippitts Hill, Loughton, Essex on 6 May 1987

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

8 July 1988

The Right Honourable Paul Channon
Secretary of State for Transport

Sir,

I have the honour to submit the report by Mr R C McKinlay, an Inspector of Accidents, on the circumstances of the accident to Bell Model 222, G-META which occurred at Lippitts Hill, Loughton, Essex on 6 May 1987.

I have the honour to be
Sir
Your obedient servant

D A COOPER
Chief Inspector of Accidents

Contents

GLOSSARY OF ABBREVIATIONS

agl	-	Above ground level
ASU	-	Air Support Unit
BHT	-	Bell Helicopter Textron
CAA	-	Civil Aviation Authority
CLA	-	Centre Line Average
CSL	-	Commercial Service Letter
CTR	-	Control Zone
FAA	-	Federal Aviation Administration
FAR	-	Federal Airworthiness Requirement
HRC	-	Hardness, Rockwell Scale C
MCD	-	Magnetic Chip Detector
MHz	-	Mega Hertz
Np	-	Power turbine spool rotational speed
OD	-	Outside Diameter
OSN	-	Operations Safety Notice
PN	-	Part Number
ppm	-	parts per million
rpm	-	revolutions per minute
SN	-	Serial Number
SOAP	-	Spectrometric Oil Analysis Programme
TSN	-	Time Since New
TSO	-	Time Since Overhaul
UTC	-	Coordinated Universal Time
VFR	-	Visual Flight Rules

Air Accidents Investigation Branch

Aircraft Accident Report No: - 3/88
(EW/C1013)

Operator:		Metropolitan Police Air Support Unit
Registered Owner:		The Metropolitan Police
Aircraft:	*Type:*	Bell Model 222
	Nationality:	British
	Registration:	G-META
Place of Accident:		Lippitts Hill, Loughton, Essex Latitude: 51° 39.4' North Longitude: 000° 01.0' East
Date and time:		6 May 1987 at 1448 hours All times in this report are UTC

SYNOPSIS

The accident was notified by the operator to the Air Accidents Investigation Branch at 1525 hrs and an investigation began the next day.

Whilst operating over the Metropolitan area of London and shortly before the planned termination of his patrol, the pilot lost indication of the No 1 engine power turbine rpm and an unusual noise became audible in the cabin. As the helicopter was approaching the landing pad at its base, the No 1 engine burst, causing damage to the adjacent engine, fuselage and cowlings and severance of the tail rotor drive shaft. The aircraft landed firmly just short of the landing pad and rolled to a halt on the pad. The occupants vacated the helicopter unaided. A small fire which broke out in the engine area was quickly extinguished.

The report concludes that the accident was caused by overspeed bursting of the No 1 engine power turbine wheel because of fatigue failure of gear teeth in the turbine drive train. The gear teeth failures resulted from gross wear in a bearing in the engine gearbox, probably caused by skidding or overload of the bearing rollers. Fourteen safety recommendations were made during the course of the investigation.

1. FACTUAL INFORMATION

1.1 History of the flight

The aircraft was engaged on a police patrol in the London Metropolitan area. It had taken off from its base at Lippitts Hill at 1335 hrs with the pilot and four police officers on board. About one hour and ten minutes later, whilst flying at a height of 1000 feet in the vicinity of Greenwich, the pilot noticed that the needle indicating the No 1 engine power turbine rotational speed (Np) fell to 40%, returned to 100% and then fell again to zero. All other engine and transmission indications appeared to be normal. The pilot decided to return to his base which was some 4 minutes flying time away.

During this transit the pilot became aware of an increased noise level. It sounded like a rushing of air and was less obvious when the police observer in the left hand front seat selected the radio station box to 'Conference' thus isolating the rearmost passenger headsets. As the helicopter neared its base, flying at about 60 knots, the rear seat observer declared that the noise was becoming worse in the rear cabin. During the approach to the landing pad, at a height of 50 feet above ground level (agl), there was a loud explosion and fragments were seen to fly from the aircraft. The pilot simultaneously closed both engine twist grip throttles, fully lowered the collective pitch lever and applied right yaw pedal. The helicopter landed heavily some 6 metres short of the concrete area and rolled forward on its wheels onto the pad.

The police officers evacuated the aircraft with the permission of the pilot who, having completed the shut-down actions and applied the rotor brake, left the aircraft. Ground personnel detected a fire burning in the engine and aft baggage bay area and extinguished it using portable appliances.

1.2 Injuries to persons

None of the helicopter occupants was injured. There were no other injuries.

1.3 Damage to aircraft

The No 1 engine was severely disrupted. The fuselage was extensively punctured in the region of the plane of the engine power turbines by fragments of the No 1 engine turbine wheel, which also severely damaged the No 2 engine and severed the tail rotor drive shaft. Main rotor and tail rotor blades sustained minor nicks and scratches. Engine bays and the aft baggage compartment beneath them were lightly fire damaged. The fuselage suffered slight localised distortion as a result of landing heavily.

1.4 Other damage

A large fragment of the No 1 engine power turbine wheel landed in a paddock some 370 metres south of the landing pad at Lippitts Hill, but caused no significant damage.

1.5 Personnel information

1.5.1	*Pilot*:	Male aged 42 years
	Licence:	United Kingdom Airline Transport Pilot's Licence (Helicopters/Gyroplanes), valid until 1 December 1996
	Helicopter ratings:	Hiller 360, Sikorsky S61N, Bell 214ST, Bell 222, Bell 47
	Certificate of test:	dated 11 February 1987, valid until 10 March 1988
	Instrument rating:	renewed 11 February 1987, valid until 10 March 1988
	Last medical examination:	23 February 1987, valid until 31 August 1987
	Flying experience:	
	Total hours as pilot:	11305 hours
	Total hours in command:	10173 hours
	Total hours on type:	613 hours
	Total hours in last 28 days:	34 hours
	Total hours in last 7 days:	3 hours 35 minutes
	Rest period before 6 May 1987:	4 days

1.6 Aircraft Information

1.6.1 Leading particulars

Manufacturer:	Bell Helicopter Corporation (now Bell Helicopter Textron (BHT))
Type:	Bell 222
Constructor's No:	47028
Year of manufacture:	1979
Powerplant:	Two Avco Lycoming (now Textron Lycoming) LTS101-650C-3 gas turboshafts
Certificate of Airworthiness:	UK Private Category, valid until 19 November 1987
Total airframe hours:	4668 hours
Hours since last check:	16 hours
Maximum authorised weight:	7850 lb
Estimated weight at time of accident:	7099 lb
Centre of Gravity range permissible:	245.7 to 256.0 inch aft of datum
Estimated Centre of Gravity at time of accident:	250.2 inches aft of datum

1.6.2 General description

1.6.2.1 Aircraft

The 222 is a helicopter of conventional layout (Appendix 1) with a two-bladed main rotor. The Metropolitan Police version was configured with a total of seven seats. Two gas turboshaft engines mounted side-by-side on the aft roof of the cabin supplied power to the main transmission. The tail rotor drive shaft, driven from the main transmission, passed between the engines to the tail rotor gearbox.

1.6.2.2 Engine

Each engine (Appendix 2) consisted of a gas producer module, supplying combustion gases to drive a power turbine situated at the rear of the engine in a combustor/turbine module. The power turbine shaft, which was integral with the turbine wheel, was located radially and axially near its aft end by a ball bearing, the No 3 bearing. The shaft passed forward, inside the bore of the gas producer shaft, into an accessory drives/reduction gearbox module, where it located in the bore of a powertrain pinion gear (Appendix 3) by means of helical splines at the forward end and a register bore at the pinion aft end.

Journals machined on the pinion on either side of the gear teeth formed the inner races for two similar roller bearings, Nos 4 and 5, which radially located the pinion. This, in turn, radially located the forward end of the power turbine shaft. Helical gear teeth formed on the pinion drove a power idler gear, which rotated in two roller bearings, Nos 6 and 7 bearings. A second gearwheel on the power idler gear shaft in turn drove the power output gear. An N_2 accessory gear was also driven by the powertrain pinion (Appendix 4). The pinion gear teeth helix angle was designed to be slightly less than that of the internal splines, such that the axial components of the tooth and spline reactions exerted a net rearward force on the pinion. A carbon bumper ring located just forward of the pinion formed a plain bearing to limit any forward axial movement of the pinion.

An Np sensor located on the gearbox forward face consisted of a short shaft fitted to the forward end of the power turbine shaft and carrying a permanent-magnet plug rotating in a cover containing an electromagnetic pick-up. The engine fuel control unit included a power turbine governor with an overspeed trip device set to operate at 109±1% power turbine speed. Nominal 100% Np was 36240 revolutions per minute (rpm) and the power turbine burst speed was reported by the engine manufacturer to be approximately 145% of this value.

The gearbox consisted of a casing, approximately 18 inches high and 17 inches wide by 5 inches deep, to which was attached a flat cover. Both the casing and cover were made of magnesium alloy and incorporated a series of steel lined bores in which were fitted the bearings for the various gear shafts. Pairs of main bores, for bearing pairs Nos 4 and 5, and Nos 6 and 7, were in-line bored with the cover attached to the casing, and cover and casing were subsequently treated as matched components. The cover was located on the casing by three dowels, and was attached to it, with a fibre gasket interposed, by 31 bolts screwed into threaded holes in the casing periphery and one bolt screwed into a central pillar forming part of the casing. A shim washer of a thickness determined by the part number of the peripheral gasket was fitted on the central bolt between the cover and the pillar.

The gearbox shared a common oil system with the engine. Oil discharged into the gearbox ran via a screen into a sump in the base of the gearbox and thence to a scavenge pump. The screen comprised a 110 x 90 mm flat horizontal sheet perforated by a series of 1 mm diameter holes. The width of the solid surface between the edges of adjacent holes was 1 mm.

Each engine was provided with a gearbox magnetic chip detector (MCD), located in the gearbox sump, and a scavenge MCD, fitted in a pipeline between the scavenge oil pump and the oil cooler. The MCDs were intended to attract ferrous particles in the oil and retain them for inspection, and also to operate an amber caution light on the cockpit annunciator panel when either MCD was electrically bridged to earth by such particles. The circuit for this system is shown schematically in Appendix 5. Unlike the airframe transmission system MCDs fitted to the aircraft, the engine MCDs did not have a fuzz-burning facility, i.e. a system capable of cancelling warnings generated by very fine particles by burning them off the MCD with an electric current, thus enabling differentiation from the cockpit between nuisance and significant warnings. An approved kit form of such a system is available (BHT Supportogram 222-86-49 of 4 June 1986). A further permanent-magnet plug, comprising an element of the gas generator spool speed sensor, was installed in the gearbox.

No permanently-installed vibration monitoring system was provided for the engines, or for any other part of the aircraft.

1.6.2.3 *Bearing No 4*

The No 4 bearing consisted of twelve rollers constrained in a cage and running in the 2.1844 - 2.1847 inch diameter trackway of a one-piece outer race. The powertrain pinion forward journal formed the inner race. Rollers were snap retained in the cage and thus the outer race, rollers and cage formed a non-dismantlable assembly. Roller nominal diameter and length were 9 x 10 mm (0.3543 x 0.3937 inch), and allowable roller diameter variation per bearing was specified as 0.050×10^{-3} inch. The axial profile of the roller rolling surface was designed to be flat over the central portion, with slight convex curvature to the outer portions. End faces had a similar profile and roller corners were rounded.

Rollers and outer race were of steel to Specification AMS 6444 with a required Rockwell C through-hardness (HRC) of 58 - 62. The journal was of steel with a required HRC of 32 - 40, case hardened to a depth of 28 - 40 x 10^{-3} inches to HRC 60 - 63.

After assembly, each outer race/roller combination was classified by the measured diameter under the rollers (i.e. the combination inner diameter) into one of four dimensional bands, A - D; and each pinion journal was similarly classified by its outside diameter (OD). Each outer race/roller combination should then have been fitted only with a journal in the same band. The allowable clearance between the diameter under the rollers and the journal OD was 0.41 - 0.9 x 10^{-3} inches.

Oil was fed to the bearing under pressure via three equispaced radial drillings in the outer race from an annulular groove formed in the outside of the race. The groove was supplied from passages in the gearbox casing and sealed on either side by an elastomeric O-ring.

1.6.3 *Maintenance history*

1.6.3.1 *General*

Records indicated that the aircraft was maintained in accordance with Maintenance Schedules contained in the aircraft and engine manufacturers' Maintenance Manuals (BHT-222/222B-MM-1 and LTS 101-2.2). The operator had utilised these Schedules, clarified by other information from the manufacturers, to compile its own schedule of segmented inspections. The engine was on a hard-time overhaul programme, with a time between overhaul, including the gearbox, of 2400 hours. A Hot-Section and Gearbox Inspection was required at 1200 hours. At the time of the accident the gearbox time since new (TSN) was 2707 hours and time since overhaul (TSO) was 1384 hours. Although the engine was modular, the gearbox concerned in the accident (Serial No 79B012) had in fact remained with the same engine (Serial No LE 41066) for over 2000 hours of operation prior to the accident. Records showed the following relevant events (Appendix 6) related to the No 1 engine and its gearbox:

Date	Engine TSN hours	Gearbox TSN hours	Event
29 Sep 79	-	0	Gearbox delivered new. Matched No 4 and 5 bearings, Class C.
6 Feb 80	0	-	Engine delivered new (with different gearbox).
28 Apr 80	-	17	Gearbox repaired by Avco Lycoming. No 4 and 5 bearings and power pinion and power idler gears replaced.
20 Oct 80	67	-	Engine repaired and converted to 650C-3 by Avco Lycoming.

10 Nov 82	1129	-	Engine LE41066 experienced excessive metal and MCD cautions.
7 Dec 82	-	531	Gearbox inspected by Avco Lycoming following chips and sudden engine stoppage. No 4 and No 5 bearings, power idler and power output gears replaced due to wear.
12 Nov 82	1129	531	Gearbox 79B012 fitted to Engine LE41066.
6 Feb 85	1921	1323	Gearbox overhauled by Avco Lycoming after axial compressor blade failure. No 3, 4 and 5 bearings and powertrain pinion replaced.
7 June 85	2057	1459	Gearbox repaired by LT101 UK Service Centre, after sharp increase in SOAP iron level and six MCD cautions in 12 hour period. "Skidding on No 4 bearing causing frosting" found. No 3,4,5,6 and 7 bearings, powertrain pinion and power idler gears replaced.
28 Nov 86	3107	2509	Scheduled 1200 Hour Hot Section and Gearbox Inspection by LT101 UK Service Centre.
20 Feb 87	3107	2509	Installation in G-META No 1 position. Vibration check conducted.
4 Mar 87	3129	2531	Increasing iron level in post-installation oil samples.
15 Apr 87	3255	2657	Oil pump and oil changed.
30 Apr 87	3286	2688	MCD caution. Small piece of debris found on both MCDs.
1 May 87	3286	2688	OP 108 of last 100 Hour Inspection prior to accident carried out (intended to include electrical check of MCD system wiring).
5 May 87	3300	2702	SOAP sample taken, but not analysed until after the accident, showed 62 parts per million (ppm) of iron.
6 May 87	3305	2707	Power turbine burst.

1.6.3.2 *Engine gearbox history*

The records indicated that excessive wear rate problems with the pinion bearings had been experienced by the gearbox since build, with, at the time of the accident, the pinion and/or bearings having been replaced four times in 2707 hours at intervals of 17, 514, 792 and 136 hours respectively. Little evidence of the reasons for the replacements was available, but in at least two of the cases the No 4 bearing had worn, and the problem had occurred both when the gearbox was fitted to the accident engine and to the engine on which it was originally installed.

The gearbox was last repaired in mid 1985, 1248 hours before the accident, by CSE Aviation Ltd in their capacity as the UK LT101 Service Centre, who reported finding signs of a skidding situation on the No 4 bearing, and replaced Nos 4,5,6 and 7 bearings and the powertrain pinion and power idler gears. The installed runout of the No 4 bearing journal of the new powertrain pinion was recorded as 0.1×10^{-3} inch, but no check of the alignment of the bearing bores in the gearbox casing and cover was required by the Maintenance Manual and none was carried out. The components removed were sent to the engine manufacturer but were not investigated.

The engine was last disassembled in late 1986, 198 hours before the accident, when the LT101 UK Service Centre carried out a scheduled Hot Section and Gearbox 1200 Hour Inspection timed to coincide with a gas producer turbine replacement required by an engine manufacturer's Service Bulletin. The gearbox inspection specified by the engine Maintenance Manual (Section 72-00-00, Table 7) comprised removal of the gearbox cover and inspection of threads, splines, gearteeth and bearings, accomplished by separating the gearbox module from the engine and removing all gears and bearings. The Manual (Section 72-00-00, Para 18) noted that whenever the combustor/turbine module or gearbox module are removed from the engine the proper relationship of the power turbine shaft to the powertrain pinion must be established to ensure correct assembly, and specified a means of doing this by locking the geartrain and marking the power turbine rotor and nozzle.

This technique could not be used when the gears were to be removed, or the power turbine was to be washed for inspection. The normal practice of the UK Service Centre was to remove the Np sensor cover and paint index marks on the speed probe shaft and the forward face of the powertrain pinion before module separation, and on reassembly of the engine to orientate the pinion and shaft splines to align the index marks. No check of the runout of the pinion No 4 bearing journal was required unless the combustor/turbine or gearbox modules or the pinion or the power turbine had been replaced, and again no check of the alignment of the bearing bores was required. Inspection of the No 4 and 5 bearings was necessarily limited to visual examination of the outer race, rollers and cage as an assembly, and no dimensional check was required, such as the feeler gauge check of roller to journal clearance specified in Avco Lycoming Commercial Service Letter (CSL) 054.

Worksheets indicated that the last 1200 Hour Inspection was carried out in accordance with this practice, and in particular that no journal runout, bearing bore alignment or bearing dimensional checks were conducted. Comparison of component identification numbers with documentation compiled prior to the Inspection indicated that no components relevant to the No 4 bearing journal runout had been changed during the Inspection.

1.6.3.3 *Vibration monitoring*

A check, using portable test equipment, of the engine vibration spectrum at various power settings was scheduled by the operator to follow engine installation. The No 1 engine had last been checked on 23 February 1987, 198 hours before the accident, on installation into G-META after its 1200 Hour Inspection, with no abnormalities indicated.

1.6.3.4 *Oil monitoring*

Engine oil was subjected to a regular analysis programme in line with recommendations in Chapter 71-00-00, Para 30, of the engine Maintenance Manual for a check of acid number and viscosity on a sample of oil when 100 hours from new, followed by an acidity check at 25 hour intervals. In fact the Air Support Unit (ASU) checked viscosity as well as acidity at approximately 25 hour intervals. If the programme were followed and limits on oil acidity or viscosity were not exceeded, there was apparently no requirement to change either the oil or the filter at any stage between 1200 Hour inspections. Engine No 1 records covering over 2000 hours of operation leading up to the accident did not indicate any unusual change or trend in either acidity or viscosity.

Engine oil samples were also analysed for wear-metal content in accordance with a Spectrometric Oil Analysis Programme (SOAP) suggested in the Maintenance Manual (Chapter 71-00-00, Para 31). The Manual outlined sampling and analysis techniques and also provided a list for six different metals of Wear-Metal Guidelines in ppm by weight, defined as "that level of wear-metal content at which an engine is considered "suspect" and must be checked. It is not the absolute point at which the engine or module must be removed. Wear-metal guidelines in general are not go no-go criteria. They are established just below that level of wear-metal content determined to be abnormal based on past experience."

The guideline given for iron was 6 ppm, but a separate note stated that an increase of 3 ppm in iron content since last analysis shall be cause for investigation. The Manual did not define the investigation required if guidelines were exceeded but, in the case of iron, noted that wear-metal sources for use in determining maintenance action requirements or checks were gears, bearings, bearing liners, oil pump or major support structures. Samples were sent by the operator, normally by post, to a specialist laboratory for analysis, and results were generally available about two to four days after sampling.

Available SOAP records for Engine LE41066 commenced with the engine's entry into service with ASU. They did not indicate any significant pre-accident trends in the content of wear metals, except in the case of iron (Appendix 6). Approximately 1250 hours prior to the accident a sudden sharp increase in iron content occurred, accompanied by multiple MCD caution light illuminations over a short period. During the gearbox repair prompted by these indications, the No 4 bearing was found to be wearing and was replaced (para 1.6.3.2).

After the repair, the iron content remained relatively constant at between 0.4 and 1.2 ppm for over 1000 hours, until the 1200 Hour Inspection towards the end of 1986. Analysis of the first three oil samples after installation of the engine in G-META immediately following the Inspection, covering a 68 hour operating period, showed a steady rapid rise in iron content to just above the guideline level of 6 ppm, although the increase between each sample was less than the 3 ppm incremental threshold.

The sampling rate was maintained above normal, with four samples taken over the next 71 hours. The iron level stabilised initially but then again increased somewhat, in company with an increase in chromium level, and the operator advised the UK Service Centre that the engine would be returned for warranty investigation if the level did not shortly stabilise, and sought advice from the engine manufacturer. Analysis of filter bowl debris by scanning electron microscopy showed it to be predominantly brass, and the engine manufacturer's advice was to change the engine oil pump, flush the oil system and change the oil, which was done.

The next two samples again showed a steady, rapid increase in iron content over an 18 hour period, and the operator informed the engine manufacturer and UK Service Centre of the intention to remove the engine for warranty investigation after trend monitoring for a further 15 hours operation if the iron level continued to rise. Iron content again reached the 6 ppm guideline in the next sample taken.

After discussions with the engine manufacturer, the operator decided to coincide the investigation with other work scheduled for 7-10 days later. A further sample taken 45 hours after the oil pump change showed a dramatic increase to 62 ppm, but the following day, before the sample had been analysed, the power turbine burst.

1.6.3.5 *Magnetic chip detectors*

The abnormal SOAP indications were accompanied by a cockpit No 1 engine chip caution light on 30 April 1987, 19 hours prior to the turbine burst. A very small piece of debris was reportedly found on each MCD. The fragments were recorded in the aircraft's Technical Log as 'minor' and considered by the engineer who found them to be so small as to not represent, in isolation, a significant indication. Study of the records for over 600 hours prior to the accident indicated that this was the only occasion in this period on which a No 1 engine chip caution occurred or debris other than fuzz was found on MCDs during visual inspection. Such inspection was scheduled at 100 hour intervals, or whenever an engine chip caution light illuminated.

Maintenance Manual instructions in the event of finding excessive quantities of chips on an MCD (Chapter 72-00-00, Para 16) were to inspect the screen filter at the scavenge outlet from the gearbox, and if any chips were present to disassemble the engine to determine the source. Brief background notes were given, but no definition was provided of a 'chip' or what constituted an 'excessive quantity'. The Manual noted that it is not unusual for a new engine to generate some chips during the first 5 to 10 hours of operation. The operator reported that a number of MCD warnings during the initial operating period of a newly rebuilt engine was not uncommon.

Some additional guidance to the operator on the action required in the event of an MCD caution was contained in CSL 035, issued on 12 August 1986, which stated in part that "....some LT101 operators are underestimating the significance of chip detector alarms....Any chip alarm accompanied by a sudden loss in oil pressure requires immediate corrective action. If more than two chip alarms occur within 50 hours, the source of chips must be determined." It also noted that light accumulations of fuzz, defined as fine hair-like particles usually of steel, resulting from normal wear, were normal, particularly on new engines, and should be cleaned from the MCD and the engine returned to service, unless more than two alarms in 50 hours resulted. Flakes, chips or slivers, defined by "having definite length and width", were listed as indicating part failure and requiring the source to be determined.

It was the operator's standard practice to have all significant fragments found on MCDs analysed by scanning electron microscope, but neither of the particles found on 30 April 1987 was considered to be in this category.

The aircraft had a facility for a cockpit operated pre-flight check of the caution annunciator system, but this did not check the integrity of the circuit from the annunciator to the MCDs. The same situation applied to the seven transmission MCDs. The Maintenance Manual Schedule required a functional check of the engine MCD caution system circuit every 100 hours, and it was intended that this formed part of the OP 108 segment of the Electrical 100 Hour Check, as defined by the Maintenance Schedule compiled by ASU. However, the ASU Schedule in error referenced the wrong section of the Maintenance Manual, which did not include the engine MCD caution system, and so the ASU Maintenance Schedule did not in fact specify a check of this system at any stage.

1.6.3.6 *Maintenance background*

Since acquiring its fleet of three Bell 222s between 1980 - 1982 the operator had experienced a relatively high engine removal rate, averaging approximately one every 190 aircraft operating hours, and this had deteriorated latterly. Neither the engine manufacturer nor the operator considered abnormal SOAP indications and/or isolated MCD warnings to be adequate grounds for immediate engine rejection, and the operator reported that, in a number of cases where this had been done previously, strip investigation had failed to reveal any defect and it had been necessary to reassemble the same components and reinstall the engine. The operator therefore considered it necessary to trend monitor an engine with abnormal SOAP indications over a period of operation, relying on an excessively high MCD warning rate as the rejection criterion.

1.7 Meteorological information

At the time of the accident the weather was fine and sunny. Visibility was in excess of 10 km and there was no cloud below 3000 feet. The wind was from 360° at 7 knots and the temperature at Lippitts Hill was +16°C.

1.8 Aids to navigation

Not relevant.

1.9 Communications

In addition to police operational radios, the aircraft was in contact with London Heathrow Radar on a frequency of 119.9 MHz. The pilot informed the controller of his intention to land at Lippitts Hill. He was also in contact with his base.

1.10 Aerodrome information

Lippits Hill landing site is a purpose built helicopter base within the confines of the Metropolitan Police training camp. It has two marked landing pads on a concrete base with an area of 1000 square metres, set on top of a hill at a height of 310 feet amsl. On the day of the accident the into wind approach to the intended landing site, Helipad No 1, was over steeply undulating terrain comprising pastures and a golf course, and terminating in a substantial 2 metre high boundary fence.

1.11 Flight recorders

Neither a Cockpit Voice Recorder nor a Flight Data Recorder was fitted or required to be fitted under existing regulations.

1.12 Examination of wreckage

1.12.1 Accident site

Ground marks indicated that the aircraft first touched down on its main wheels 15 metres short of the centre of Helipad No 1 on a flat area of mown grass. Touchdown was heavy, with the aircraft essentially level but yawed 10° left and skidding to the right, with forward speed estimated at 20-30 knots. Very shortly after mainwheel touchdown the nosewheel contacted the ground moderately heavily and the aircraft rolled forward on its wheels onto Helipad No 1.

Portions of the No 1 engine power turbine wheel were found either side of the initial touchdown point, with one large piece approximately 370 metres away.

1.12.2 Aircraft

The only evidence of damage to the aircraft as a result of ground contact was slight downward bending of the tail boom relative to the main fuselage caused by localised buckling of the boom in the area of its attachment to the fuselage. This was consistent with the effects of excessive vertical speed at touchdown, and similar deformation has reportedly occurred in previous heavy landing cases.

Both engine bay doors and the No 1 engine bay floor sustained extensive puncture holes, and the fuselage in the region of the engine power turbine plane was punctured in a number of places. A considerable quantity of small debris was found in the aft baggage compartment beneath the engine bays, and nylon-covered plastic foam intake blanks and a rotor blade tie stored in a plastic bag in the compartment had been locally melted and consumed by fire. The compartment and parts of both engine bays were sooted.

The tail rotor drive shaft running between the engines was found completely severed, with an approximately 11 inch length adjacent to the engine combustor/turbine modules severely distorted and partially fragmented and with minor fire damage. The shaft was of 3 inch diameter and located around 14 inches from the centre of rotation of the spools of either engine. The damaged area of the shaft was located between the normal position of the No 1 engine power turbine and a portion of the turbine disc found embedded in the No 2 engine combustor housing.

Although both MCDs associated with No 1 engine were found packed with metal fragments (para 1.12.4.1), the cockpit annunciator MCD caution light did not illuminate when electrical power was restored to the aircraft after the accident. Examination revealed that an electrical cable (W81B22) had detached from its terminal on the gearbox MCD, and that disconnection at this point (Appendix 5) disabled both of the No 1 engine MCDs. The failure was at the end of an approximately 9 inch length of cable that ran from a loom clip near the engine bay floor and across the gap between the floor and the bottom of the engine to the MCD, onto which the cable was held by its terminal tag. The cable derived some support from an elastomeric boot fitted over both the terminal post and the ends of the two MCD cables, but was not clipped to the engine. The portion of cable appeared susceptible to inertia loading and to snagging by personnel accessing engine bay components through the gap under the engines. The evidence indicated that the failure had resulted from overload. No signs were found to suggest that the cable had been struck by debris from the turbine non-containment.

1.12.3 *Engine No 2*

The outer casing of the combustor housing was holed by a portion of the No 1 engine power turbine disc, measuring approximately 2 x 1.5 x 1 inch and weighing approximately 0.5 lb. The disc piece remained deeply embedded in the combustor housing.

1.12.4 *Engine No 1*

1.12.4.1 *General*

The aft end of the engine was grossly disrupted. The power turbine wheel had fragmented and largely departed the aircraft, leaving its integral shaft in situ in the engine. The combustion chamber lining assembly and the power turbine nozzle assembly, which also forms the housing for the No 2 and 3 bearings, had both been completely severed circumferentially and were lying loose in the engine bay. The damage and wreckage distribution characteristics were indicative of a very high speed turbine burst. Approximately 60 % of the power turbine wheel was recovered, fragmented into two large and a number of small pieces. Detailed examination revealed no evidence of pre-burst defect or failure.

Metallic fragments were evident in large quantities throughout the gearbox, many retained on the screen above the sump, but both MCDs were found packed with metal debris fragments, as was the gas producer spool speed sensor permanent magnet.

1.12.4.2 *Power turbine speed sensor*

The shaft of the Np sensor plug had fractured and the plug was found lying loose in the sensor cover. Both fracture surfaces of the shaft had been heavily smeared by relative rotation between the two parts of the broken shaft, indicating that rotation of the power turbine shaft had continued for a significant period after the failure had occurred. The shaft fracture surfaces showed evidence of extensive low strain fatigue cracking.

1.12.4.3 *Gears*

The powertrain pinion could be turned by means of the power turbine shaft without significant resistance and with no resultant rotation of the power output gear, and gearbox cover removal revealed that all teeth had been stripped from the powertrain pinion. Additionally, a number of teeth had been either partially or wholly stripped from the power idler gear, including one sector with five adjacent teeth missing, and remaining portions of the teeth exhibited severe damage, particularly on their crowns, consistent with having operated in foul mesh with the pinion at some stage. Examination by the Materials Department of the Royal Aircraft Establishment, Farnborough, revealed evidence of extensive fatigue cracking associated with many of the teeth failures, although much of the detail had been obliterated by smearing of the original fracture surfaces. Tests indicated no significant deviations from requirements in the hardness of either gearwheel, except for a rehardened surface layer to the No 4 bearing journal, which was consistent with high temperature running.

All teeth on the N_2 accessory gear were severely distressed and distorted, consistent with the effects of having operated in mesh with a grossly damaged power idler gear, and no evidence was found to indicate that the N_2 accessory gear had contributed to the failures of the other two gearwheels.

1.12.4.4 *Power turbine shaft / powertrain pinion assembly*

A) No. 4 Bearing

No. 4 bearing identification marking indicated the following:

Manufacturer	SKF
Avco Lycoming Part No / Serial No	4-301-145-03 / 1005
Dimensional Class	C

The No 4 bearing outer race, rollers and cage are normally non-separable, but when the journal was withdrawn all the rollers were free to fall out. No significant defects were found in the outer race, and its trackway appeared normal, with a smooth, shiny surface, and exhibited no significant out-of-round, with a diameter of 2.1845 - 2.1846 inch that was within limits. O-rings were extensively damaged, consistent with their having been sliced between the outer race groove lands and the gearbox casing bore lip, but it was not possible to establish whether this had occurred on installation or disassembly.

Full dimensional checks of the cage were precluded by lack of information, but no defects were found. In particular, there were no signs that might have indicated binding of the cage on other parts of the bearing.

All twelve rollers were grossly undersize, with diameters of 0.330 - 0.335 inch, between 19 - 24 x 10^{-3} inch less than the nominal requirement. All rollers were also out-of-round, with the difference in minimum and maximum diameter of individual rollers varying between 1.5 - 2.5 x 10^{-3} inch. The appearance of all the rollers was very similar, each having a rolling surface with a slightly convex axial profile, and a small lip of material formed at each end overhanging the normally rounded corners which had been truncated by the reduction in roller diameter. Surface finish was smooth and shiny. Metallurgical examination revealed the presence of a re-hardened layer of material on the rolling surface indicative of high temperature running.

The No 4 bearing journal was marked as dimensional class C. It had a measured diameter on unworn portions of between 1.4751 - 1.4754 inch, which was above the required diameter of 1.4751 - 1.4753 inch, but only marginally so. A band of polishing and frosting was present over about half the circumference, and material had been removed from the other half in a circumferential track 0.38 inch wide to a maximum depth of between 1.0 - 1.5 x 10^{-3} inch. Light surface wear had also taken place aft of the worn track, over an additional band 0.11 inch wide. The degree of wear was quite abnormal in comparison with other used journals, including that of the No 5 bearing. Surface roughness was 12 - 16 micro inch (inch x 10^{-6}) centre line average (CLA) on the unworn portions of the journal, which was within limits, and 5 - 12 micro inch on the worn areas.

B) No. 5 Bearing

No evidence of defects in the No 5 bearing was found. A feeler gauge check established that the gap between the journal and rollers was virtually on the limit of 1 x 10^{-3} inch maximum. This bearing was similar to the No 4 bearing and also marked as dimensional class C. The journal diameter was at the nominal dimension for this class, and the surface was within roughness limits and showed only light surface marking from the rollers, similar to that seen on other used pinions.

C) Shaft/Pinion assembly

No significant deviation from requirements was found in the dimensions of the powertrain pinion and power turbine shaft. It was not possible to confirm that the engine had been assembled with the index paint mark found on the Np probe shaft aligned with that on the pinion, because establishment of the relative orientation of the two parts of the Np probe shaft was precluded by damage. With the probable assembled orientation of the pinion and power turbine shaft, determined from witness marking, the maximum runout on the No 4 bearing journal, with the shaft supported in vee-blocks on its apparently undamaged forward section, was 1.9 x 10^{-3} inch, compared to a required limit of 1.2 x 10^{-3} inch and a recorded value of 0.1 x 10^{-3} inch on the last occasion it was checked (para 1.6.3.2). Damage precluded checking of the runout by the normal method, and the possibility that the measurement was affected by either the method used, or by shaft or pinion deformation as a result of the effects of gear tooth break-up and/or turbine burst, could not be dismissed.

D) No. 3 bearing

No. 3 bearing was found severely damaged. No evidence of pre-accident damage was found.

E) Gearbox casing and cover

No apparent damage was sustained by the gearbox casing or cover. Location dowels fitted into the cover without forcing and held it firmly on the casing. Detailed high-accuracy measurement checks were made on the casing and cover, both individually and when bolted together, using a DEA Omicron A001

Coordinate Measuring Machine with a calibrated accuracy of $\pm 0.2 \times 10^{-3}$ inch in all axes, with particular attention paid to the alignment of the pairs of bores for Nos 4 and 5, and Nos 6 and 7 bearings, datumed from the plane of the engine attachment flange face. The misalignment of No 4 bore compared to No 5 bore was 0.9×10^{-3} inch, and that for No 6 compared to No 7 was 1.7×10^{-3} inch, both exceeding the new-build requirement of 0.5×10^{-3} inch but within the overhaul requirement of 2.0×10^{-3} inch listed in the Overhaul Manual.

1.13 Medical and pathological aspects

Not relevant.

1.14 Fire

A fire discovered in the engine area as the helicopter came to rest was extinguished by ground personnel using hand-held extinguishers. It appeared to have involved almost exclusively the bagged plastic intake blanks stored in the aft baggage compartment beneath the engine bays, possibly together with a little engine oil and fuel released by the turbine burst. Despite the proximity of the fuel tank cells to the extensive disruption of the engine bays the tanks were not affected.

1.15 Survival aspects

Not relevant.

1.16 Tests and research

1.16.1 General

Attempts to research the design and in-service history of relevant aspects of the engine were hampered by lack of information. The engine manufacturer was invited to participate in the investigation and provided a representative on-site for two days, but furnished only part of the information requested on dimensional and material requirements for relevant components, the history of the engine and gearbox, details of previous cases with similar features and the background of the No 4 bearing. The following summarises the information obtained from various sources, but is unlikely to be complete.

1.16.2 *Engine background*

The engine was certificated by the United States Federal Aviation Administration (FAA) to Federal Aviation Requirement (FAR) 33 Amendment 5 of 1976. This required containment of failed compressor and turbine blades but not of failed discs. Three previous non-containments of this engine type in the Bell 222 were reported, which had accumulated approximately 250,000 operating hours at the time of G-META's accident.

1.16.3 *Bearing No 4 and 5 background*

The bearing was reportedly designed by Avco Lycoming, and, excluding the journal, manufactured by SKF Industries Inc (now a division of MRC/SKF Aerospace). It was reported that the bearings have a history of roller skidding, causing rollers to wear and acquire a rehardened surface layer without any effects on the outer race, and that nine different modifications to the bearing have been made over its period in service.

Bearings were originally interchangeable but, because cases of roller skidding were experienced, tolerances were tightened and classification of bearings and journals into four dimensional bands was introduced. Further cases of roller skidding were experienced, reportedly when the bearing was lightly loaded, and as a result the cage was redesigned from outer to inner land riding. Problems were then encountered with cracking of the cross bars forming the roller pockets of the redesigned cage, and the original outer land riding cage design was reintroduced. It is believed that this outer land riding design of cage was installed in the No 4 and 5 bearings of the No 1 engine of G-META.

Roller skidding, reportedly occurring under low-load conditions, has continued to be a problem experienced with both inner and outer land riding cages. It is understood that a further redesigned inner land riding cage was in service in some LT101 engines at the time of the accident.

1.16.4 *Previous cases*

Some evidence was found to suggest that there had been a significant incidence of cases of excessive wear rate of Nos 4 or 5 bearings over the service life of the LT101 engine type. However, it was not possible to quantify the problem as the only documentary evidence available concerned previous cases of gross No 4 and 5 bearing wear on the Bell 222, of which the following are known:

1)

Engine PN/SN - LTS 101-650C-2 / 47081
Date of incident - 14 July 1982

After repeated MCD warnings, No 4 bearing was found worn 40 x 10^{-3} inch and teeth at the rear of the power idler gear were found broken. The bearing had 20 hours TSN. The wear was attributed to excessive journal roughness. No defect investigation report was produced.

2)

Engine PN/SN - LTS 101-750C-1 / 47004
Date of incident - 28 October 1982

After metal was found in the oil system, No 4 bearing rollers were found 23 x 10^{-3} inch undersize and teeth at the rear of the power idler were found broken. The bearing had 77 hours TSN. The wear was attributed to excessive clearance between the journal and bearing due to mismatched parts. No defect investigation report was obtainable.

3)

Engine PN/SN - LTS 101-650C-3 / LE41066
Date of incident - 30 May 1985

This case was one of the previous incidents of excessive No 4 bearing wear on the engine responsible for the accident to G-META. Known details of the case are given in para 1.6.3. No defect investigation was conducted.

4)

Engine PN/SN - LTS 101-750C-3 / LE1240
Date of incident - 27 November 1986

Shortly after the finding of three chips on the No 2 engine MCDs in the first 50 hours of operation after overhaul of the engine, a large chip described as 0.5 x 4.0 mm in size and appearing to be the end of a gear tooth was found following an MCD caution. The chip was removed and the aircraft took-off to return to base. A further No 2 engine MCD caution about five minutes from destination was followed by loss of Np indication, and three minutes later at approximately 500 ft agl, whilst on the approach, the power turbine suffered a non-contained burst. Debris damaged the No 1 engine and severed the tail rotor drive shaft, and a low rotor speed warning occurred. After a successful autorotative landing a fire in the baggage compartment was smothered.

The basic circumstances of this case were communicated to operators by BHT Operations Safety Notice OSN-222-86-9, issued 5 December 1986, which promised pertinent additional information when available.

Examination reportedly showed no evidence of pre-burst malfunction except in the No 2 engine gearbox. Fracture of the Np sensor plug shaft had occurred, together with loss of all teeth from the powertrain pinion and from a 90° segment of the power idler gear, in all cases associated with fatigue. No 4 bearing rollers were grossly undersize, giving a clearance between rollers and journal of 41 - 45 x 10^{-3} inch. Both Nos 4 and 5 bearings and their journals were Class B. The misalignment between the No 4 and 5 bearing bores in the gearbox casing and cover was measured at 3.3 x 10^{-3} inch, in excess of the overhaul limit of 2.0 x 10^{-3} inch. No indications were given as to how this might have occurred, but the engine manufacturer concluded that it had resulted in alternating loads on the No 4 bearing, causing it to wear and allow changes in the stress distribution of the powertrain pinion and power idler gear teeth which had led them to fail in fatigue. Experience reportedly showed the manufacturer that in the event of excessive misalignment the No 4 bearing generally suffered a high wear rate, rather than the No 5 bearing.

5)

Engine PN/SN	-	LTS 101-650C-3 / LE41141
Date of incident	-	June 1987 (post G-META's accident)

No MCD indications of an abnormality were given in this case but, at a TSN of around 450 hours, SOAP data showed a gradual increase in the level of a number of wear metals, including iron, over an operating period of some 130 hours. The oil filtration level of this engine was 3 micron rather than the basic 5 micron standard. Strip inspection revealed evidence of an abnormal meshing pattern and localised damage on the teeth of the powertrain pinion, and of pitting of the contact area of many power idler gearwheel teeth.

Both Nos 4 and 5 bearings and their journals were marked as Class C. No signs of distress in the No 4 bearing were found, with the exception of a number of dents in the surface of the journal but, on removal of the powertrain pinion to facilitate a runout check, the rollers of the No 5 bearing fell out and were found to be 15 - 16 x10^{-3} inch undersize. Characteristics of all components of the No 5 bearing, and the journal, were extremely similar to those of the No 4 bearing involved in G-META's accident.

1.17 *Additional information*

1.17.1 *The Metropolitan Police Air Support Unit (ASU)*

The ASU have operated two Bell 222 helicopters in support of the Metropolitan Police since 1980 and a third since 1982. Their aircraft were equipped with police radios and role equipment, including Nitesun, Helitele and Skyshout. The operation was conducted in the Private Category, with certain operational exemptions having been granted by the Civil Aviation Authority (CAA).

1.17.2 *Remedial Action*

Since the accident, measures in part related to some of the recommendations made in Section 2 of this Report have been taken, as required by the following:

CAA Emergency Airworthiness Directive 007-05-87, initial issue 8 May 1987.

FAA Airworthiness Directive AD 87-10-04, initial issue 14 May 1987.

Bell Helicopter Textron Alert Service Bulletin 222-87-42, initial issue 14 May 1987.

2. ANALYSIS

2.1 *General*

The evidence made it clear that the accident resulted from an uncontained failure of the No 1 engine power turbine. The resultant sudden total loss of power from No 1 engine was simultaneously accompanied by severe damage to No 2 engine, probably resulting in almost instantaneous and complete power loss from this engine also, and by severance of the tail rotor drive shaft.

2.2 *Conduct of the flight*

The first indication to the pilot of an abnormality was the loss of Np indication, around four minutes prior to the turbine burst. Although a similar event had been a precursor of a turbine burst in a previous very similar case five months earlier, only basic circumstantial information had been disseminated by the engine manufacturer to operators, and G-META's pilot was not aware that the loss of Np indication could by itself presage an engine problem. With all other engine and transmission indications normal, the natural assumption would have been to suspect the gauging system. With the ASU base only approximately four minutes away, the decision to return there rather than make a precautionary field landing was perfectly reasonable.

Although an increased noise level became apparent during the transit to base, engine and transmission indications remained normal, with the sole exception of the continued loss of Np indication, and in particular no MCD alarms were indicated. There was little to suggest to the pilot the imminence of a potentially catastrophic engine failure, and the decision to continue the short remaining distance to a landing at the ASU base was also reasonable.

The pilot was presented almost simultaneously with a explosion, complete loss of power and tail rotor drive failure so shortly before touchdown that there was scarcely time for any assessment of the situation. His actions, based on his training and considerable experience, in fully lowering the collective pitch lever and closing both engine throttles proved entirely correct in the circumstances, and his skill in achieving a generally controlled landing without injury and with relatively little additional damage to the aircraft was commendable. It is noteworthy that the design and location of these controls in the Bell 222, with the throttle twist grips forming the hand grip for the collective lever, enabled simultaneous operation of these controls. It would not be possible for a single pilot to do this in other twin-engined helicopter types which have engine controls located in a cockpit overhead panel. It has therefore been recommended that the

CAA re-examine the requirements for engine control layout in relation to the emergency actions required to be completed by the pilot in the event of engine and tail rotor malfunctions.

Evacuation after the accident was disciplined and orderly, and the ground personnel effectively tackled a small fire in the engine bay area.

2.3 *Effects of power turbine burst*

The power turbine burst caused not only sudden and total loss of power from No 1 engine but also severe damage to No 2 engine and severance of the tail rotor drive shaft. Although no direct evidence on the effects on No 2 engine power output was available, it was considered highly probable that the disruption to the combustor would have caused almost instantaneous and complete power loss from this engine also.

Although the aircraft's occupants escaped without injury in this case, such an instantaneous total loss of engine power and yaw control is potentially catastrophic, and the accident demonstrated the vulnerability of aircraft with this configuration to any non-contained engine failure. Each engine and the tail rotor drive shaft are mounted on virtually parallel axes and in close proximity to each other. They thereby represent a relatively large target for non-contained debris from the other engine. In spite of the efforts made to avoid events which lead to engine non-containment they do occur, and this was the fourth known case for this aircraft type in around 250,000 hours of operation. It has therefore been recommended that the CAA requires the installation of shielding from possible engine debris of components for which a high integrity is necessary. (Recommendations for protection to be considered were previously made in AIB Accident Reports No.8/82 and 4/83)

2.4 *Cause of power turbine burst*

The lack of evidence of pre-accident defect in, or damage to, the No 1 engine power turbine or its integral shaft or thrust bearing (No 3), together with the relatively severe damage caused by the power turbine fragments, suggested that the disc had failed as a result of an overspeed which had imposed excessive centrifugal stresses on the turbine disc and led to its disintegration and the release of its abnormally high rotational energy. This was also entirely consistent with the evidence of disconnection in the drive train between the power turbine and the main rotor transmission by virtue of tooth stripping of gearwheels in the accessory drives/reduction gearbox of the engine (para 2.5). Such a disconnection would suddenly and totally unload the power turbine and allow it to accelerate very rapidly to its burst speed (approximately 145% of its nominal 100% operating speed of 36240 rpm). Avco Lycoming has stated that the acceleration in such an event would be much too rapid for the fuel control unit's 109% overspeed trip facility to contain the power turbine speed to below its burst speed. It has therefore been recommended that the CAA consider a requirement for gas turbine engines to have a facility for rapid auto-shutdown capable of preventing turbines from overspeeding to the point of non-containment in the event of output drive disconnection.

2.5 *Gearwheel failures*

The power idler gear and powertrain pinion geartooth losses had preceded the turbine burst, as evidenced by the signs found on the remnants of the failed teeth of extensive fatigue, which could not have occurred during the very brief run-down period following the turbine burst. Additionally, the wide distribution of gear tooth fragments, including the packing of both MCDs with small tooth debris, indicated that pieces of tooth had been breaking off the gearwheels for some period before the turbine failed. It was likely that the first detachment of a tooth from either the idler or pinion was the event responsible for the increased noise level experienced a few minutes before the turbine burst. However, the possibility could not be dismissed that substantial pieces of a tooth or teeth had broken off well before this, undetected because no major disturbance of gear meshing and consequent noticeable increase in noise level had resulted, and because the pieces had failed to trigger the MCD caution light.

Debris generated in the gearbox was restricted or prevented from reaching either of the MCDs by the screen in the bottom of the gearbox, and failure of a cable in the MCD caution light system was found to have disabled the system some time prior to the accident (para 2.8). It seems likely that the smaller cross sectioned fragments that had in fact found their way through the screen and onto both MCDs had probably been generated fairly late in the failure sequence as a result of foul meshing between the gearwheels after one or more teeth had already detached, but before teeth failures progressed to the point of drive train disconnection.

No sign of significant material or dimensional defect in the gearwheels was found, and the available evidence was consistent with the powertrain pinion and power idler gearwheels having suffered tooth fatigue failure as a result of incorrect meshing between them. Such a mismesh was consistent with inadequate restraint of the pinion because of the excessive clearance found in the No 4 bearing (para 2.6), which was intended to support the forward end of the powertrain pinion. The journal to roller clearance found, at around twenty times the permissible maximum, would have left the pinion largely supported by the No 5 Bearing at its aft end, and by the splined attachment to the power turbine shaft at its forward end.

2.6 *No 4 Bearing clearance*

The undersize of 19 - 24 x 10^{-3} inch in the diameter of each roller of the No 4 bearing, together with the groove of up to 1.5 x 10^{-3} inch depth on the journal forming the bearing inner race, produced a gross exceedance of the maximum permissible diametric clearance of 1 x 10^{-3} inch. It was clear from the appearance that both the journal groove and either part or all of the roller undersize had resulted from a wear process, and this was also entirely consistent with the increased iron level in the oil shown by SOAP data, which indicated that the wear had largely taken place over approximately the last 200 hours of operation. Also consistent was the only MCD alarm, which probably resulted from small fragments released when pieces of the small lip, which had formed at each end of roller rolling surfaces, broke off as the wear progressed. Wear of the bearing was probably well advanced at this stage, and it was notable that in a previous case (1.16.4 (5)) rollers wore 15 - 16 x 10^{-3} inch without any MCD warnings.

It was not reasonable to suppose that the roller gross undersize had been present at manufacture as, at the very least, the lack of ability of the cage to retain the rollers should have provided unmistakable signs of a defect. Metallurgical evidence indicated that it was unlikely that roller wear had resulted from a material abnormality. With the lack of smearing or pick-up of the worn surfaces and, on the contrary, a good finish to all the rolling surfaces, the evidence did not indicate that gross lack of lubricant had contributed to the wear.

The outer race was little worn, the rollers appeared smooth and generally round, although grossly outside the stringent permissible roundness limits, and both the rollers and the journal had suffered surface heating. These characteristics were most consistent with much or all of the undersize having resulted from wear caused by roller skidding or overload, but no reason for either of these to have occurred was established. It was noteworthy that the gearbox had suffered, throughout its life, from problems with the pinion and/or its bearings. This included at least one incident which apparently constituted an embryonic stage of the wear process that, after pinion replacement, led to the accident. However, lack of information precluded much meaningful assessment of the gearbox's history, and of whether or not it was abnormal.

It was also noteworthy that the high bearing wear rate had apparently started immediately after the 1200 hour inspection, as evidenced by SOAP records. No significant deviation from the engine manufacturer's requirements in rebuilding the engine following the 1200 Hour Inspection was apparent. However, the highly uneven wear circumferentially of the No 4 bearing journal was consistent with excessive journal runout. The possibility that such a condition had arisen from incorrect orientation of the powertrain pinion on the power turbine shaft because of failure to realign index marks during reassembly could not be dismissed, although there was no direct evidence to indicate that this had occurred and the LT101 UK Service Centre was confident that their procedures should have prevented it. However, given the undoubted importance of maintaining runout within limits, as emphasised in the Maintenance Manual, the absence of a requirement for a confirmatory check of runout after the disturbance of disassembly and rebuild of original components was surprising, particularly when the measurement can quite readily be made. It has been recommended that the CAA impose a requirement for a check of the journal runout during rebuild following inspection disassembly.

The lack of requirement for any dimensional check of the No 4 and 5 bearings during the 1200 Hour Inspection, such as a feeler gauge check of the clearance between rollers and journal, was also surprising in view of the limitations of a visual examination of an assembled bearing and the history of an excessive roller wear rate. It has been recommended that the CAA impose a requirement for such a dimensional check.

Possible roller skidding causes or contributory factors such as dimensional or surface finish anomalies in components of the bearing could not be totally dismissed as no areas of rollers or the outer race trackway remained unworn. However, the fact of the gross wear rate starting at the Inspection rebuild suggested that only surface finish damage caused at this time was likely to have been relevant, although no evidence of such damage was found.

The engine manufacturer opined that excessive side loading (*ie* perpendicular to the power turbine shaft axis) as a result of bearing misalignment had been responsible for the wear of the bearing, although without suggesting how this might have occurred, and proposed tightening overhaul alignment limits. Subsequently, the manufacturer appeared to dismiss bearing misalignment as the cause of bearing wear. Possible causes of unusual side loading in comparison with other engines of the type were:

i) Bearing misalignment - With the LT101 engine's configuration of three, rather than two, bearings supporting the effectively rigid shaft assembly, close bearing alignment was clearly vital. It is considered that a check of bore alignment should form part of a gearbox inspection and it has been recommended that CAA should impose a requirement for such a check.

In the case of G-META, accurate measurement showing that the static alignment of Nos 4 and 5 bearing bores, while outside initial-build limits was within the comparatively rigorous overhaul limits, indicated that misalignment between these two bearings should not have applied unusual side loading to No 4 bearing. Although the effects of engine and gearbox casing deformation under operating loads could not be investigated, no reasons were found to suggest that the accident engine might have been unusual in this respect.

Engine disruption precluded assessment of the alignment of No 3 bearing with Nos 4 and 5, but, had such a misalignment caused No 4 bearing to wear, it was likely that the wear would have been fairly evenly distributed circumferentially and that No 5 bearing would have also suffered. Neither of these was the case and no evidence was found that bearing misalignment had been a factor.

ii) Pinion/shaft imbalance - Checks of the dynamic balance of the power turbine and shaft and the powertrain pinion, either individually or as an assembly, were precluded by damage. Routine vibration checks made at around the start of the heavy wear showed that no out-of-limits imbalance existed at this time. No means were available to continuously monitor vibration, and there was a possibility that the wear or failure of a component could subsequently have caused an excessive imbalance. Dynamic imbalance would explain the circumferential asymmetry of the journal wear, but it could also be that excessive No 4 bearing clearance resulting from initial wear allowed an acceptable degree of imbalance to take effect.

2.7 *Previous similar cases*

Although the evidence showed that wear of the Nos 4 or 5 bearings of the LT101 engine at an excessive rate was a known problem, its severity could not be quantified as no details of cases were available except where wear had reached gross levels. Of the five known previous cases of grossly worn No 4 or 5 bearing rollers having been found, geartooth breakage was associated with three of them. In two of the cases the damage was found in time to prevent complete power drive train disconnection and consequent power turbine overspeed burst, but in the third, five months prior to G-META's accident, gearwheel damage did proceed to this point (para 1.16.4 (4)). Lack of information made it impossible to assess the engine manufacturer's original conclusion that the failure had been caused by excessive misalignment of bearing bores. No evidence was found to indicate that attempts had been made to investigate effectively the defect prior to this case; or to take effective measures to rectify or contain the problem after this failure had made the potentially serious consequences obvious.

Undoubtedly, both G-META's failure progression and its effects were very similar to those in this case and, had G-META's operator been more fully aware of the details of the previous case, the warning signs might have been interpreted differently.

2.8 *Advanced warning*

With hindsight, there had been a number of warnings to both the operator and the engine manufacturer of developing bearing wear and it was therefore necessary to assess the reasons why misinterpretation of the signs allowed the failure to proceed to the point of turbine non-containment.

The operator's maintenance organisation did not ignore the signs from the sudden, rapid and sustained increase in oil iron content indicated by SOAP of an excessive wear rate in some component of the engine, including its gearbox. The operator kept the engine manufacturer informed of the abnormal indications and took advice from the manufacturer on the action to be taken However, SOAP indications alone were not normally considered suitable grounds for rejecting an engine, but were used for trend monitoring unless an abnormally high MCD warning rate also occurred. This approach had been influenced by the operator's experience of SOAP having indicated anomalies at such an early stage that the problem could not be found on tear-down, a valid consideration with an engine with a high unscheduled removal rate, although one that could probably be at least partially resolved by more stringent inspection requirements, including those recommended above.

The approach was also apparently in line with the attitude of the airworthiness authorities involved, who had made no requirement for the operator to conduct the SOAP, and of the engine manufacturer, who had categorised SOAP in the Maintenance Manual as a suggested procedure for engines on a hard-time overhaul programme, rather than as a requirement. Additionally, the engine manufacturer made it clear in the Manual that guidelines were not absolutes, or go no-go criteria; and the 3 ppm increase between samples suggested as a limit had not been exceeded.

It can now be seen that the SOAP provided a clear warning of the developing failure and it has been recommended that the CAA makes mandatory such a programme, with clear procedures optimised for the timely detection of impending failure.

The perception of MCD cautions as carrying more immediate weight than SOAP results was consistent with the Maintenance Manual's instructions in the event of such a caution having been in the form of requirements. However, they were unclear in that they dealt with finding excessive quantities of chips on an MCD, without defining these terms. Nevertheless, the two, reportedly very small, fragments found by the operator shortly before the turbine burst would not seem to have matched this description, and the action required therefore became by default a matter for the operator's judgement. It seems likely that this could have been influenced by further guidance on MCD warnings given in a Commercial Service Letter. This noted that the source of chips must be determined, but, by emphasising, in the context of some operators reportedly having underestimated the significance of MCD alarms, that action was required in the event of a chip alarm accompanied by a sudden loss of oil pressure or if more than two chip alarms occurred within 50 hours, it also implied that it was not necessary in the case of a single warning to determine the source of debris responsible.

With this background information, the experience of frequent MCD warnings commonly being generated by new and newly rebuilt engines, and the knowledge that the oil pump had been changed 31 hours before, it would have been reasonable for the operator to assume that the single event of finding very minor debris did not constitute grounds for suspecting that a major failure was imminent.

It has therefore been recommended that the CAA ensure that effective, clear and unambiguous instructions on the action required in the event of an MCD caution are available to operators.

The evidence from G-META's accident and from previous cases suggested that debris generation from the failure initially comprised very small fragments broken from the lip formed at either end of the rollers, followed, probably quite shortly before the turbine burst, by fragments of gear tooth. A similar sequence appeared to have occurred in at least some of the previous similar cases, although with a lower frequency of MCD cautions than might have been expected. This could have been influenced by the screen in the bottom of the gearbox, and it had clearly prevented much of the tooth debris from reaching the MCDs in G-META's case. Any debris generated in the gearbox had to pass through the 1 mm diameter holes in the screen in order to reach either of the MCDs, whereas, with the fatigue cracking occurring near the root of the teeth, the cross-section of the earlier tooth fragments generated was likely to be around 3 x 2 mm. Many of the tooth fragments found in the gearbox after the failure had a cross-section in this order, and could not have crossed the screen, and it was probably not until relatively late in the sequence that small tooth fragments of less than 1 x 1 mm cross-section had been generated, as a result of tooth chipping when gearwheels had reached an advanced state of break-up.

It has therefore been recommended that the CAA require modification to ensure that no debris generated in the gearbox is restricted or prevented from reaching MCDs.

The lack of any further MCD warning, in spite of the evidence that clearly suggested that further debris had found its way onto the MCDs prior to the turbine burst (para 2.5), was totally consistent with the cable failure found in the MCD caution light circuit. Since the wiring was in series, failure at this point disabled the whole MCD system for this engine. The evidence indicated that the failure had probably resulted from snagging by personnel reaching under the engine, but had not been apparent because the cable end had been held and hidden by an elastomeric boot, which in turn had been supported by the second cable. An operator's Maintenance Schedule error leading to omission from the Schedule of a functional check of the circuit meant that it was not known if or when a check had been made, but the final break of the cable apparently occurred sometime between the caution on 30 April 1987 and the accident.

It was noted that a very simple circuit modification such as the example possibility shown in Appendix 5, mainly involving the addition of a single cable from the engine MCD to the annunciator panel, would enable a cockpit pre-flight check of the whole MCD circuit, rather than just the annunciator panel. In view of the importance of the system, as demonstrated by this and previous accidents, it has been recommended that the CAA require incorporation of a modification to achieve a pre-flight check facility of the whole circuit, and consider the need to require additional support for the cables to the MCDs.

Although not a direct factor in this accident, it was considered that provision of a fuzz-burning facility, as provided for airframe transmission MCDs, and available as an FAA approved kit, would improve the level of confidence in the engine MCD system and thereby the probability of effective reaction to an alarm. It has therefore been recommended that the CAA consider requiring such a facilty to be fitted.

It was considered likely that the developing failure, by critically affecting the support of components rotating at up to 36240 rpm, would probably have generated an abnormal vibration signal, possibly over an extended period of operation. No means of continuously monitoring engine vibration was available on the aircraft, although such a facility would be capable of providing an effective and powerful indicator of many aspects of the mechanical integrity of high speed rotating equipment. It has been recommended that CAA require continuous vibration monitoring for all high speed rotating components whose integrity is relevant to flight safety.

a) Findings

(1) The helicopter had been maintained in accordance with the manufacturers' Maintenance Schedules and its Certificate of Airworthiness was valid.

(2) The pilot was properly licenced and adequately experienced to conduct the flight.

(3) The handling of the emergency was greatly facilitated by the provision of twistgrip throttles rather than roof-mounted speed select levers.

(4) The No 1 engine suffered sudden and complete loss of power output shortly before touchdown as a result of the bursting of its power turbine.

(5) Debris from the No 1 engine power turbine penetrated the No 2 engine casings, probably causing complete power loss, and also severed the tail rotor shaft which resulted in loss of yaw control.

(6) The No 1 engine power turbine burst due to overspeeding because its power output drive train was disconnected as a result of fatigue failure of gearwheels in the engine gearbox, induced by abnormal loading caused by excessive clearance in the No 4 bearing.

(7) Excessive No 4 bearing clearance resulted from gross wear of the bearing rollers and journal, probably as a result of roller skidding or overload.

(8) The cause of roller skidding or overload was not established. No evidence was found to substantiate an assessment by the engine manufacturer that static misalignment of gearbox bearings had caused or contributed to the failure.

(9) A substantial incidence of No 4 or 5 bearing excessive wear rate had probably been experienced over the worldwide engine fleet. In three of the five known previous cases of No 4 or 5 bearing gross roller wear, gearwheel tooth failures had resulted, in one case leading to power turbine non-containment. With the exception of the latter case, little evidence was found that substantial investigation of the defects had been conducted by the engine manufacturer.

(10) Although the circumstances of the previous non-containment were made known by the aircraft manufacturer, action taken by the manufacturers or appropriate Airworthiness Authorities was insufficiently effective to ensure the continuing airworthiness of the Bell 222 and prevent a recurrence.

(11) Problems with the powertrain pinion and/or its bearings had afflicted the gearbox responsible for G-META's accident throughout its life, but it could not be established whether the extent of the problem was abnormal. No evidence was found to indicate why this engine would have been particularly susceptible.

(12) The SOAP provided clear indications of accelerated wear in the engine, but neither the engine manufacturer nor the operator considered SOAP indications as satisfactory grounds for engine rejection.

(13) Instructions in the engine manufacturer's manual for action in the event of finding metallic debris on MCDs were ambiguous. They did not indicate that the two very small fragments found prior to the accident were adequate grounds for suspecting that a potentially serious failure was well advanced.

(14) Further MCD cautions were not obtained because the system was disabled by an undetected cable failure at an unknown time during the six days preceding the accident.

(15) The MCD caution system was perceived by the operator and the engine manufacturer as the primary means of monitoring the mechanical health of the engines, but the design was such that the pre-flight cockpit check of the annunciator captions did not check the MCD caution light system circuit. The operator erroneously failed to schedule a check of the circuit.

(16) The detectability of debris by a functioning MCD caution system was probably substantially reduced by the positioning of both MCDs downstream of a 1 mm screen.

b) Cause

The accident was caused by overspeed bursting of the No 1 engine power turbine wheel because of fatigue failure of gear teeth in the turbine drive train. The gear teeth failures resulted from gross wear in a bearing in the engine gearbox, probably caused by skidding or overload of the bearing rollers.

4. SAFETY RECOMMENDATIONS

It has been recommended that the CAA:

4.1 Re-examine the airworthiness requirements for helicopter engine control layout in relation to the emergency actions required to be completed by the pilot in the event of engine and tail rotor malfunctions.

4.2 Require gas turbine engines to have a facility for rapid automatic shutdown capable of preventing turbines from overspeeding to the point of non-containment in the event of output drive disconnection.

4.3 Require, for the 222 and other aircraft types with a similar configuration, the installation of shielding from possible engine non-containment debris of components for which a high integrity is necessary.

4.4 Require, for the LT101, a check of No 4 bearing journal runout during engine rebuild after inspection disassembly.

4.5 Require, for the LT101, a dimensional check of the No 4 and 5 bearings during gearbox maintenance inspections.

4.6 Require, for the LT101, a check of the alignment of gearbox bores for Nos 4,5,6 and 7 bearings during maintenance inspections.

4.7 Make a SOAP mandatory for the LT101 engine, with clear procedures optimised for the timely detection of impending failure, and require such a programme in other applications where worthwhile flight safety benefits would result.

4.8 Ensure for the 222's engines and other relevant applications, that clear and unambiguous instructions on the action required in the event of an MCD warning are available to operators.

4.9 Require modification of the 222 engine MCD caution light system to provide a pre-flight check facility of the whole circuit, and consider the need for a similar facility for safety-critical warning systems in all applications.

4.10 Consider the need to require additional support for the cables to the 222 engine MCDs.

4.11 Consider requiring fitment of a fuzz-burning facility for 222 engine MCDs.

4.12 Require modification of the LT101 engine to ensure that no debris is restricted or prevented from reaching MCDs; and in all applications require that MCDs whose ability to capture debris could have important repercussions on flight safety be located upstream of screens or filters.

4.13 Require, for all aircraft types, the early provision of a facility to continuously monitor the vibration of all high speed rotating equipment whose integrity is critical to flight safety.

4.14 Take measures to ensure the continuing airworthiness of aircraft granted CAA Type Certification for operation on the UK Register where a defect with potentially severe flight safety repercussions is encountered in non-UK aircraft of the type by:

a) Endeavouring to persuade all other Contracting States to fully discharge the requirements of ICAO Annex 8, Part II, Section 4 (Continuing Airworthiness of Aircraft), and

b) Satisfying itself that such a defect which is clearly of long standing and results in a foreign aircraft accident which is brought to CAA's attention is effectively investigated and rectified, and

c) Monitoring foreign accidents and incidents sufficiently to satisfy itself that adequate rectification action for such a defect is taken by the Airworthiness Authority of the manufacturer.

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Inspector of Accidents

Air Accidents Investigation Branch
Department of Transport
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