Australian Government
Australian Transport Safety Bureau

ATSB TRANSPORT SAFETY REPORT

Aviation Occurrence Investigation – AO-2007-030

Final

In-flight engine failure
23 km N of Ardrossan, SA
25 July 2007
VH-OAA
Cessna Aircraft Company 'Conquest II' 441

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CONTENTS

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Abstract

On 25 July 2007, a twin engine Cessna 441 (Conquest II) aircraft carrying three passengers was being operated on a scheduled passenger flight from Port Augusta to Adelaide, SA. At 1035 Central Standard Time, while cruising at flight level 210, the aircraft's right engine failed suddenly approximately 23 km north of Ardrossan, SA.

When the failed right Garrett TPE331-8 turboprop engine was removed from the aircraft and subsequently disassembled, it was revealed that the compressor bearing at the front end of the engine had catastrophically failed. That bearing provided both axial and lateral support for the turbine section. Once that support was lost, the engine's rotating turbine section shifted forward under the influence of thrust loads, resulting in rotor-to-case contact and rapid engine failure.

The aircraft had been inspected two months prior to the engine failure for a suspected lightning strike, however the inspection did not reveal any obvious electrical damage at that time. Considerable levels of residual magnetism were found within the compressor bearing and other engine components during the ATSB examination. Such levels indicated that direct electrical current (DC) from an aircraft lightning strike had passed through the engine during service. The passage of such currents resulted in undetected electrical damage and led to the eventual failure of the compressor bearing.

THE AUSTRALIAN TRANSPORT SAFETY BUREAU

The Australian Transport Safety Bureau (ATSB) is an operationally independent multi-modal bureau within the Australian Government Department of Infrastructure, Transport, Regional Development and Local Government. 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.

FACTUAL INFORMATION

History of the flight

On 25 July 2007, a Cessna 441 (Conquest II) twin-engine aircraft, registered VH-OAA, carrying three passengers, was being operated on a scheduled flight from Port Augusta to Adelaide, SA. At 1035 Central Standard Time[1], while cruising at flight level (FL) 210, the aircraft's right engine failed, approximately 23 km north of Ardrossan, SA.

The first indication to the pilot in command of a flight abnormality was a slight yaw to the attitude of the aircraft, followed by an observed gradual reduction of torque from the right engine. Approximately 30 seconds later, the right engine failed. The pilot then secured the engine in accordance with the emergency procedures for an in-flight single-engine failure.

The pilot notified air traffic services of the engine problem and obtained a clearance to descend to 9,000 ft above mean sea level (AMSL). While passing through FL180, the pilot noted a rapid reduction in the aircraft's cabin pressure. In order to avoid possible cabin pressurisation problems from the engine power loss, the pilot initiated an increased rate of descent in accordance with emergency procedures.

During the descent, while passing through FL150, the passenger's emergency oxygen masks were reported to have deployed as a result of the reducing cabin pressure. The pilot kept the passengers informed about the situation in order to alleviate any safety concerns.

Subsequently, a normal approach and landing on runway 30 at Adelaide airport was completed. No injuries were sustained by the pilot or the passengers as a result of the engine failure.

Aircraft information

Manufacturer	Cessna Aircraft Company
Type and Model	441 (Conquest II)
Year of Manufacture	1979
Year of Australian Registration	1985
Airframe Serial Number (S/N)	4410102
Total Airframe Time	24,894.40 hours
Engine Model (number of)	TPE331-8-402S (2)
Propeller Type (number of)	Hartzell HC-B3TN-5 (2)

1 The 24-hour clock is used in this report to describe the local time of day, Central Standard Time (CST), as particular events occurred. Central Standard Time was Coordinated Universal Time (UTC) + 9:30 hours.

Damage to the aircraft

After landing at Adelaide airport, the failed right engine was removed from the aircraft by engineering maintenance personnel and was submitted to an engine overhaul facility for disassembly and teardown.

A serviceable engine was fitted and the aircraft was returned to service.

Right engine examination

Following the occurrence, an Australian Transport Safety Bureau (ATSB) investigator, along with representatives from the aircraft operator, the engine manufacturer (Honeywell) and the Civil Aviation Safety Authority (CASA), attended the maintenance facility, where the right engine was disassembled and inspected.

The engine was a Garrett TPE331-8-402S (serial number P31430C). The initial teardown findings showed that the compressor bearing at the front end of the compressor section had catastrophically failed (see Figure 1 and Figure 3 for location). The bearing cage had fractured and two of the balls had come loose. Those loose bearing components had collided with and caused damage to numerous internal rotating engine components.

Other damage of significance included severe machining and metal loss where the first and second-stage compressor turbines had made forceful rotational contact with their respective housings.

The remaining bearing that supported the turbine section was inspected and no obvious indications of damage or degradation were found. In addition, no evidence of a blockage or an obstruction was found within any of the lubrication ports or channels within the engine that may have otherwise contributed to the compressor bearing failure.

Aircraft chip detector warning system

The engine had been fitted with a magnetic chip detector, which was installed on the lower portion of the reduction gearbox (Figure 2). When there is abnormal wear occurring inside the engine, magnetic poles on the detector attract and retain the metallic chips from the engine lubrication oil. The detector is removed and examined for signs of contamination as part of routine maintenance checks of the aircraft. Although not mandatory, the aircraft was not equipped with an electrically connected engine chip detector system which provides a warning light in the cockpit.

Figure 1: The compressor bearing as found within the right engine showing the location of the missing bearing balls and fractured cage (arrowed)

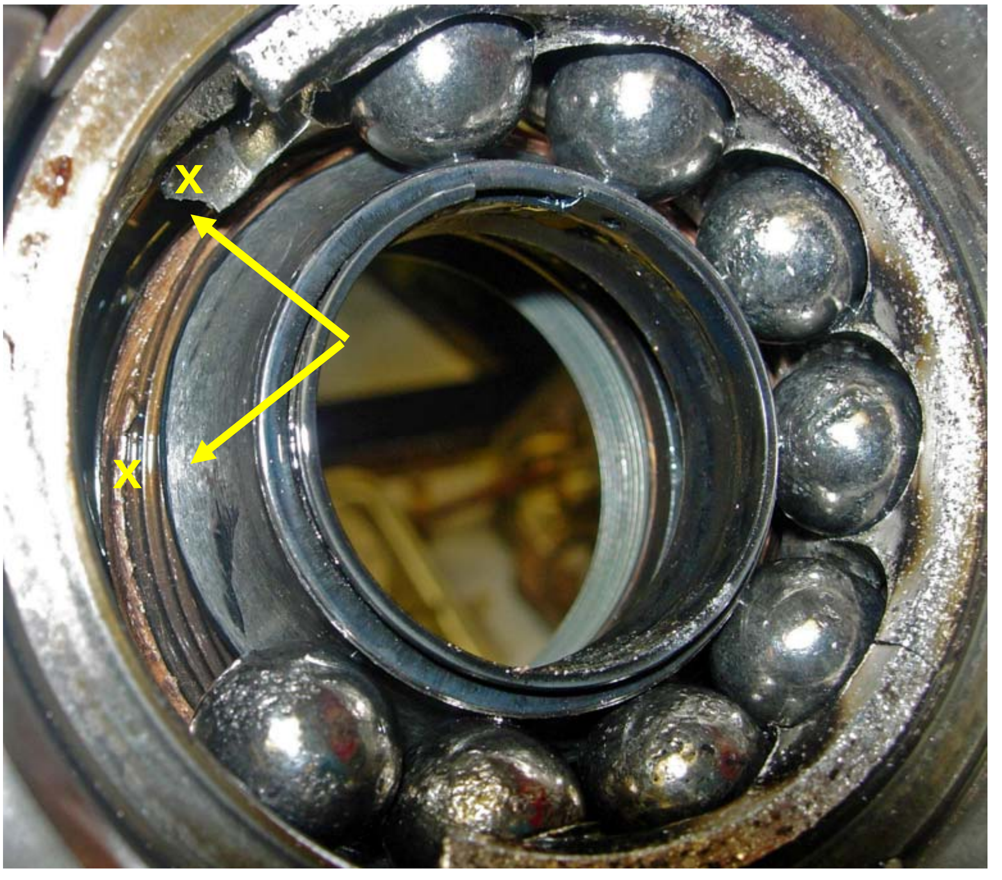


Figure 2: A picture of the reduction gearbox chip detector with metal particles clearly visible

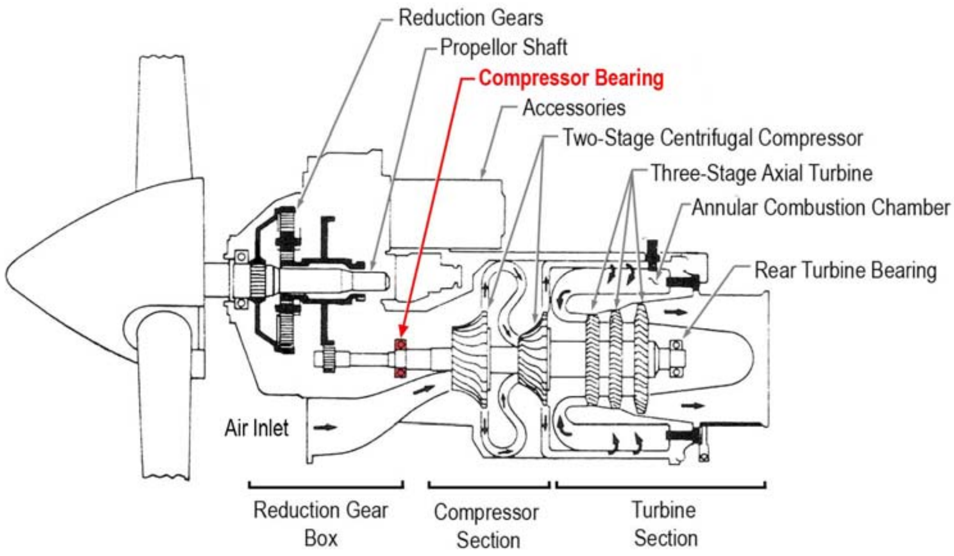
Aircraft and engine information

The TPE331-8-402S turboprop engine fitted to the Cessna 441 aircraft comprised a single fixed-shaft that used a two-stage centrifugal compressor, an annular combustion chamber and a three-stage axial turbine (Figure 3).

Inlet air drawn into the engine was pneumatically compressed by the centrifugal radial flow compressor. Air exiting the compressor was then mixed and ignited with fuel within the combustion chamber. High velocity compressed hot gas was then directed into the three-stage axial flow turbine section.

The main rotating group, known as the ‘gas generator’, was comprised of the compressor, combustor, and turbine sections. Supporting the gas generator was the compressor bearing at the front of the compressor and a roller bearing at the rear of the axial turbine. At 100 per cent thrust, the gas generator rotated at 41,730 RPM.

Figure 3: Cutaway illustration of the TPE331-8 engine



Maintenance history

Examination of the operator’s maintenance records for the aircraft indicated that at the time of the occurrence, the engine (serial number P31430C) had accumulated some 13,529 total hours since new. The engine had last been overhauled in July 2006. A new compressor bearing (part number 3101405-1A, serial number MS060233004207) had been installed into the compressor section during that overhaul.

The engine was installed onto the right wing of VH-OAA on 15 September 2006, whereby it accumulated a further 1,294.5 hours and 1,648 start cycles until the engine failed.

Other maintenance activity of note included the removal of the right engine starter generator (serial number 1609) for overhaul in October 2006. That unit was replaced with another generator unit and in February 2007, the overhauled starter generator was reinstalled into the right engine.

The aircraft's maintenance release indicated that the aircraft had been inspected on 15 May 2007 for a lightning strike. No electrical damage was reported to have been found. That lightning strike occurred some 308 hours prior to the engine failure.

Spectrometric oil analysis program (SOAP)

The failed engine had been maintained under Honeywell's program of Continuous Airworthiness Maintenance (CAM). The engine inspection intervals required to participate in the CAM program were described in Honeywell service bulletin TPE331-72-0829. One aspect contained in that service bulletin was for the engine oil to be assessed in a spectrometric oil analysis program (SOAP). Such analysis enabled the health of the internal engine components to be assessed, by continuous monitoring of the type and quantity of the deposits found within the engine oil and oil filter. The engine manufacturer recommended that the SOAP sampling period not exceed 155 hours of service.

The operator's records indicated that engine oil and oil filter SOAP sampling had been performed on the engine since the previous overhaul in accordance with the CAM program as prescribed by the Honeywell SB (TPE331-72-0829). The engine had accrued 58.15 hours since a SOAP check had last been performed. The previous two SOAP samples had been tested on 20 June 2007 and 11 July 2007. Each sample was analysed and was considered to be in the normal range, with no significant observed increase in particulate trending.

Subsequent to the engine teardown, the engine's oil filter was sent to the engine manufacturer for analysis. The filter examination revealed a considerable amount of thin metallic debris, which was chemically consistent with M-50 bearing steel.

ATSB bearing examination

Examination of the compressor bearing and a number of other engine components was performed by the ATSB. Following the ATSB examination, the engine parts were transferred to the engine manufacturer, Honeywell International, in the United States for additional assessment and comment. A detailed report was submitted to the ATSB[2], and while an assessment of the compressor bearing failure mode was made, Honeywell was unable to provide comment on the factors that contributed to the bearing damage.

The ATSB's examination (Appendix A) found that the compressor bearing had collapsed from severe mechanical and thermal distress (Figure's 1 and 4). The part and serial number details for the compressor bearing matched the operator's maintenance documentation and confirmed that it had been installed into the engine during the July 2006 overhaul.

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2 Honeywell International, Materials Analysis report number MA 3933846.

Figure 4: The compressor bearing as recovered from the right engine showing the major area of damage (arrowed)

All of the bearing balls were severely damaged and displayed numerous indentations and extensive shallow spalling[3]. The bearing cage had fractured into several pieces and was heavily deformed. A section of the fractured cage had separated from the assembly and had probably been consumed by the engine's rotating hardware. Both halves of the inner race exhibited spalling and deformation from thermal and mechanical distress.

Metallurgical examination of the bearing components showed the bearing to be in compliance with the manufacture’s design specifications. No manufacturing defects or damage associated with installation was found during the examination, nor was any evidence found of lubricant loss or starvation that might otherwise have explained the premature bearing failure.

One aspect of particular note revealed during the examination was that most bearing elements, including the compressor bearing housing, the inner race, the outer race and the cage, displayed significant levels of residual magnetism. Ferrous steel components will become magnetised if they have been exposed to direct electrical current (DC).

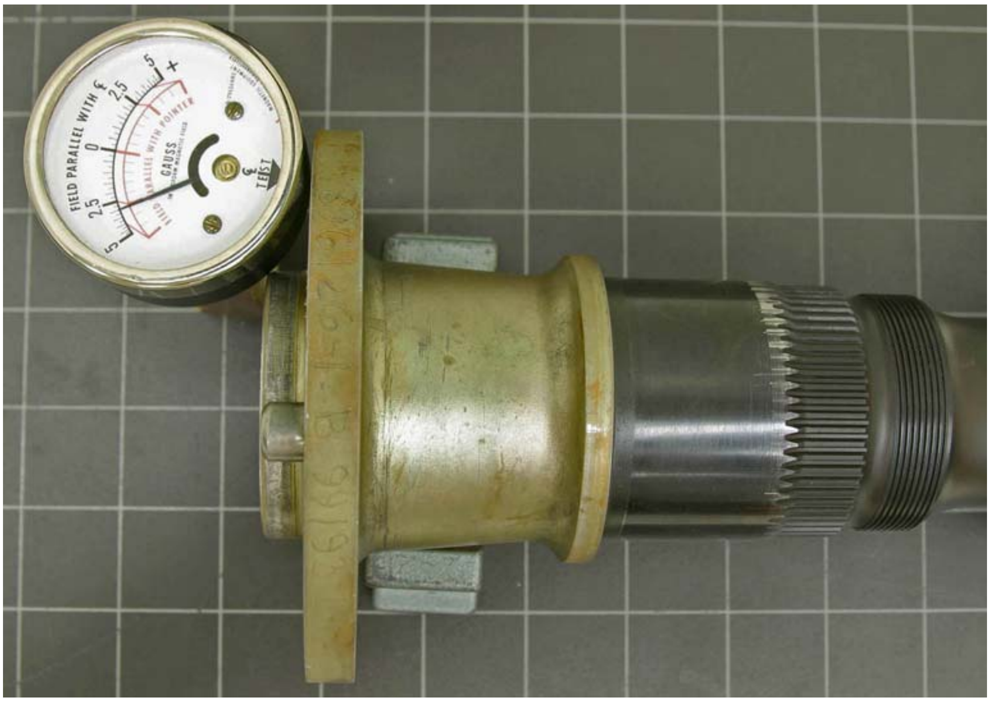
Other components from the engine that were subsequently inspected for evidence of residual magnetism included: the propeller shaft (Figure 6), numerous gears from the reduction gearbox, and the rear roller and turbine bearings.

3 Spalling, otherwise known as rolling contact fatigue, is a mechanism usually associated with the final stages in the service life of a bearing component.

Figure 5: Inner race magnetisation as measured with a Gauss meter

Note: The inner race had been sectioned for metallurgical examination

Figure 6: The flange on the propeller shaft showing considerable residual magnetism



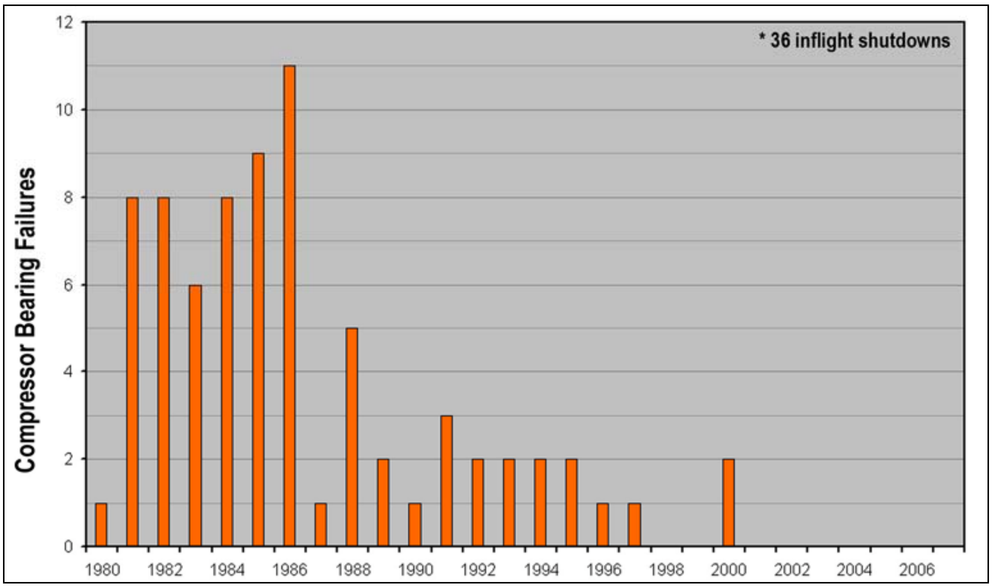
TPE331 engine reliability

The engine manufacturer also supplied historical data on the known reliability of compressor bearings within the world fleet of TPE331-series engine. The data showed that since 1980, 75 engines had sustained compressor bearing failures. The number of compressor bearing failures that resulted in an in-flight engine shutdown totalled 36. The data also indicated that there had been very few instances of bearing failures within the last 10 years of world-wide engine operation. A plot of the yearly number of bearing failures is shown in Figure 7.

The plotted data indicated that a peak failure rate occurred through the mid-1980s. The rising failure rate was attributed to propeller strikes that led to damage to the compressor bearing. The manufacturer subsequently revised the TPE331 engine maintenance manual by requiring the compressor bearing to be replaced after such a strike. Following those changes, an improvement in TPE331 engine reliability was achieved.

The manufacturer also reported that there had been no record of returns/failures to the Honeywell repair and overhaul facilities of compressor bearings within the same serial number batch range as the bearing from engine P31430C.

Figure 7: History of compressor bearing failures from TPE331-series engines



ANALYSIS

Engine failure

The examination of the components from the Cessna 441 determined that catastrophic failure of the compressor bearing was the principal contributing factor that led to the in-flight failure of the right engine. That bearing provided axial location and support to the rotating compressor/turbine shaft assembly at the front of the engine. Through its design, the compressor bearing also resisted the axial thrust loads that were generated during the operation of the compressor/turbine shaft. Once the bearing failed, the entire rotating turbine assembly shifted forward under the influence of the engine driven thrust loads. That shift resulted in considerable contact and machining damage to the compressor and turbine cases. The engine failed at that point during the flight.

Bearing failure

The compressor bearing had been installed as a new item into the engine at the time of last overhaul. Since then, it had accumulated some 1,294.5 hours of service prior to the failure. Details supplied by the engine manufacturer indicated that the compressor bearing failure was an infrequent event within the worldwide fleet of TPE331-series engines.

The examination found that the inner and outer races, and the bearing balls, had spalled from rolling contact fatigue. Spalling is a degenerative process that produces small cracks in the contact surfaces and once started will eventually lead to component failure. The cage had cracked and then fractured from unstable load interactions with the bearing balls. The highly heat affected regions found in each bearing element had been produced from frictionally induced effects as the balls skidded and slid during operation. As the balls and ball-races began to breakdown, increased levels of heat and vibration would have been produced. No evidence was found of a material or manufacturing defect that could have contributed to the failure.

Residual magnetism

One aspect that explains the compressor bearing failure was the level of residual magnetism found in each of the bearing elements. The residual magnetism was particularly strong in the housing and inner race of the compressor bearing. Other engine components exhibiting similar residual magnetic properties included the attachment flange on the propeller shaft. The observed magnetisation suggested that the turbo machinery bearing components had been exposed to direct electrical current (DC). Residual magnetism can be created from the passing of electrical current through a component.

Stray localised DC electrical sources are chiefly from lightning strike, or due to leakage currents from nearby heavy current devices such as the engine's starter generator. The damage from stray current manifests itself through localised welding and pitting of bearing surfaces. This then develops into spalling of the bearing, which creates vibration and overheating, and ultimate bearing failure. Thrust bearings are prime candidates for electrical damage and can provide conditions for the circulation of damaging currents and notable voltages. This is because of the extremely thin oil film between the thrust face of each race, especially when the thrust faces are highly loaded.

Records from the aircraft operator indicated that the aircraft had been inspected for a lightning strike in May 2007. Evidence of a lightning strike can often be established by inspecting the aircraft exterior surfaces (typically wing tips or propeller blades) for the physical presence of arc or burn patterns. These characteristic witness marks may not always be found or even produced, which may explain why the engine electrical damage remained undetected.

SOAP sampling

The operator had been monitoring the internal health of the engine components by participating in a spectrometric oil and filter analysis program (SOAP). That program relied on detecting the type and quantity of wear material products within the engine oil and oil filter that were generated from the breakdown mechanisms of internal engine components. SOAP checks were recommended not to exceed 155 hours of service.

The engine oil from the aircraft's right engine had been routinely sampled at three separate intervals following the reported lightning strike to the aircraft. The final SOAP sample had been analysed some 58 hours prior to the engine failure and the results from that check indicated that no unusual trends or signs of internal damage had been developing at that time.

One explanation as to why the compressor bearing degradation was not detected during the preceding SOAP checks is that bearing degradation can develop at an exponential rate. In the case of a critical engine component, such as the compressor bearing, by the time the breakdown had developed to a point where it would be reasonable to expect a positive detection through a SOAP check, the component was likely to be have been at risk of imminent total failure.

Engine chip detector

The right engine had been manufactured with a magnetic chip detector that was fitted to the lower portion of the propeller reduction gearbox. The function of the chip detector was to magnetically attract wear material products from the engine oil during service. When removed from the engine during maintenance, a visual inspection of the detector will establish whether or not engine deterioration has been occurring. A significant quantity of metallic debris from the failed compressor bearing was found to have accumulated on the chip detector when it was removed during the right engine disassembly.

Owners and operators of Cessna 441 aircraft have the option of upgrading the magnetic chip detector system by wiring it to a warning light in the cockpit of the aircraft. When the magnetic plug of an electrified system accumulates a sufficient quantity of metallic debris, the cockpit warning light will illuminate and alert the pilot of an engine problem. Although the fitment of such devices are not mandatory, had the aircraft been equipped with an electrically connected engine chip detector system, it is likely that the pilot would have had advanced warning of an impending engine failure.

Previously related safety occurrence – engine chip detector warning lights

The ATSB has previously investigated and reported on the importance of engine chip detectors for passenger aircraft[4]. In 2006, a Cessna 208 float plane (VH-KLP) carrying 10 passengers was forced to land the aircraft on Lake Burbury, Tasmania, after the aircraft's single-engine failed. The pilot had been alerted to a possible problem by the illumination of the engine's accessory gearbox chip detector warning light.

During the course of that investigation, the benefits of accessory gearbox chip detector warning systems for Cessna 208 aircraft were discussed. Two specific recommendations were made to the Australian Civil Aviation Safety Authority (CASA), and the US Federal Aviation Administration (FAA).

ATSB Recommendation R20070023

ATSB Recommendation R20070024

The context of both recommendations asked for CASA and the FAA to consider the mandatory implementation of a chip detector warning system to the cockpit of all Cessna 208 aircraft used in commercial passenger operations.

While the intent of those recommendations were directed toward single-engine Cessna 208 aircraft, the ATSB considers that such cockpit warning systems offer safety benefits, regardless as to whether they are used in single or twin-engine commercial passenger operations.

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4 ATSB Aviation Occurrence Report 200600563, 'Engine Failure, Lake Burbury, Tasmania, 5 February 2006 VH-KLP Cessna Aircraft Company 208'

FINDINGS

From the evidence available, the following findings are made with respect to the in-flight engine failure of VH-OAA and should not be read as apportioning blame or liability to any particular organisation or individual.

Contributing safety factors

- The right engine of the Cessna-441 aircraft failed in flight as a result of the catastrophic breakdown of the engine's compressor bearing.
- Considerable levels of residual magnetism were found within the compressor bearing. Such levels indicated that direct electrical current (DC) from an aircraft lightning strike had passed through the engine during service. The passage of such currents resulted in undetected electrical damage and led to the eventual failure of the compressor bearing.

Other safety factors

- The aircraft's right engine reduction gearbox chip detector had not been electrically connected to a warning system in the cockpit. Although it was not a mandatory requirement to be electrically fitted as standard equipment, the connection of such a system would have been instrumental in providing prior warning to the pilot of a developing problem. *[Safety Issue]*

SAFETY ACTION

The safety issues identified during this investigation are listed in the Findings and Safety Actions sections of this report. The Australian Transport Safety Bureau (ATSB) expects that all safety issues identified by the investigation should be addressed by the relevant organisation(s). In addressing those issues, the ATSB prefers to encourage relevant organisation(s) to proactively initiate safety action, rather than to issue formal safety recommendations or safety advisory notices.

All of the responsible organisations for the safety issues identified during this investigation were given a draft report and invited to provide submissions. As part of that process, each organisation was asked to communicate what safety actions, if any, they had carried out or were planning to carry out in relation to each safety issue relevant to their organisation.

Civil Aviation Safety Authority

Engine chip detector warning lights

Safety issue

The aircraft's right engine reduction gearbox chip detector had not been electrically connected to a warning system in the cockpit. Although it was not a mandatory requirement to be electrically fitted as standard equipment, the connection of such a system would have been instrumental in providing prior warning to the pilot of a developing problem.

Response by the Civil Aviation Safety Authority

> CASA has no comments to make on the draft report, however notes that on page 11, reference is made to ATSB recommendation R20070024, formerly draft recommendation 0:
>
> > *The Australian Transport Safety Bureau recommends that the Civil Aviation Safety Authority consider the benefits of requiring the fitment of AGB chip detectors on all Australian registered Cessna 208 aircraft used in commercial passenger operations.*
>
> CASA has provided a response to this recommendation on two occasions.
>
> CASA does not support this recommendation and is still of the opinion that, since the time between chip detector indication and the actual failure is known to be a few minutes, the proposed fitment of an MCD light in the cockpit will be of marginal benefit.

ATSB assessment of CASA response

The ATSB does not accept CASA's suggestion that magnetic chip detector lights in the cockpit of an aircraft are of marginal safety benefit. The ATSB considers that the time between a positive chip detection and engine failure is variable and dependent upon the breakdown mechanism. In all but extreme cases, a cockpit system would provide advanced warning of an impending engine problem and thus increase the pilot's time available for planning an appropriate course of action.

As CASA's position on the fitment of engine chip detector systems remains unchanged despite the issues raised in this investigation and the previously issued safety recommendation R20070024, the status of that recommendation remains Closed – Not accepted.

Cessna Aircraft Company

Engine chip detector warning lights

Safety issue

The aircraft's right engine reduction gearbox chip detector had not been electrically connected to a warning system in the cockpit. Although it was not a mandatory requirement to be electrically fitted as standard equipment, the connection of such a system would have been instrumental in providing prior warning to the pilot of a developing problem.

Response by the Cessna Aircraft Company

As of the publication date of this report, no response had been received from the aircraft manufacturer with regard to any aspect of the investigation report.

APPENDIX A: TECHNICAL ANALYSIS REPORT

Physical examination

Engine components recovered

A number of components from the TPE331-8 engine were retained for detailed technical examination at the ATSB engineering facility in Canberra. Information on each of the retained components is contained in Table 1. Following the ATSB examination, the engine parts were transferred to the engine manufacturer, Honeywell International, in the US for additional assessment and comment.

Table 1: Recovered components from the right engine, serial number P31430C

Description	Part Number	Serial Number	Lot Number
Compressor Bearing	3101405-1A	MS060233004207	NA
Bearing Housing	NA	061686800134	LN0616868021
Seal Runner	NA	NA	NA
Bellow Seal Housing	NA	06051589113	LN0605158859
Bellow Seal	NA	NA	NA
Oil Filter	NA	NA	NA

Compressor bearing

All components that comprised the compressor bearing were in a highly advanced state of failure. The compressor bearing was categorized as an annular thrust ball bearing that contained: 10 bearing balls (or rolling elements), a silver-plated cage, a two-piece split inner race and a solid outer race. Manufacturing identifiers on the inner and outer races showed the bearing to have part number 3101405-1 and serial number MS060233004207. Those details matched the operator's maintenance documentation.

Bearing balls / rolling elements

When the engine was initially disassembled and the compressor bearing examined, only eight of the 10 bearing balls were found within their assembly. Two of the balls had come loose from their bearing retainer and had migrated within the internal cavities of the engine. Those bearing balls were recovered after complete disassembly of the engine. All 10 bearing balls were severely damaged (Figure 8). The surfaces of each damaged ball displayed numerous indentations and extensive spalling. The spalled layers were quite shallow and confined to the surface. Much of the surface damage had been over run, with smearing, heavy wear and significant deformation present on the rolling contact surfaces. Such deformation signalled that sliding contact of the balls against the inner and outer races had occurred.

Figure 8: The rolling surface of each bearing ball had spalled

Cage

The silver-plated cage (or retainer) was heavily deformed and had fractured into several pieces (Figure 9). A significant section of the cage had separated from the bearing assembly. That section was not recovered; it had probably been consumed by the engine's rotating hardware. Other damage included a significant degree of distortion and wear within each of the cage pockets. A large increase to the internal pocket dimensions was observed. The external surface layer of silver plating was worn through to the steel backing in many places from sliding contact with the inner and outer raceway.

The cage had fractured centrally through the pocket cross members and high magnification examination of the fracture surfaces clearly showed that fatigue cracking had propagated through each section (Figure 10). Intergranular[5] regions were observed at the fatigue crack origins. X-ray analysis of the fractures showed the presence of silver from the plating throughout the intergranular regions at the crack origins. This indicated that silver plating had melted and had embrittled[6] the high strength steel. Furthermore, it indicated that the compressor bearing temperature had exceeded 962 degrees Celsius (the melting temperature of silver) during the failure sequence.

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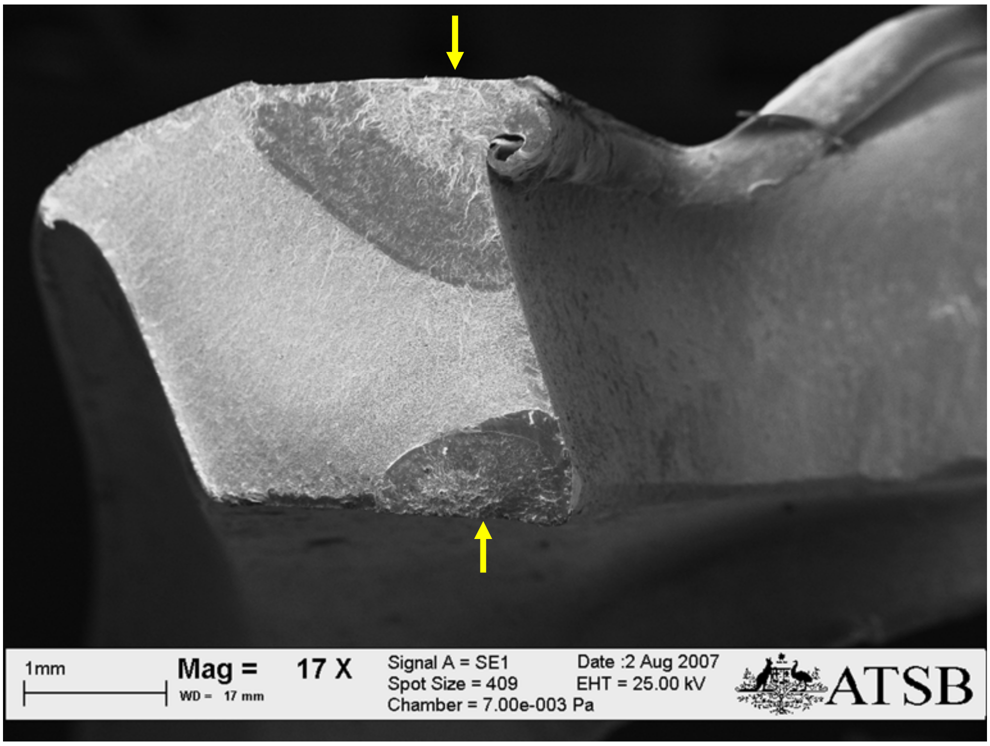
5 Cracking or fracturing that occurs between the grains, or crystals, that form the material, ASM Metals Handbook, Failure Analysis and Prevention, Volume 11, ASM International, p6.

6 The severe loss of ductility and/or toughness of a material, usually a metal or alloy, ASM Metals Handbook, Failure Analysis and Prevention, Volume 1 1, ASM International, p2.

Figure 9: Close-up of the fractured and heavily deformed cage

Figure 10: SEM image of one of the bearing cage fracture surfaces showing the origins of fatigue cracking (arrowed)



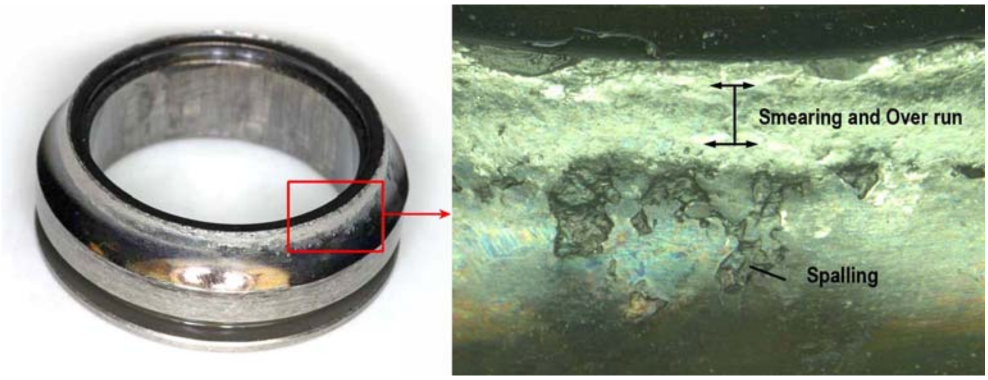
Internal and outer race

The inner race was a two-piece split design that comprised a thrust half and a puller-groove half. Both halves exhibited deformation and mechanical damage to the rolling contact surfaces, and displayed a level of discolouration from excessive heating.

The contact surfaces of the puller-groove half of the inner race exhibited some evidence of spalling. Spalling, otherwise known as rolling contact fatigue, is a mechanism usually associated with the final stages of component life. Much of the spalled surfaces had been smeared and over run through rolling contact with the balls. This is shown in Figure 11.

Examination of the outer races showed that the contact surfaces were also heavily deformed with multiple spalled locations.

Figure 11: Image montage of the inner race puller-groove raceway surfaces showing over run and spalling damage



Residual magnetism

The examination also revealed that most bearing elements including the compressor bearing housing, the inner race, the outer race and even the cage, displayed significant levels of residual magnetism.

Other components from the engine that were subsequently inspected included the propeller shaft, several gears from the reduction gearbox and the rear roller and turbine bearings. The variability of the component magnetic field density was measured using a gauss meter and the results of those measurements are shown in Table 2.

Table 2: Measured magnetic field strength of the magnetised compressor bearing components

Part	Magnetic Field Density (Gauss)
Compressor Bearing Housing	2.5
Compressor Bearing Inner Race: Thrust Half	> 5
Compressor Bearing Inner Race: Puller Groove Half	1
Compressor Bearing Outer Race	2
Compressor Bearing Cage	0.5
Propeller Shaft	3

Metallurgical examination

Detailed metallurgical examination of several compressor bearing components (including the cage, a ball, and the inner and outer races) was performed. The individual chemistry, tensile properties and microstructure was examined and compared with the original engineering specifications listed by the engine manufacturer[7]. The results of the examination are contained in Table 3.

Bearing microstructure

The core microstructure of each element exhibited a through-hardened quenched and tempered martensite structure typically found in most aerospace bearing applications (Figure 12). Pockets of highly transformed microstructure associated with the smeared surface zones of the bearing balls were found. This indicated that the balls had been frictionally heated during the final breakdown process as the balls slid and skid against the races. Sectioning of the cage and race also revealed highly heat affected areas.

No obvious defects, such as non-metallic inclusions, were found in any of the bearing elements during the metallurgical examination that would have otherwise contributed to the bearing failure.

Hardness

The tensile mechanical properties for each bearing component were measured as a function of the material hardness and compared with the manufacturer's engineering material specifications. The core hardness of the inner and outer races, and the rolling elements, was found to measure between 58 and 67 Rockwell C (R_C). The core hardness of the bearing cage was found to measure 36 R_C. Although some of these values were marginally outside the limits set by the bearing manufacturer, considerable frictional heating had occurred during the failure sequence which would have tempered the steel. Therefore, the mechanical properties of the bearing were considered in compliance.

Chemical analysis

An assessment of the type of material used in each of the bearing components was performed using an energy dispersive spectrometer (EDS) attachment to a scanning electron microscope (SEM). The results indicated that each of the bearing components had been manufactured from a high-carbon alloy steel and were either AISI-SAE M-50 or AISI-SAE 4340 (Table 3). Each of the bearing components was in compliance with the engine manufacturer's material specifications.

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7 AiResearch Manufacturing Company of America, 'Bearing, Ball, Annular' drawing number 3101405, dated 4 February 1974.

Figure 12: Section through a bearing ball showing the least heat affected microstructure

Table 3: Compressor bearing sub-element chemistry and compliance

Element	C	Cr	Ni	Mo	Other	Material Specification	Hardness Specification (R_C)	Core Hardness (R_C)
Outer Race	NA	4.3	- -	4.0	0.9 V 0.4 Si	AISI-SAE M-50	61 – 64	58-67
Inner Race	NA	4.3	- -	4.2	1.0 V 0.3 Si	AISI-SAE M-50	61 – 64	58-67
Balls	NA	4.2	- -	4.2	0.8 V 0.3 Si	AISI-SAE M-50	61 – 64	58-67
Cage	NA	0.8	1.6	0.9	0.3 Si	AISI-SAE 4340	36 – 42	36

Note: C (carbon), Cr (chromium), Ni (nickel), Mo (molybdenum), V (vanadium), Si (silicon)

APPENDIX B: SOURCES AND SUBMISSIONS

Sources of information

The sources of information during the investigation included:

- the operator
- the aircraft's maintenance organisation
- the aircraft's maintenance records
- the engine manufacturer.

Submissions

Under Part 4, Division 2 (Investigation Reports), Section 26 of the Transport Safety Investigation Act 2003, the Executive Director may provide a draft report, on a confidential basis, to any person whom the Executive Director considers appropriate. Section 26 (1) (a) of the Act allows a person receiving a draft report to make submissions to the Executive Director about the draft report.

A draft of this report was provided to the aircraft operator and maintainer, the engine manufacturer, the aircraft manufacturer, the State of Manufacturer, and the Civil Aviation Safety Authority.

Submissions were received from the Civil Aviation Safety Authority, the aircraft operator and the engine manufacturer. The submissions were reviewed and where considered appropriate, the text of the report was amended accordingly.