Australian Government

Australian Transport Safety Bureau

ATSB TRANSPORT SAFETY INVESTIGATION REPORT

Aviation Occurrence Report – 200501912

Final

Tower Shaft Failures on PWC Engines

Pratt and Whitney Canada
PW100 Series Engines

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Abstract

On 28 April 2005, at approximately 0910 Western Standard Time, a EMB-120ER Brasilia aircraft, registered VH-XUD, was being operated on a chartered flight from Perth, Western Australia to Telfer, Western Australia when the left engine failed. The failure occurred approximately 100km NE of Meekatharra while the aircraft was cruising at 25,000 ft. A PAN alert was declared by the crew and the flight was then redirected by air traffic control to Meekatharra where the aircraft was landed without further incident.

On 3 December 2005, at approximately 0725 Eastern Summer Time, a De-Havilland Canada Dash 8 aircraft, registered VH-TQW, was being operated on a chartered flight from Wynyard, Tasmania to Melbourne, Victoria when the left engine failed. The failure occurred approximately 74 km from Melbourne aerodrome. The crew continued with their approach conducting a single engine landing without further incident.

Subsequent inspection revealed that the tower shaft within the turbomachinery section of the engines of both aircraft had failed. The ATSB received the failed components for examination and analysis. The investigation revealed that fracture of the tower shafts led to the loss of fuel pump operation and subsequent failure of the engines.

It was found that fatigue cracking of the tower shaft had initiated from surface damage that had been produced during the assembly process when the spiral bevel gear was pressed onto the tower shaft.

THE AUSTRALIAN TRANSPORT SAFETY BUREAU

The Australian Transport Safety Bureau (ATSB) is an operationally independent multi-modal Bureau within the Australian Government Department of Transport and Regional Services. ATSB investigations are independent of regulatory, operator or other external bodies.

The ATSB is responsible for investigating accidents and other transport safety matters involving civil aviation, marine and rail operations in Australia that fall within Commonwealth jurisdiction, as well as participating in overseas investigations involving Australian registered aircraft and ships. A primary concern is the safety of commercial transport, with particular regard to fare-paying passenger operations.

The ATSB performs its functions in accordance with the provisions of the Transport Safety Investigation Act 2003 and Regulations and, where applicable, relevant international agreements.

Purpose of safety investigations

The object of a safety investigation is to enhance safety. To reduce safety-related risk, ATSB investigations determine and communicate the safety factors related to the transport safety matter being investigated.

It is not the object of an investigation to determine blame or liability. However, an investigation report must include factual material of sufficient weight to support the analysis and findings. At all times the ATSB endeavours to balance the use of material that could imply adverse comment with the need to properly explain what happened, and why, in a fair and unbiased manner.

Developing safety action

Central to the ATSB's investigation of transport safety matters is the early identification of safety issues in the transport environment. The ATSB prefers to encourage the relevant organisation(s) to proactively initiate safety action rather than release formal recommendations. However, depending on the level of risk associated with a safety issue and the extent of corrective action undertaken by the relevant organisation, a recommendation may be issued either during or at the end of an investigation.

The ATSB has decided that when safety recommendations are issued, they will focus on clearly describing the safety issue of concern, rather than providing instructions or opinions on the method of corrective action. As with equivalent overseas organisations, the ATSB has no power to implement its recommendations. It is a matter for the body to which an ATSB recommendation is directed (for example the relevant regulator in consultation with industry) to assess the costs and benefits of any particular means of addressing a safety issue.

About ATSB investigation reports: How investigation reports are organised and definitions of terms used in ATSB reports, such as safety factor, contributing safety factor and safety issue, are provided on the ATSB web site www.atsb.gov.au.

1 FACTUAL INFORMATION

1.1 Initial failure

On 28 April 2005 at about 0910 WST[1], an Embraer[2] EMB-120ER, registered VH-XUD, was cruising at approximately 25,000 ft en route to Telfer, Western Australia. At approximately 100 km North East of Meekatharra, Western Australia, the left engine (number-one) failed.

The crew reported that the first indication of an engine malfunction was a slight change in the sound of the engine pitch. Shortly after, multiple aural warnings from the left engine's electronic engine control (EEC) and oil pressure unit were heard. The pilot in command (PIC) reviewed the left engine gauges which revealed there was no engine torque or oil pressure and 85% gas turbine speed (Ng). The crew feathered the propeller by activating the left engine electric propeller feather mechanism. The engine was then shut down.

After declaring a PAN[3], which was acknowledged by air traffic control, clearance to Meekatharra and a flight level change was issued. The crew performed a single-engine landing at Meekatharra.

The subject engine, a Pratt and Whitney Canada (PWC) PW118A (S/N 115622), was inspected, then removed from the aircraft and transported to the operator's maintenance facility in Perth, Western Australia, where a more detailed inspection was performed. On recommendation from the engine manufacture, the turbomachinery accessory drive cover was removed, whereby the spiral bevel gear lock nut and cup washer were found loose within the housing.

The engine was then transported to the manufacturer's overhaul facility in Singapore for disassembly and examination. A detailed inspection of the tower shaft assembly was performed under supervision of the Air Accident Investigation Bureau of Singapore (AAIB Singapore) on behalf of the Australian Transport Safety Bureau (ATSB). The teardown revealed that the accessory drive spiral bevel gear lock nut and cup washer were loose within the tower shaft housing. The accessory drive spiral bevel gear and number-29 bearing were also badly damaged. Further disassembly found that the tower shaft had fractured in two locations.

The fractured tower shaft and the other damaged components were sent to the ATSB for further detailed analysis.

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1 The 24-hour clock is used in this report to describe the local time of day, Western Standard Time (WST), as particular events occurred. Western Standard Time was Coordinated Universal Time (UTC) +8 hours

2 Empresa Brasileira de Aeronautica.

3 Urgency call by pilot to alert all listening parties of a special handling condition which will receive Air Traffic Control priority for issuance of a clearance or assistance. Normal broadcast is PAN PAN PAN.

1.2 Subsequent failure

During the course of the investigation, the ATSB received notification of a subsequent PW100-series engine failure incident involving a different operator. The details of that engine failure are described below.

At approximately 0725 ESuT[4] on 3 December 2005, while inbound approximately 74 km from Melbourne aerodrome, during a scheduled passenger flight from Wynyard, Tasmania, the crew of a De-Havilland Canada, Dash 8 aircraft, registration VH-TQW, heard a loud bang from the left side of the aircraft. The crew then observed the loss of the left engine's torque and a corresponding low oil pressure indication.

Following company procedures, the crew conducted an in-flight engine shut down, advised Melbourne centre of their situation, and continued with their approach. A single engine landing was conducted at Melbourne.

After initial inspection, it was determined that an internal engine failure had occurred. The engine, a model PW121 (S/N 120257) was removed from the aircraft and sent to the manufacturer's overhaul facility in Singapore for disassembly and examination. That process was again conducted under the supervision of the AAIB Singapore on behalf of the ATSB.

The reduction gearbox magnetic chip detector and oil filter were examined and found clear of debris, however, the turbomachinery magnetic chip detector and oil filter were found to contain metal particles.

A modular disassembly of the engine revealed multiple dents to the turbomachinery accessory drive cover. The accessory drive spiral bevel gear lock nut was found loose, with its corresponding cup washer fractured into three pieces. There was damage observed to the meshing teeth of the accessory drive coupling gear and the spiral bevel gear. On removal of the tower shaft, it was found to have separated into three fragments. The number-29 bearing had been badly damaged with two of its rollers dislodged and the bearing seized.

These components were sent to the ATSB for further examination.

1.3 Additional tower shaft finding

As a result of the incident involving aircraft VH-XUD, the operator decided to conduct an inspection of the tower shaft from another PW100-series engine (S/N 120187) within their fleet that was undergoing scheduled maintenance. To facilitate that inspection, the unscheduled removal of the spiral bevel gear was required.

On removal of the spiral bevel gear, the operator found evidence of scoring to the spiral bevel gear interface region of the shaft. That (third) tower shaft was also sent to the ATSB for further detailed analysis.

4 Australian Eastern Summer Time (ESuT) was Coordinated Universal Time (UTC) +11 hours.

1.4 Engine components received

The components received by the ATSB from the accessory drive section of the PW100 engines S/N 115622 and S/N 120257 are detailed in table 1 below.

Table 1: Components received by ATSB from PW100 engines S/N 115622 (VH-XUD) and S/N 120257 (VH-TQW).

Item	Engine S/N 115622 (VH-XUD)	Engine S/N 120257 (VH-TQW)	Item Reference Figure 2	Figure Reference
Tower Shaft	P/N 3111968-01 S/N 72B575	P/N 3111968-01 S/N 50B758	1b	Figures 3 - 9
Half Retaining Ring (Qty 2)	P/N 3106286-01 Nil		2	-
Gear Shaft Collar	P/N 3110862-01 Nil		3	-
Adjusting Spacer	P/N 3101390-05 Nil		4	-
Roller Bearing #29	P/N 3107496-01 S/N FC78164	P/N 3107496-01 S/N FC38592	5	Figures 13 - 15
Bearing Shield	P/N 3106297-01 Nil		6	-
Bearing Shield	P/N 3106297-01 Nil		6	-
Retaining Ring	P/N AS3215-15 Nil	P/N AS3215-15 Nil	7	-
Spiral Bevel Gear	P/N 3111969-01 S/N 85B751	P/N 3111969-01 S/N 85B759-20	8	Figures 10 - 12
Cup Washer	P/N 3111957-01 Nil	P/N 3111957-01 Nil	9	Figure 16
Lock Nut	P/N 3111100-01 Nil	P/N 3111100-01 Nil	10	-
Roller Bearing #28	P/N 3107496-01 S/N FC22358	P/N 3101393-01 S/N 37S461	-	-
Coupling Bevel Gear Shaft		P/N 3106258-01 S/N 86B364	-	-

1.5 Engine design

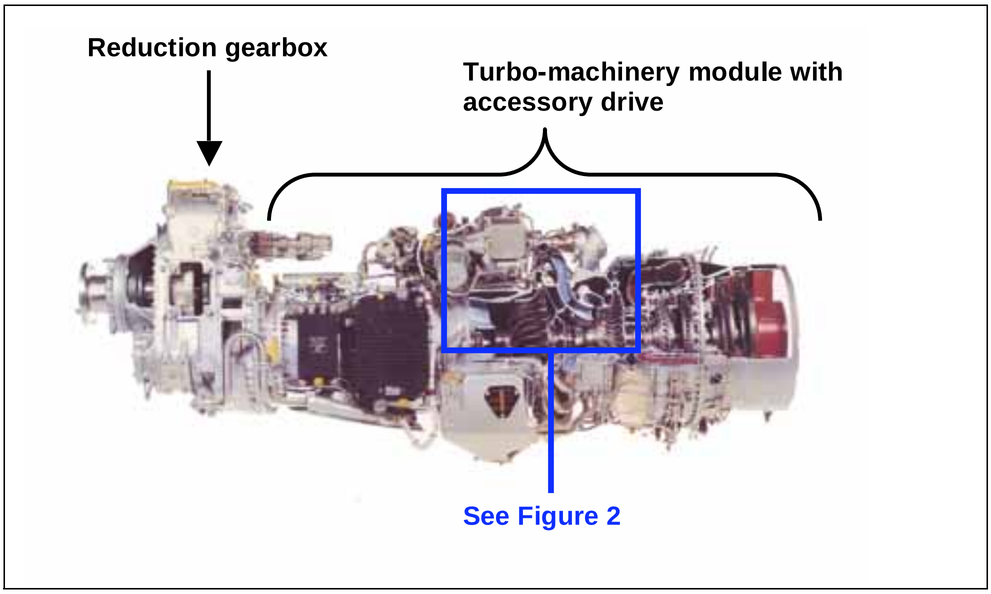
The PW100-series was a free turbine, turbo propeller engine. It contained two modules designated turbomachinery and reduction gearbox, see figure 1. The turbo-machinery module consisted of low pressure (LP) and high pressure (HP) impellers and turbines, and a two stage (free) power turbine (PT) that was connected by a shaft to the reduction gearbox.

The reduction gearbox drove the propeller and contained two speed reduction stages. As the propeller was connected through the reduction gearbox to the PT shaft, it had no direct mechanical inter-connection to the engines HP and LP stages.

There were two accessory drive sections on the engine. One accessory drive section was located directly on the reduction gearbox, which drove the pitch control unit (PCU), the hydraulic pump and the PCU oil pump. The other was attached to the turbomachinery module and incorporated the starter/generator, fuel pump and main oil pump. Actuation of this accessory gearbox was accomplished through the tower shaft and spiral bevel gear which were connected directly to the PT shaft.

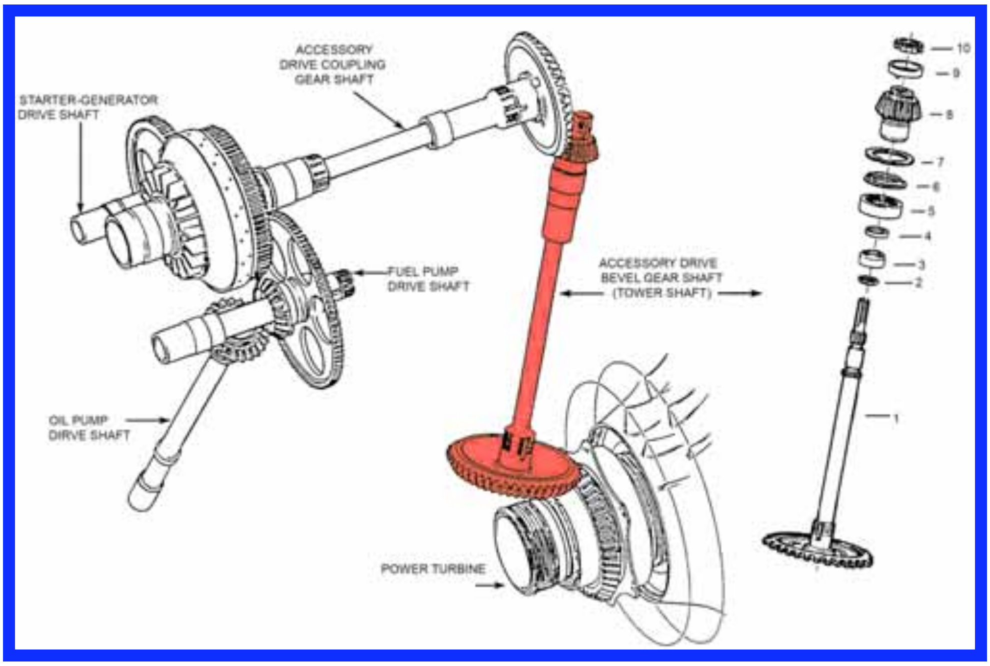
The engine was started by the starter-generator rotating the HP impeller and turbine. During engine operation, the bevel gear splined to the HP impeller rotated the associated drive shaft (tower shaft) to drive the accessory gearbox. Upper and lower axial support of the tower shaft was provided through the number-29 roller bearing and number-30 ball bearing. Operational loss of the tower shaft would have prevented the engine from operating due to fuel and oil starvation.

Figure 1: PW100 Engine Modules: The tower shaft assembly is driven from the power turbine and operates various turbo machinery accessories.



The tower shaft assembly comprised numerous detailed components, see figure 2. A spiral bevel gear was installed onto a spline at the output end of the tower shaft, and provided direct contact with the turbomachinery gearing through the accessory drive coupling gear shaft. Upper and lower axial support of the tower shaft was provided through the number-28 and number-29 cylindrical roller bearings. The number-29 bearing was installed onto the journal of the spiral bevel gear.

Figure 2: Illustration of the mechanical systems driven by the tower shaft (coloured). The numbered part breakdown of the items comprising the tower shaft assembly is detailed in table 2.



1.6 Engine maintenance history

1.6.1 Engine S/N 115622 (VH-XUD)

Maintenance records indicated that engine S/N 115622 fitted to VH-XUD had accumulated 23,416.8 hrs since new. It was last overhauled on 2 March 1999 at 15,098.4 hrs

During that overhaul, the engine was completely disassembled, inspected and reassembled in accordance with the manufacturer's overhaul procedures[5]. New upper and lower (number-28 and number-29) bearings were installed at that time.

1.6.2 Engine S/N 120257 (VH-TQW)

Engine S/N 120257 fitted to VH-TQW had accumulated 32,403.43 hrs since new. Its last maintenance was on 15 March 2003 at 26,973 hrs where it underwent a complete overhaul in accordance with the manufacturer's overhaul procedures.

1.6.3 Engine S/N 120187

The third tower shaft received by the ATSB was from engine S/N 120187 and had accumulated 31,335 hrs since new. The operator advised that the tower shaft had been last overhauled on August 1999 after accumulating 22,385 hrs since new.

5 PWC Overhaul Manual 3034623 Rev 10.

1.7 History of related engine failures

The manufacturer's records showed that tower-shaft failure was a recurring issue in relation to the PW100-series engine. At the time of this report there had been 34 recorded shaft failures. At the time of this investigation, there were a significant number of PW100-series engines in operation globally, which included a variety of models within the range. The configuration of the tower shaft/spiral bevel gear on the two engines was common to the majority of the PW100-series.

Typical findings after a tower shaft related incident on the engines included; fractured tower shaft and loose or separated lock nut/cup washer assemblies, with resulting secondary damage to the surrounding gears and bearings (i.e. number-29 bearing). The manufacturer had documented their findings as being attributed to:

- Improper stacking and preload of the detail parts;
- The lock nut being used as a seating tool for the detail parts;
- Number-29 bearing rollers interfering with the spiral bevel gear journal surface during assembly; and
- Improper assembly processes causing surface damage to the seating diameter of the shaft under the spiral bevel gear.

Since 1998, the manufacturer, attempted to address the failure issues through several phases of repair, modification and changes to assembly procedures. These phases are described below.

Phase I - January 1998

The initial PWC corrective phase (Phase-I) commenced in January 1998 and included an amended procedure to the Workscope Planning Guide and Overhaul Manual when installing the spiral bevel gear onto the tower shaft.

While the importance of heating the spiral bevel gear and cooling the tower shaft as part of the assembly procedure was emphasized, a new hydraulic tool was introduced to facilitate the final seating of the gear and pre-load of the detail components. The new hydraulic loading tool resolved problems associated with incomplete seating of the gear on the shaft.

Phase II - November 2001

Phase-II of reliability improvement commenced in November 2001 with the release of a service information letter (SIL) PW100-079. When an engine had been inducted for Hot Section Inspection (HSI) the SIL added an optional procedure to the recommended 'Minimum Workscope Planning Guide'. The procedure concentrated on careful inspection of the tower shaft seating diameters while installing the spiral bevel gear onto the tower shaft.

Phase III - November 2002

Phase-III of additional maintenance action was introduced in November 2002 and recommended that maintenance shops use assembly fluid to retain the number-29 bearing rollers against the outer race during tower shaft overhaul. This was implemented to prevent damage to the lead-in chamfer of the spiral bevel gear journal surface during the installation process.

Phase IV – November 2005

The most recent improvement (Phase-IV) was issued in November 2005 with the introduction of a service information letter (SIL PW100-104) that advised of additional changes to the Overhaul Manual. It was recommended that during engine overhaul, the number-29 bearing and the spiral bevel gear be replaced as a set.

A breakdown of the number of PW100-series engine failures and a summary of their modification/phase level is shown in Table 2. Detailed is the number of PW100 engines that failed due to tower shaft distress for any given year, and what phase of modification had been incorporated onto those particular shafts.

Table 2: Summary of reported tower shaft failures for the PW100-series engine.

PWC Maintenance Action	2001	2002	2003	2004	2005	2006
Pre-Phase I	2	6	1	2	2	2
Phase I (Introduced January 1998)	0	3	4	3	4	0
Phase II (Introduced November 2001)	--	0	0	0	0	0
Phase III (Introduced November 2002)	--	--	0	2	3	0
Phase IV (Introduced November 2005)	--	--	--	--	--	0
Total	2	9	5	7	9	2

Advice from the manufacturer indicated that the tower shaft from engine S/N 115622 and S/N 120187 had incorporated phase-I improvements. The tower shaft from engine S/N 120257 had incorporated phase-I and -II improvements.

1.8 Spiral bevel gear overhaul procedures

The tower shaft and the spiral bevel gear were made to precise tolerances. In order to create the required assembly interference fit[6], the manufacturer's manual[7] containing overhaul procedures required that heating[8] of the spiral bevel gear and cooling[9] of the tower shaft be performed. For assembly after that process, the manual provided the following cautionary instruction:

> The spiral bevel gearshaft (1) must be seated as quickly as possible to ensure proper seating of the gear on the towershaft (3) (Pratt and Whitney Canada Overhaul Manual, Part Number 3034623 72-03-10 Turbomachinery (PW118A, PW118B) – Assembly 2, page 549, dated June 24 2005).

No maximum allowable time for assembly of those components following their removal from the respective heating/cooling environments was given.

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6 Interference fit: A fit which everywhere provides an interference between the hole and the shaft when assembled, i.e. the maximum size of the hole is smaller than or, in the extreme case, equal to the minimum size of the shaft. International Organization for Standardisation 286-1: 1988.

7 Pratt and Whitney Canada Overhaul Manual, Part Number 3034623 72-03-10 Turbomachinery (PW118A, PW118B) – Assembly 2, page 549, dated June 24 2005.

8 Heating: place bevel gear in an oven at 141℃ for 15 minutes (minimum).

9 Cooling: shroud the tower shaft end-section with dry ice for 15 minutes (minimum).

1.9 Physical examination

The failed tower shafts and their sub-components were examined optically using a binocular microscope and at higher magnification using the scanning electron microscope (SEM). Semi-quantitative chemical analysis using the energy dispersive spectrometer (EDS) attachment to the SEM was also performed on some of the components.

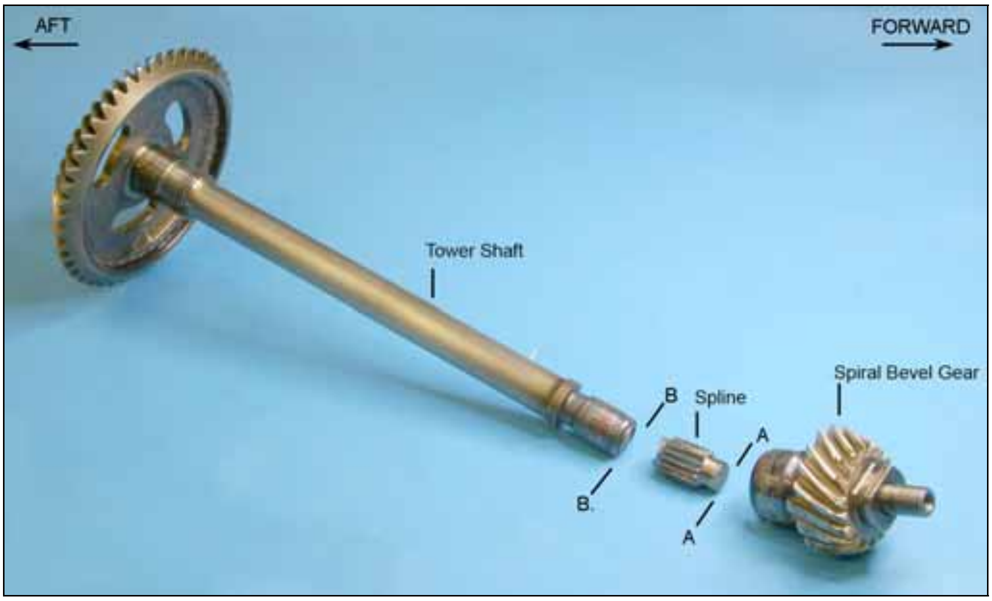
1.9.1 Tower shafts S/N 115622 (VH-XUD) and S/N 120257 (VH-TQW)

Preliminary examination of tower shafts from engine S/N 115622 and S/N 120257 revealed that they had fractured into three discrete fragments. As received, the mid-shaft spline and the threaded stub-end had separated from the main body of the tower shaft. Each failure was located near the radius runout regions either side of the mid-shaft spline. While the spline had separated completely from the main body of the shaft, the threaded stub of the shaft end was still in position and locked within the liberated spiral bevel gear of both shafts (figures 3 and 4).

Other damage to the tower shafts included circumferential abrasion from metal-to-metal contact adjacent to the mid-section fracture at location B-B of figure 3. Discolouration, commonly referred to as ‘heat tint’, was also observed in the abraded region of both shafts, which indicated that the shafts had experienced localised high temperature distress at that location. The shaft from engine S/N 120257 displayed significantly more discolouration than shaft from S/N 115622.

Figure 3: **Photographs of the failed tower shafts from engines S/N 115622 (VH-XUD) and S/N 120257 (VH-TQW). Both shafts fractured at two locations (labelled A-A and B-B) allowing separation of the spiral bevel gear and mid-shaft spline gear.**

S/N 115622



S/N 120257

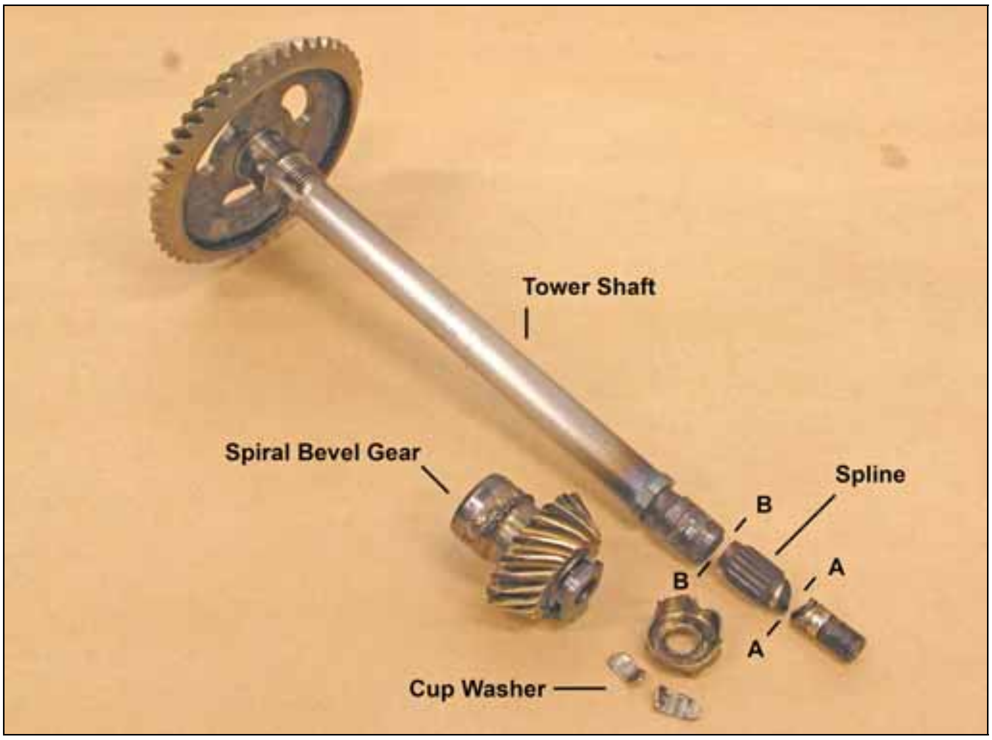
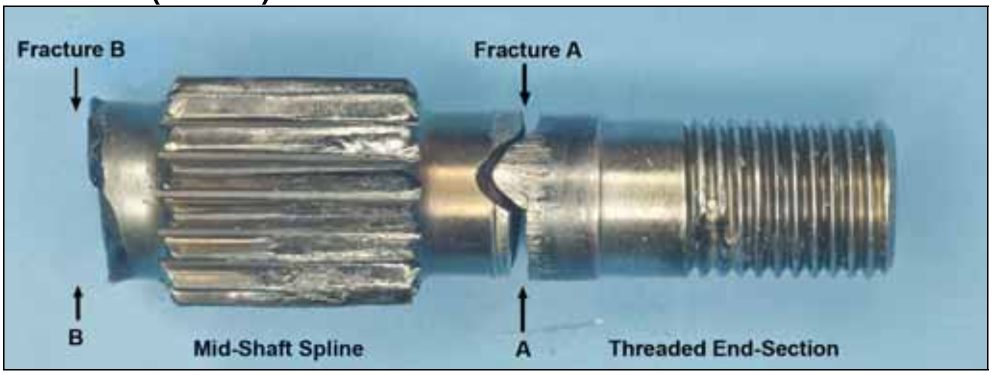
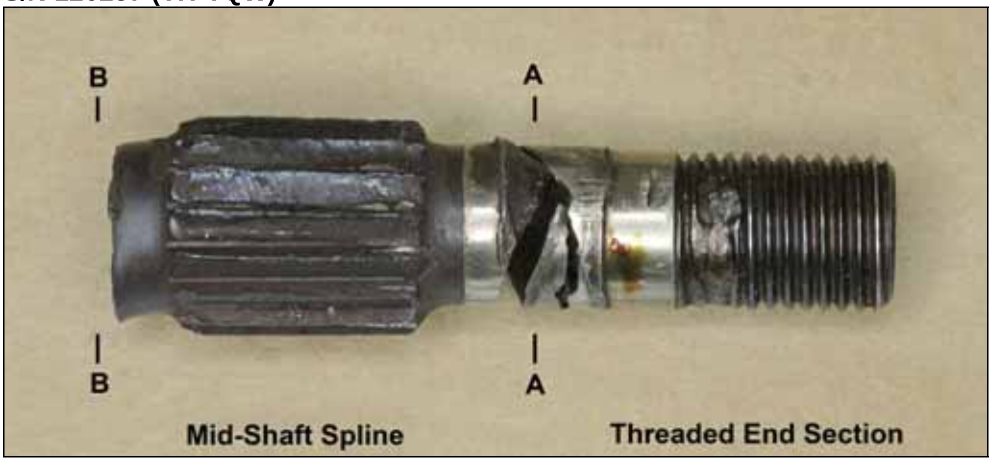


Figure 4: General view of the liberated mid-shaft spline gear and threaded end section of the tower shaft showing the location of both fractures.

S/N 115622 (VH-XUD)



S/N 120257 (VH-TQW)



Mid-Shaft spline and threaded end section

The threaded end-sections were removed from within the spiral bevel gears by destructive sectioning and eased from within the gear without introducing additional damage to the seating diameters.

Close examination of the mid-shaft splines and the threaded end-section from each shaft, showed clear and severe galling[10] on the seating diameter close to fracture location A-A, see figure 4 and figure 5. The galling damage was aligned longitudinally with the shaft axis with many well defined scores observed, which was consistent with being produced during the pressing of the spiral bevel gear onto the shaft.

When the fractures at location A-A were examined at high magnification using the scanning electron microscope (SEM), it was revealed that the surfaces were flat and transgranular consistent with a fatigue crack growth mechanism. It was found that the fatigue cracking had initiated from within the galled region, see figures 6 – 8.

10 Galling is a condition whereby excessive friction results in localised welding and adhesive wear that further roughens one or both sliding contact surfaces.

In contrast, the fractures at location B-B displayed plastic deformation and ductile tearing consistent with that of a torsional overload.

Figure 5: Close-up of fracture A-A showing the identical nature of the damage to the seating diameters of tower shafts from engine S/N 115622 (VH-XUD) and S/N 120257 (V/H TQW).

Other damage to the mid-shaft splines included accelerated wear of the spline teeth whereby the profile of each gear tooth had deteriorated into a sharpened edge. Thread damage was also observed near the runout region of each shaft stub where the profile of the rear threads had been flattened.

Figure 6: Opposing views of the fractured mid-shaft spline gear from engine S/N 115622 (VH-XUD) and engine S/N 120257 (VH-TQW).

Figure 7: **Low magnification SEM image of the tower shaft fracture surface A-A from engine S/N 115622 (VH-XUD). See also figure 8.**

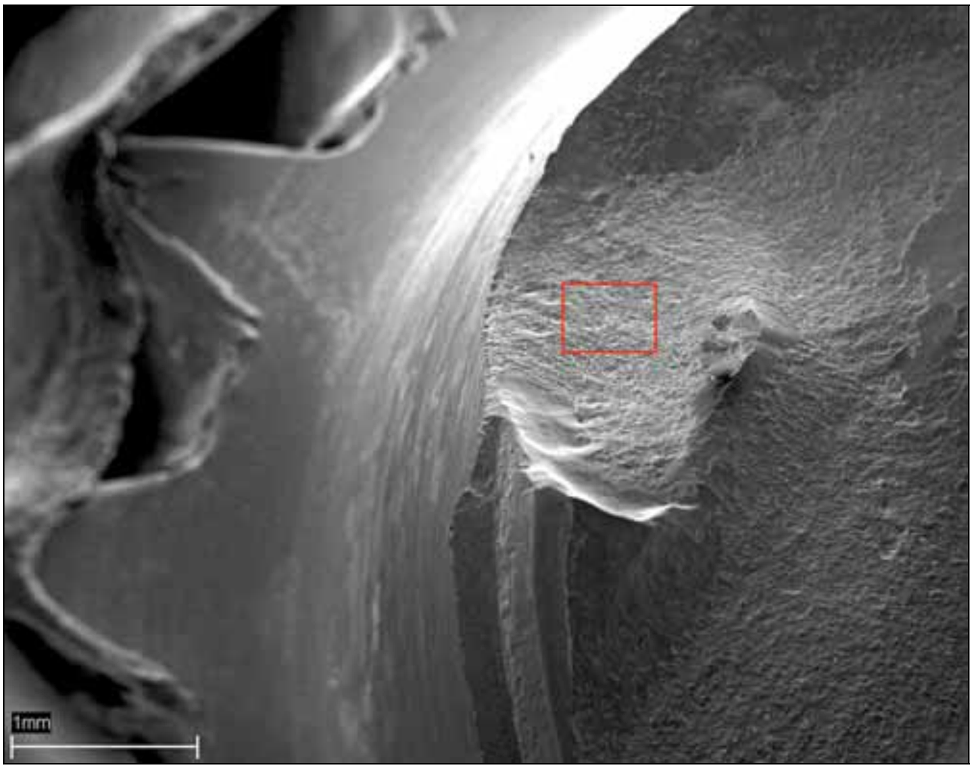
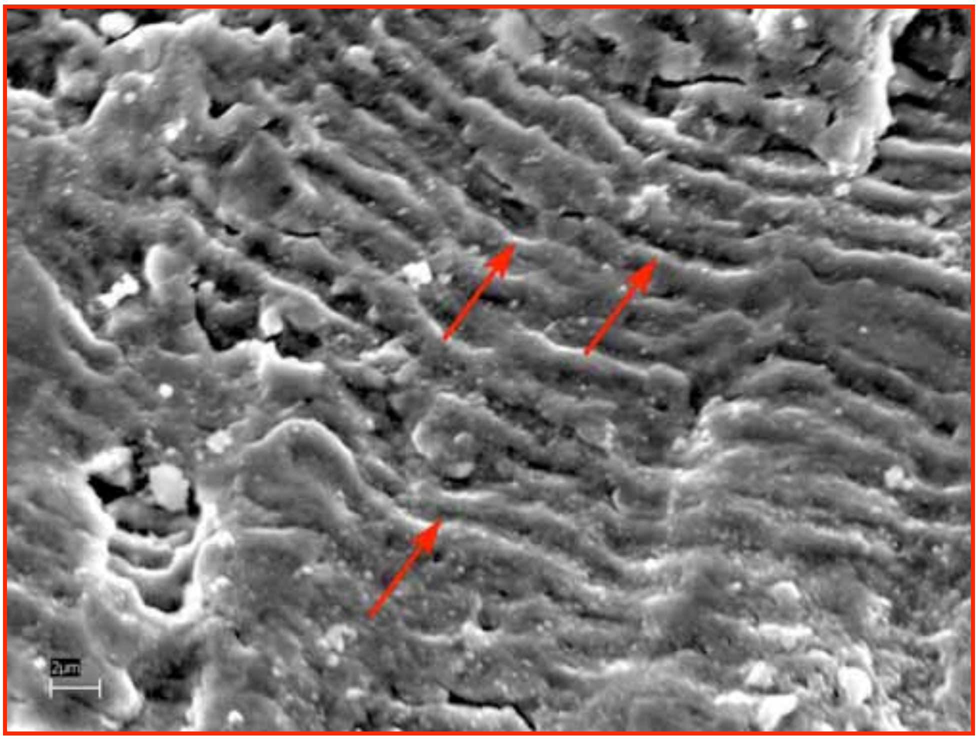


Figure 8: **High magnification image of fracture A-A showing finely spaced fatigue striations (arrowed).**

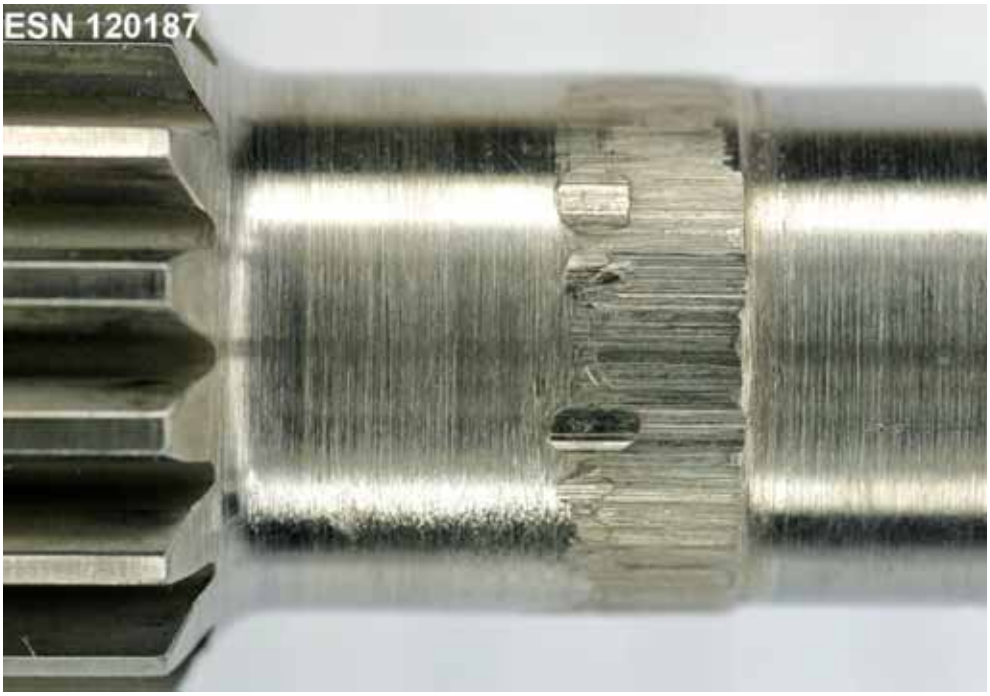


1.9.2 Tower shaft S/N 120187

When the tower shaft from engine S/N 120187 was examined, clear and distinct galling damage was observed on the shaft surface where the assembled spiral bevel gear had been was normally seated. The direction of the damage was evident through the scoring and indicated that it had occurred during hydraulic pressing of the spiral bevel gear onto the shaft, see figure 9. No evidence of cracking was found at that location.

Aside from the galling damage, the tower shaft appeared to be in an otherwise serviceable condition with no indications of abnormal wear or degradation to the component.

Figure 9: Surface damage was produced during assembly of the spiral bevel gear onto the tower shaft from engine S/N 120187.



1.9.3 Spiral bevel gears

Initial examination of the spiral bevel gear from both engines revealed substantial damage to most surfaces. Portions of the gear teeth were missing, cracked or scored. Other damage included brinelling[11], overheating and misalignment damage to the number-29 bearing journal surfaces, see figure 10.

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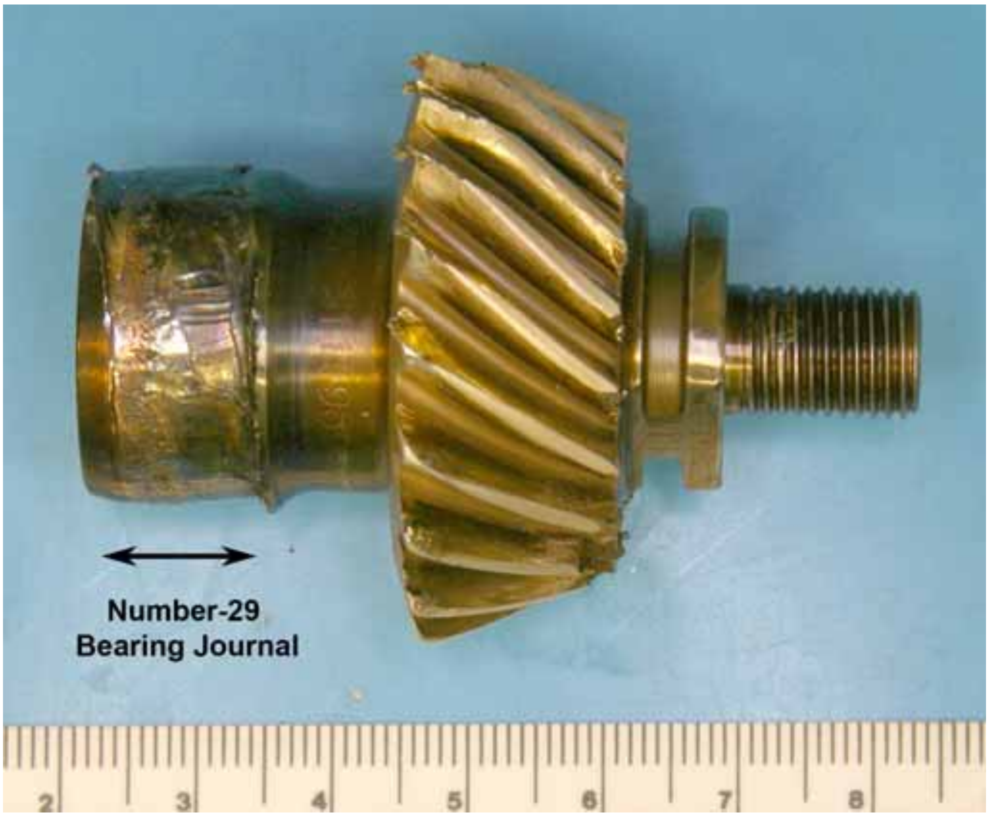
11 Brinelling occurs when loads imparted from the rolling elements exceed the elastic limit of the race material. Static overloads or severe impact can cause brinelling to these surfaces.

Figure 10: Photograph of the spiral bevel gear (P/N 3111969-01) from engine S/N 115622 (VH-XUD). Severe damage to the journal surface (labelled) and gear teeth had occurred. The threaded stub of the tower shaft can be seen protruding from the forward face of the gear.



Destructive sectioning was performed in order to examine the internal seating surface of each spiral bevel gear. Once sectioned, longitudinal scores from galling were observed on the inner surfaces. These scores matched the galling damage seen on the seating diameter of the tower shaft stubs. Figure 11 shows a cross-section through the spiral bevel gears from each engine highlighting the damage.

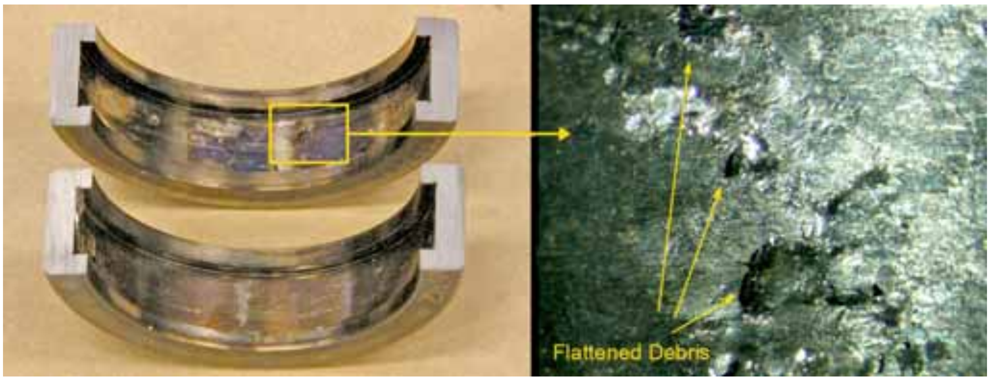
Figure 11: Close-up of the internal seating diameter from the spiral bevel gear of both engines (S/N 115622 and 120257). Axial aligned scores can be seen.

1.9.4 Number-29 bearings

Preliminary examination of the number-29 bearings from each engine revealed evidence of seizing. Many thin bright flecks of metallic debris had contaminated the bearings and could be seen dispersed between the rolling elements, cage and cage pockets, see figure 12. Both bearings showed evidence of lubricant in the form of a thin film on most surfaces.

Sectioning of the bearings revealed the presence of more metallic flakes on the rolling surfaces, which were consistent with the external contamination. No evidence was found to indicate the contaminating debris had been produced by raceway spalling or any other such failure mechanism. The cage and cage pockets were intact with no obvious indications of failure or damage. Two rollers were missing from the bearing removed from engine S/N 120257. Both bearings displayed chipping and wear of their cylindrical rollers.

Figure 12: Photographs of the number-29 bearing from engine S/N 120257 after sectioning. Flakes of flattened contamination can be seen on the raceway surfaces (labelled).



Chemical analysis of bearing contamination

Semi-quantitative chemical analysis of the material comprising the damaged engine components was performed in order to characterise the metallic contaminants that had seized the number-29 bearings of both engines. This was performed using the energy dispersive spectrometer (EDS) attachment to the SEM.

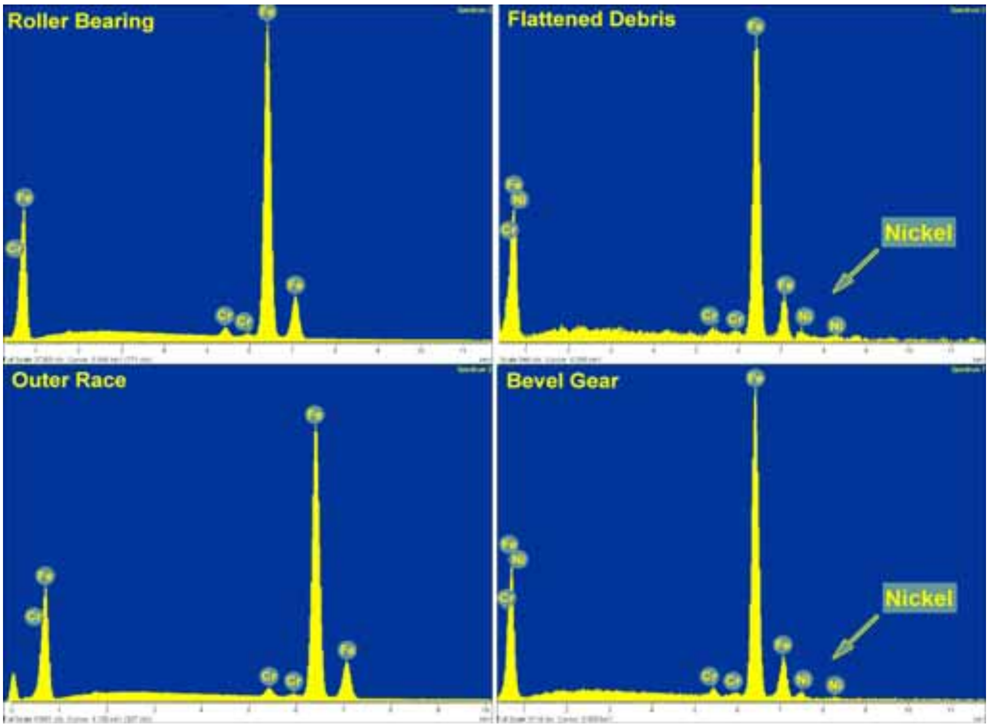
The analysis revealed that the metallic contaminants consisted primarily of iron (Fe) with alloying additions of chromium (Cr) and nickel (Ni). Chemical analysis of the bearing rollers and outer race revealed their composition to be of iron and chromium only. No nickel was found in any of the bearing materials.

Chemical analysis of the spiral bevel gear revealed a composition of iron, chromium and nickel. The alloy composition of contaminant debris that had seized the number-29 was found to be closely match that of the spiral bevel gear, see table 3 and figure 13 for detail.

Table 3: Chemical composition of the various tower shaft components.

Item	Alloying Element (wt%)		
	Fe	Cr	Ni
Number-29 Bearing			
- Rolling Element	98.36	1.64	-
- Outer Race	98.28	1.72	-
Spiral Bevel Gear	95.43	3.23	1.34
Metallic Debris	95.45	3.15	1.40

Figure 13: Comparison of EDS chemical spectra between various tower shaft components.



1.9.5 Cup washer and lock nut

During the tower shaft/spiral bevel gear assembly, a torque was applied to the lock nut to produce a tensile load within the tower shaft and a compressive load within the spiral bevel gear. Such clamping loads were the primary mechanism to ensure that the tower shaft stack remained correctly assembled and in place during normal engine operation. To prevent the nut from loosening and backing off during service, the cup washer was fitted and crimped into the scalloped recesses of the lock nut acting as a further locking device.

When both engines were initially disassembled after failure, removal of the turbomachinery accessory drive covers revealed that the cup washers and lock nuts had become loose within the tower shaft housings.

The cup washers displayed fatigue cracking and had fractured circumferentially through the sidewalls. Overload fracture of the underside tabs and distortion to the inner holes had also occurred. Both the upper and lower surfaces of the washers showed evidence of fretting[12], see figure 14.

12 Fretting is a wear phenomenon that occurs between two mating surfaces having vibratory motion of relatively small amplitude.

Figure 14: Top view showing the lock nut and damaged cup washer from engine S/N 115622. Identical features were observed on engine S/N 120257. Underside damage shown in lower view.

2 ANALYSIS

The ATSB investigation into the in-flight failures of PW100-series engines fitted to aircraft registrations VH-XUD (engine S/N 115622) and VH-TQW (engine S/N 120257), determined that both engines displayed identical failure modes. It was revealed that fracture of the tower shafts led to the engine failures. Once the tower shafts had fractured, mechanical drive to the turbomachinery accessories section was lost with vital engine components ceasing to operate.

2.1 Engine failure sequence

2.1.1 Primary failures

The fractures identified in both tower shafts at location A-A were the result of fatigue cracking that was directly attributed to galling damage that had been created during hydraulic assembly of the spiral bevel gears onto each tower shaft. During that process, the interference fit between the contacting surfaces of the tower shaft and spiral bevel gear resulted in scoring, material pick-up and localised deformation. These stress raisers increased the potential for crack initiation. Once the cracking had initiated, peak stresses within the overall engine load spectrum drove the crack growth to the point of failure.

After the shafts had fractured at location A-A, drive to the turbomachinery accessories section would have continued due to the mechanical connection between the splines of the tower shaft and the spiral bevel gear.

Evidence from the investigation suggested that once the shafts had fractured at location A-A, preload of the spiral bevel gear through the lock nut would have been lost. As a result, longitudinal movement of the spiral bevel gears along the shaft axis was possible. That behaviour was supported by the observed spiral bevel gear tooth damage as they became misaligned.

As a result of the misalignment, tooth fragments from the spiral bevel gear migrated to the number-29 bearing resulting in seizure of that bearing. Once number-29 bearing seizure had occurred, the increased rotational resistance between the spiral bevel gear and the tower shaft resulted in torsional overloading at location B-B. Free rotation of the lower segment of the tower shaft followed. These events were supported by the observed damage to the spiral bevel gear journals and the fracture morphology of the shafts at location B-B.

Although the tower shaft was still being rotated by the HP impeller at that point, once the shaft had fractured at B-B, all mechanical drive to the turbomachinery section was lost, resulting in fuel starvation and subsequent engine failure.

2.1.2 Secondary failures

Lock nut and cup washer

At some stage during the primary failure sequence (post location A-A failure), preload of the lock nut and cup washer was lost. That loss allowed relative movement between the cup washer and lock nut, which resulted in fretting and subsequent fatigue cracking of the cup washer sides. Failure of the cup washer sides allowed the lock nut to unwind and migrate within the tower shaft housing.

Number-29 bearing failure.

Seizure of the number-29 bearing was a secondary event in the engine failure sequence. It was shown that the bearing seizure in each engine occurred when the rolling elements became contaminated due to the migration of tooth material from the spiral bevel gear. The analysis indicated that migration of the tooth material only occurred after the tower shaft fractured at location A-A.

In addition, the physical characteristics of the failure sequence would have been different had the number-29 bearing failed first. Had seizure of the number-29 bearing occurred first, fracture of the tower shafts at two locations (A-A and B-B) would have been physically unlikely. Each tower shaft would have only exhibited evidence of torsional overload and not the combination of overload and fatigue as observed in both events.

Lack of bearing lubrication was not considered a factor in the seizures as lubricant was found in both bearings during their examination.

2.2 Damaged tower shaft from engine S/N 120187

The galling damage found on the tower shaft that had been fitted to engine S/N 120187 was shown to have been produced during the assembly process. That damage was identical in physical nature and orientation to the damage that had precipitated fatigue cracking in the other two shafts. When the shaft was initially removed from 120187 it was intact and still serviceable but had sustained damage to the interfering contact surfaces. Close inspection of the affected area showed an axial alignment to the damage indicating that it had been produced during an overhaul period when the bevel gear was pressed onto the tower shaft.

The discovery of the galling damage on an otherwise serviceable component provides additional evidence to indicate that galling found on the other tower shafts had been produced during assembly/overhaul.

2.3 PWC tower shaft overhaul procedures

The manufacturer had introduced several phase changes to the maintenance procedures for these engines. The intent of the improvements was to minimise the potential for assembly damage of the tower shaft, bevel gear and the number-29 bearing. Their primary focus was, a more consistent stacking of the spiral bevel gear onto the tower shaft and, minimising damage between the spiral bevel gear and the number-29 bearing.

Maintenance records showed that the tower shaft from engine S/N 115622 and S/N 120187 were at Phase-I status with tower shaft from engine S/N 120257 having incorporated Phase-I and -II improvements.

The ATSB identified that the primary contributing factor in these failures was galling damage created during assembly of the bevel gear onto the tower shaft. Such damage would be directly attributed to the fitting tolerances.

All examined tower shafts had been assembled using the hydraulic press method (Phase-I). That procedure required the tower shaft end section to be dry-ice cooled and the bevel gear to be oven heated prior to hydraulic assembly in order to create the necessary fitment clearances.

The heating/cooling process was time critical. Any delay in assembly would have resulted in dimensional changes of each component as their temperatures equalized, increasing the probability of interference and for galling damage to be created between the seating surfaces.

The manufacturer's overhaul manual[13] provided the following cautionary instruction:

> The spiral bevel gearshaft (1) must be seated as quickly as possible to ensure proper seating of the gear on the towershaft (3). (Pratt and Whitney Canada Overhaul Manual, Part Number 3034623 72-03-10 Turbomachinery (PW118A, PW118B) – Assembly 2, page 549, dated June 24 2005).

That statement, however, did not provide assemblers with specific instructions regarding; the 'maximum allowable working time' for assembly of the components once removed from their respective heating/cooling mediums. By providing a 'maximum allowable working time', the likelihood of producing surface damage as a result of temperature equalisation and reduced fitment clearance would be removed.

13 Pratt and Whitney Canada Overhaul Manual, Part Number 3034623 72-03-10 Turbomachinery (PW118A, PW118B) – Assembly 2, page 549, dated June 24 2005.

3 FINDINGS

3.1 Contributing safety factors

The ATSB identified that the failure of PW100-series engines S/N 115622 (VH-XUD) and S/N 120257 (VH-TQW) were identical in nature and sequence. The following contributing factors have been identified:

- The current overhaul manual provides no guidance to assemblers on the maximum allowable assembly time following the tower shaft/bevel gear heating and cooling process to reduce the likelihood of producing surface damage (galling damage) to the components during assembly *[Safety Issue]*.
- It is likely that dimensional changes of these components occurred following the heating/cooling process required to prepare the tower shaft and bevel gear from engine S/N 115622 and S/N 120257 during an overhaul procedure, which resulted in galling damage.
- The galling damage produced during hydraulic assembly of the bevel gear onto the tower shafts led to fatigue cracking and shaft fracture.
- Contamination of the number-29 bearing, by fragments of liberated bevel gear teeth, led to bearing seizure and torsional overload of the tower shaft.
- The torsional overload failure of each tower shaft resulted in the loss of mechanical drive to the engine fuel pump and subsequent uncommanded shutdown of the engine.

3.2 Other key findings

The galling damage found on the tower shaft from engine S/N 120187 was consistent with that found on the failed tower shafts. That damage was a clear indication that it could only have been a product of the bevel gear hydraulic assembly process.

4 SAFETY ACTIONS

The Australian Transport Safety Bureau (ATSB) expects that the safety issue identified by the investigation should be addressed by the relevant organisation. In addressing this issue, the ATSB prefers to encourage the relevant organisation to proactively initiate safety action, rather than release formal safety recommendations.

4.1 Pratt and Whitney Canada

Pratt and Whitney Canada (P&WC) has recognised the recurrent nature of tower shaft failures within the PWC100-series engine. Since 1998, they have proactively campaigned to improve engine reliability by the graduated introduction of process changes (phases I – IV) to the tower shaft overhaul procedures. The reported rate of in-flight engine shutdowns from tower shaft failures has decreased since the introduction of those improvements.

The manufacturer has since carried out a revision of SIL PW100-104. The revision was to inform operators of the recommended replacement of the number-29 bearing and the bevel gear with new components as a set at each engine overhaul/major refurbishment.

In response to the safety issue identified in this report that the current overhaul manual provides no guidance to assemblers on the maximum allowable assembly time following the tower shaft/bevel gear heating and cooling process, P&WC advised that a time limit would be difficult to implement due to the fact ambient temperature is a crucial factor that will determine the validity of such a limit. P&WC have offered an alternative approach to addressing the issue, and have advised the ATSB it had already initiated a revision to the PW100 Overhaul Manual to include an additional cautionary note for assurance that the bevel gear be completely seated using only manual seating of the gear (no loading tool).

The ATSB acknowledges P&WC's ongoing actions to address this safety issue and the need to continue to monitor the reliability of towershaft systems within the PW100 series engines.