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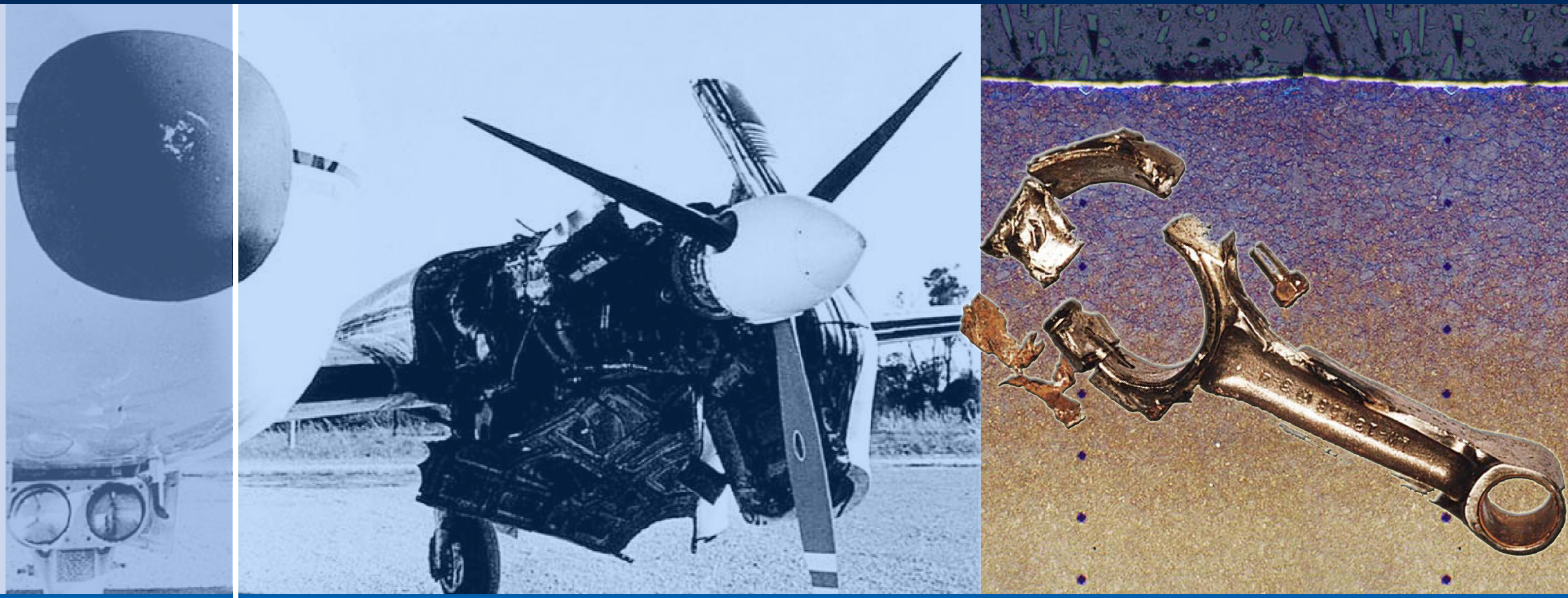

ATSB TRANSPORT SAFETY INVESTIGATION REPORT

Aviation Research and Analysis Report – B20070191

Final

Aircraft Reciprocating-Engine Failure:
An Analysis of Failure in a Complex Engineered System

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An Analysis of Failure in a Complex Engineered System

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Aircraft Reciprocating-Engine Failure: An Analysis of Failure in a Complex Engineered System

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Abstract

Reciprocating-engine powered low-capacity transport aircraft (8 to 10 passengers) provide an important public transport connection throughout regional Australia. In the period January 2000 to December 2005, twenty powertrain structural failures of high-power (300 to 375 brake horsepower) horizontally-opposed, reciprocating engines were associated with air safety occurrences reported to the ATSB. These occurrences ranged in severity from; in-flight engine shutdown; engine failure and forced landing; engine failure combined with in-flight fire and fracture of both upper engine mounts; to the fatal accident of a regular public transport flight following the structural failure of both engines to ditching at night. It is evident that the reliability of high-power reciprocating engines is an important requirement for the safe operation of this class of aircraft. This research investigation is a study of the factors that affect reciprocating engine reliability.

The study found that powertrain structural failure was not restricted to one engine model, one engine manufacturer, or one powertrain component. The events that initiated sequences that led to engine in-flight failure could be grouped into three categories: combustion chamber component melting; bearing breakup; and powertrain component fatigue cracking. Analysis of the factors that were associated with each category of initiating event revealed that powertrain component reliability is affected by the development of shockwaves during combustion, the response of bearings to boundary lubrication and out-of-plane alternating loads, the increase in component alternating stress magnitudes, and creation of stress-concentrating features in components during engine operation. These factors may act singly, but on many occasions it is the synergistic effect of the presence of multiple factors that result in a sequence of events ending with engine in-flight failure.

The recurrence of powertrain component structural failure events suggests that the corrective actions that are a part of the airworthiness assurance system may have been ineffective. Corrective action is dependent on accurate analysis and feedback. It is evident that analysis is affected by the complexity of reciprocating engine systems and feedback requires a broad view of the interaction of systems and a detailed view of the components of a system.

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

EXECUTIVE SUMMARY

The safe operation of an aircraft depends on the reliable performance of systems that provide thrust, lift, stability, control, collision avoidance, navigation, and cabin environment. The wellbeing of crew, passengers, and bystanders may be threatened by the failure of any one these systems to perform their designed function – they are safety-critical systems.

The focus of this safety study is the reliability of propeller-based propulsion systems that provide thrust for the operation of aircraft commonly used in low-capacity public-transport operations during the period 2000 - 2005. In particular, the study critically examines the issues arising from the in-flight failure of propeller propulsion systems powered by reciprocating engines.

During the period 2000 - 2005 1,270 aircraft, powered by multiple reciprocating engines, on the Australian register operated for a total of about 220,000 hours. Of these aircraft around 200 were employed in low-capacity public transport with (8 to 10 passengers) providing an important public transport connection throughout regional Australia.

In the period January 2000 to December 2005, twenty powertrain structural failure events in high-power (300 to 375 brake horsepower) horizontally-opposed, reciprocating engines were associated with air safety occurrences reported to the ATSB. These occurrences range in severity from: in-flight engine shutdown to engine failure and forced landing; engine failure combined with in-flight fire and fracture of both upper engine mounts; and a fatal accident involving a regular public transport flight following the structural failure of both engines. Powertrain structural failure has the capability to create a threat to safe operation despite the redundancy provided by twin propulsion systems and pilot training to respond to a period of abnormal operation following the failure of one propulsion system.

This research investigation focuses on:

- developing an understanding of aircraft safety-critical systems and how reliable propulsion system performance is achieved;
- evaluation of the available evidence associated with powertrain component failures events, from the period 2000 to 2005, against a background of component failure control plans;
- analysis of powertrain component failure events, individually and as a group, to uncover the factors that initiate event sequences leading to powertrain component failure; and
- analysis of the airworthiness assurance system to determine why there was a reduction in high-power reciprocating-engine reliability over the period 2000 to 2005.

The powertrain structural failure events investigated in this study are dominated by combustion chamber component melting, plain bearing breakup or movement, and the initiation and growth of fatigue cracking in components that are designed to have a life not limited by fatigue. Analysis of these events revealed that the initiating factors are those that affect heat transfer to and from components, affect bearing surface behaviour and bearing insert retention in their housing, and affect the fatigue endurance strength of a component and the magnitude of alternating stresses in the component during engine operation. Failure events were not restricted to one engine model, one engine manufacturer, or one component type.

A change in the combustion process – from flame propagation throughout the fuel-air mixture to the auto-ignition of some part of the mixture – has the potential to affect the reliability of powertrain components. The effect of detonation is related to the intensity of detonation, which in turn, is dependent on the volume of end-gas that undergoes auto-ignition. Light to medium detonation may result in some mechanical damage. The actual nature of mechanical damage is dependent on the robustness of powertrain components and assemblies to abnormal loading. Heavy detonation results in the melting of aluminium alloy combustion chamber components.

Detonation-free operation, for a fuel of known detonation resistance, is based on limiting the operator-controlled engine parameters of manifold pressure (power), speed, mixture, and engine load. Additionally, detonation-free operation is based on designed limits for; combustion chamber surface temperatures (spark plugs, piston crown and cylinder head inner surface, the presence of deposits), inlet air temperature, and rate of pressure rise (spark ignition advance, ignition from sites other than spark plugs). Variations in any of these factors, beyond designed limits, will increase the likelihood of detonation during engine operation. In addition, the cumulative effect of variations in a number of factors may also act to increase the likelihood of detonation.

For the engine failure occurrences investigated in this study, it is clear that leaning at climb power settings increases the likelihood of detonation. It is also evident that the fuel-air mixture settings – lean climb and lean cruise, resulted in the deposition of a non-volatile lead compound on combustion chamber surfaces. The presence of non-volatile deposits also increases the likelihood of detonation.

With normal combustion, the pressure rise in a combustion chamber acts uniformly on the piston. However, when detonation occurs, localised regions of high pressure are created. As these regions of high pressure move, shockwaves are created. The direction of shockwave propagation has an important effect on connecting rod loading in horizontally-opposed engines. For the case of a horizontally-opposed engine layout, end-gas detonation in horizontally-opposed engines will occur in the regions over the piston pin ends, with shockwave propagation in a direction parallel with the piston pin. The rocking of the piston pin in the plane of the little-end bearing axis, and out-of-plane rocking of the big-end bearing, will affect the integrity of the connecting rod assembly.

The rate of heat transfer from the combustion gas to the combustion chamber (cylinder head and piston) is controlled, under normal combustion conditions, by heat transfer across a gas boundary layer adjacent to the combustion chamber surface. However, as the intensity of detonation and associated shockwave propagation increases, the increasing turbulence in the combustion gases disrupts the gas boundary layer. Once the gas boundary layer is disrupted, heat is transferred rapidly to the combustion chamber components, leading to a rapid, large increase in component temperature, and component failure when the incipient melting point is reached.

For the engine failure occurrences investigated in this study, it is clear that leaning at climb power settings increased the likelihood of detonation. It is also evident that the fuel-air mixture settings – lean climb and lean cruise, resulted in the deposition of a non-volatile lead compound on combustion chamber surfaces. The presence of non-volatile deposits also increases the likelihood of detonation.

The failure of bearings in aircraft horizontally-opposed engines can be related to factors that: lead to a loss of hydrodynamic oil film stability or an increase in the temperature of bearing materials or factors that control the magnitude of the bearing insert retention force or the magnitude of forces which act to displace the bearing insert. These factors are shaped by the functioning of other engine subsystems and the actions of operators and maintainers.

Analysis revealed that events associated with the loss of oil film stability occurred as a result of the development of high combustion gas pressures during high power operation and, on other occasions, occurred as a result of inadequate bearing clearance following maintenance actions performed to resize crankshaft journals.

Factors that were found to increase the temperature of bearings were: operation under boundary lubrication conditions; the presence of an adherent nickel layer between the lead-tin and aluminium-tin bearing layers exposed after bearing surface wear; and the loss of metal-to-metal contact between the bearing insert and housing through the inclusion of a lubricant.

The effect of increased bearing temperature during operation, on those bearing inserts manufactured with an aluminium-tin intermediate layer, was the change in the distribution of tin through diffusion. The formation of coarse tin particles at the interface with the insert backing results, in a reduction of strength of the intermediate layer and the breakaway of sections of the bearing.

The resistance of bearing inserts to movement in their housings is a function of the magnitude of the friction force created by the interference fit and the magnitude of forces acting to move the insert circumferentially and axially.

The magnitude of the forces acting to move an insert in its housing are affected by increases in sliding surface friction (boundary lubrication and, in particular, the sliding of a steel journal against an adherent nickel bearing surface) and the nature of loading created by combustion. Combustion may have an effect through an increased load on the bearing surface, increased bending moments on the main bearings of crankshafts, and increased big-end bearing edge loads associated with non-uniform gas loads on the piston created by the propagation of shock waves in the combustion gases during combustion with light to medium detonation.

Powertrain components are designed to have a life not limited by fatigue crack initiation and propagation to final fracture, within the bounds of specified operational limits.

For the case of component designs that have passed certification testing and have demonstrated fatigue-free operational performance, component failure analysis indicates that:

- the component was subjected to alternating stresses that exceeded the maximum design allowable value;
- a change in the distribution of component endurance strength from the design state has occurred;
- a change in the component has occurred so that it is no longer bounded by the component fatigue endurance strength distribution parameters; or

- a combined reduction in component endurance strength and increase in maximum alternating stress has occurred.

Crankshafts, regardless of the end application of the engine, are designed to have an operational life not limited by fatigue. The complex interrelationships between loads, geometric stress concentrators, residual stress, surface finish, surface hardening, and material results in scatter in fatigue behaviour. Fatigue initiation at the boundary between the surface hardened (nitrided) zone and core is a normal location when bending or torsional loads just exceed the endurance strength of the component.

The initiation of fatigue cracks in a powertrain component is not simply a matter restricted to the material from which the component is manufactured. It is a matter of all factors that affect the magnitude of component alternating stresses and the component endurance strength. In addition to the complex interrelationships between loads, preloads, geometric stress concentrators, residual stress, surface finish, surface hardening, and material of an individual component, there are clear interdependencies between the combustion process in individual and multiple cylinders of a horizontally-opposed engine, the physics of plain bearing lubrication, the mechanics of bearing insert retention, and the process of fatigue crack initiation.

The resolution of differences between reliability of propulsion systems achieved during operation and the design level of reliability, is achieved by appropriate adjustment or correction of the sub-systems and components that form the propulsion system. Recurrent propulsion system failures suggests that system adjustment or correction, through an effective feedback process, is not occurring.

Barriers to feedback may arise at various levels in a system hierarchy: individual interactions, organisational goals and interactions, and societal influences. For feedback in response to system malfunction to be effective, information must be sensed, perceived, put into context, evaluated, analysed, and communicated. Feedback in a complex engineered system is a function that relies on human performance. Potential barriers to feedback may occur as a result of poor communication, complacency, lack of knowledge, distraction, lack of teamwork, fatigue, lack of resources, pressure, lack of assertiveness, stress, lack of awareness, and accepted norms.

The complexity of systems has an important effect on the feedback process through the inability to predict, with complete certainty, the consequences of interactions between physical, chemical, mechanical and human processes.

The means of overcoming the barriers to effective feedback lies in developing an awareness of the factors that: prevent the seeing of evidence clearly and in context, result in incorrect classification, result in incorrect cause and effect linkages, and interfere with communication at all levels. Feedback is highly dependent on viewing the system in its entirety, and viewing its elements in detail. Feedback to ensure continued safe operation should be based on the potential consequences of a sequence of events.

1 INTRODUCTION

Motion is fundamental to aircraft – without motion flight ceases. The safe operation of an aircraft is based on the reliable performance of systems that provide motion – systems that provide thrust.

This safety study is concerned with the performance of the propulsion systems that provide thrust for aircraft commonly used in low-capacity public transport operations. Typically, this class of operation utilises twin propeller propulsion systems. While the engines that drive the propellers may be turbine or reciprocating types, this study addresses the issue of reciprocating engine reliability.

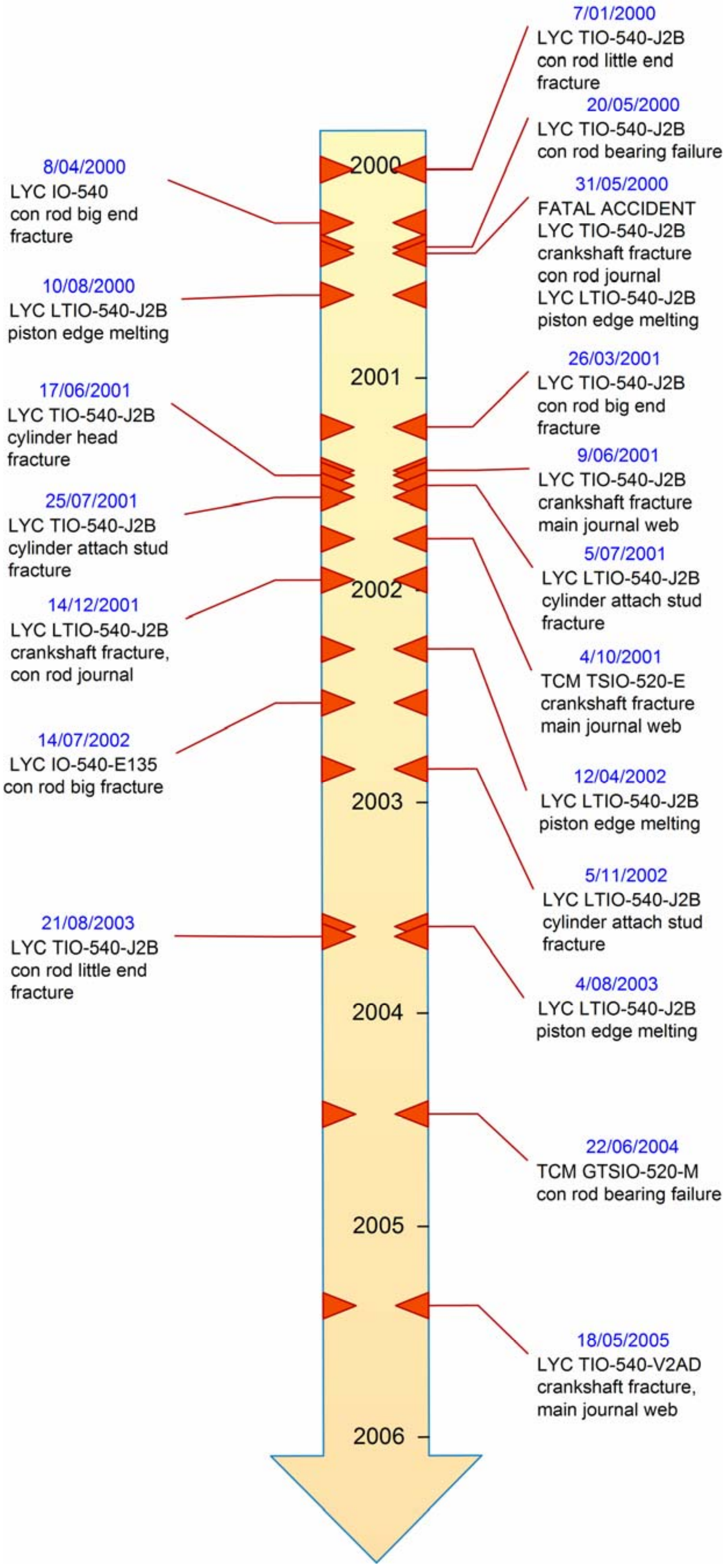
The purpose of this study is to analyse the reported occurrences in order to identify the factors affecting engine reliability. In doing so, it is intended that this report will increase industry awareness of the identified factors and encourage safety action to correct possible weaknesses or deficiencies in the system created to ensure engine reliability. This study is an analysis of failures in a complex engineered system – an aircraft reciprocating engine – it is not a treatise on engine design or operation. However, a general understanding of engine design, manufacture, operation and maintenance is necessary for effective analysis.

Reciprocating-engine powered low-capacity transport aircraft (8 to 10 passengers) provide an important public transport connection throughout regional Australia. It has been argued that these aircraft form the backbone of Australia's rural and regional air services (Swift, 2003). Around 1,270 multi reciprocating-engine powered aircraft flying a total of around 220,000 hours for calendar years 2000 - 2005 are on the Australian register (BTRE, 2007 & CASA, 2007). Of these, about 200 reciprocating-engine powered aircraft were employed in the low-capacity public transport operation (CASA, 2007).

The Piper Chieftain (PA-31-350) aircraft, is powered by two 350 brake horsepower (bhp) Lycoming turbocharged six-cylinder horizontally-opposed engines, (L)TIO-540-J2B(D). The Cessna Company has produced a series of 8 to 10 seat commuter aircraft (models 401,402, 404, 411, 414, 421) powered by two Teledyne Continental Motors turbocharged six-cylinder horizontally-opposed engines, ranging from TSIO-520 (310 to 325 bhp) to GTSIO-520 (340 to 375 bhp) models. These engines are very well-established designs with extensive demonstrated reliable performance for their specified operational lives, in many countries, and across many operators.

In the period January 2000 to December 2005, twenty powertrain structural failures of high-power (300 to 375 bhp) horizontally-opposed, reciprocating engines were associated with reported air safety occurrences. These occurrences range in severity from: in-flight engine shutdown to engine failure and forced landing; engine failure combined with in-flight fire and fracture of both upper engine mounts; to a fatal accident of a regular public transport flight following the structural failure of both engines and ditching at night, see figure 1.1.

Figure 1.1: High-power reciprocating-engine structural failure occurrences, 2000 to 2005



In addition to these reported air safety occurrences, several other structural issues with this class of engine have been reported to the regulatory authority as major defects[1]. In particular, there were a large number of reports of crankshaft bearing failure (Sprigg, 2003).

While reciprocating engines have failed during service prior to January 2000, the frequency of structural failure in the period 2000 to 2005 suggests that there was a breakdown in the systems created to ensure engine reliability, in particular, the systems created to ensure that structural failure of engine components does not occur during flight.

The aim of this safety study is to examine the issue of high-power reciprocating engine reliability in detail. The study is based on:

- developing an understanding of aircraft safety-critical systems and how reliable propulsion system performance is achieved;
- evaluation of the available evidence associated with powertrain component failures events, in the period 2000 to 2005, against a background of component failure control plans;
- analysis of powertrain component failure events, individually and as a group, to uncover the factors that initiate event sequences leading to powertrain component failure; and
- analysis of the airworthiness assurance system to determine why there was a reduction in high-power reciprocating-engine reliability over the period January 2000 to December 2005.

1.1 References

Bureau of Transport and Regional Economics (BTRE), *Regional Airline Performance,* 2007.

Civil Aviation Safety Authority (CASA), Civil Aircraft Register, *http://www.casa.gov.au/casadata/regsearch/findairs.as,* May 2007.

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Swift, SJ 2003, *Big Challenges for Little Airliners*, 10th Australian International Aerospace Congress, 29 July to 1 August 2003, paper number AIAC 2003-1173.

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[1] Prior to June 2001 CASA operated the Major Defect Reporting (MDR) system. The system is now known as Service Difficulty Reporting (SDR).
Major defects in relation to an aircraft, are defects that may affect the safe operation of an aircraft or cause the aircraft to become a danger to person or property.

2 AIRCRAFT SAFETY-CRITICAL SYSTEM RELIABILITY

2.1 Introduction

The safe operation of an aircraft depends on the reliable performance of systems that provide the fundamentals of flight: thrust, lift, stability and control. Safe operation also depends on systems that maintain a habitable cabin environment, assist navigation, and prevent collisions with the ground or other aircraft. These systems are safety-critical systems

The success of a system, whether it be purely mechanical or human in nature, or a combination of mechanical and human (socio-technical), is measured by its ability to perform a designed function for a specified period of time. A successful system is considered to be a reliable system. The study of system performance is also known as the study of system reliability, where the term reliability relates to the ability to provide a function for a defined period of time or the ability to prevent a loss of function within the defined period of time. When a system loss of function creates a threat to the wellbeing of operators, passengers and bystanders – a safety hazard – the term system reliability may be translated to system safety. For the case of aircraft, the term airworthy is used to encompass the issue of the reliable performance of all systems that affect safe flight.

The analysis of the performance of a safety-critical system must be based on an understanding of all facets of the system created to achieve safe operation. These systems are engineered systems that rely on the ability of designers to predict future system behaviour, and on feedback control to respond to threats to safe operation encountered during continued operation.

2.2 Engineered systems

The systems that form the basis of public transport are engineered systems. Engineered systems are socio-technical systems that are founded on the creation and operation of man-made structures and machines. Engineered systems may be broken down into a number of subsystems that may be divided further into system elements that relate to technology and elements that relate to society.

The technological elements of engineered systems are based on our understanding of the physical world (Ellis, 2004), a world of physical materials. The other element of the technology framework is the set of physical laws that prescribe the boundaries of what is possible, how objects are created and how machines are operated. These laws are causally effective.

The societal elements of engineered systems are based on our understanding of individual and communal consciousness – ideas, emotions and social constructions. The structural hierarchy develops from the ideas and emotions through language, individual knowledge and communal knowledge, to human goals and intentions. Explicit social constructions such as language, customs, roles, and laws shape and enable human social interaction. These social constructions have been developed over time through conscious legislative and governmental processes. Each of these elements is causally effective. Finally, there are societal elements that are derived from human behaviour and the behaviours of groups in society, people and their customary attitudes, values, styles and relationships, reward systems, formal power structures and informal power structures (from knowledge and personal power).

As socio-technical systems, engineered systems are not just simple relationships between man and machine. The behaviour of an engineered system depends on the relationships between all subsystems and system elements. System function is more than the sum of individual elements, the interconnections between system elements, more than each element, individually determines system performance.

2.3 Engineered system design

An underlying feature of engineering design is the need to predict the future behaviour of structures, mechanisms, machines and operators. Will it work safely and will it continue to work safely? In this less-than-perfect world our understanding of materials, structures, mechanisms, machines and human behaviour is not complete. System design requires human judgement and insight (especially in decisions regarding safety). Structural analysis is done in support of, not in place of, the creative process of design (Curtis, 1997). Mathematical models have limitations — they are approximations of reality, the danger is that mathematical models can hide a lack of knowledge.

2.3.1 The effect of complexity

Complexity affects the design of engineered systems. When the output of a system is dependent on complex relationships between its component parts, our understanding, and mastery, of system behaviour – to allow the prediction of future behaviour of natural systems or the creation of man-made systems that achieve specified goals – is based on decomposing the system into smaller and smaller parts (modules), each of which may be refined or designed independently.

In addition to modularisation, the processes of abstraction and labelling in which the system elements are reduced by ignoring their inessential details, forming an idealised, labelled model of the element are used (Ellis, 2004). Elements are simplified by encapsulation and information hiding. The system element is treated as a black-box abstraction by specifying the expectation of the system element while leaving the precise details of inner workings hidden. Each class of black-box abstraction must have two parts, an interface – its exterior view that is common with all other elements of the class of elements/objects, and an internal representation and mechanism that achieves the desired behaviour/output. An important property of classification is that each element class inherits all the properties of its superclass.

Structural hierarchies define relationships between elements and further abstraction through inheritance. Causal functioning within a hierarchy can occur from the bottom up; what happens at a higher level depends on what happens at lower levels, or top down; higher levels direct what happens at lower levels. Causal functioning may also occur through less well defined interactions between system elements regardless of their level.

The complexity of system element interaction leads to variations in output for the same inputs. If there is a reliance on a particular output, then unexpected system variation may result in an unanticipated output. Unexpected system element behaviours and/or interactions can cause new types of output that fail to meet design expectations and affect system reliability. Faults can be propagated through a system, through interdependencies between elements in unforeseen ways. It is impossible to anticipate all possible relationships (Ellis, 2004).

2.3.2 Multiple goals

A characteristic of engineered systems is the presence of multiple and competing goals. There will always be a tension between the desire for decreased threat to life (safety) and the willingness to pay (cost to the user and profitability to the operator). For the case of aircraft propulsion-system engines, there is competition between the goals of economy, power, weight, bulk, and frontal area.

The state of balance between safety and profitability depends on the ability of the creators, operators and regulators of an engineered system to learn. The rate at which learning is achieved is dependent on the immediate goals of the various players in the system, for example, driven by a need to satisfy a market, compete with alternatives, or in reaction to an accident. Adjustments from learning in one area may result in consequences that are not immediately apparent in another. The connection between cause and effect in different areas may occur over widely different time frames. Learning may also have to wait for developments in the understanding of physical phenomena or human behaviour.

2.3.3 Fine tuning goals

The conflict that is created by the multiple goals of conservative system design for system safety, cost, performance and profitability, results in the process of subsystem and system element fine tuning. The danger of fine-tuning subsystems and elements in a system that has multiple and conflicting goals is that changes can always be justified and generate a benefit in one area while having an unrecognised effect in another area.

System designers and operators are almost certain to reduce some safety factors after creating a system, as continued successful system operation makes safety factors look more and more wasteful (Starbuck and Milliken, 1998). Conservative design with large safety factors, while ensuring safe operation in the face of variations and uncertainties, may render projects prohibitively expensive or technically impossible and thus prevent the solving of serious problems or the attaining of important goals.

2.3.4 Risk management[1]

A dilemma has been created by the need to quantify risk. The act of quantifying risk results in the acknowledgment of a finite probability of failure. If failure occurs, is this the failure predicted by statistics? If a predicted, extremely rare, event occurs can it be argued that analysis to prevent recurrence is unnecessary because of the small probability of recurrence?

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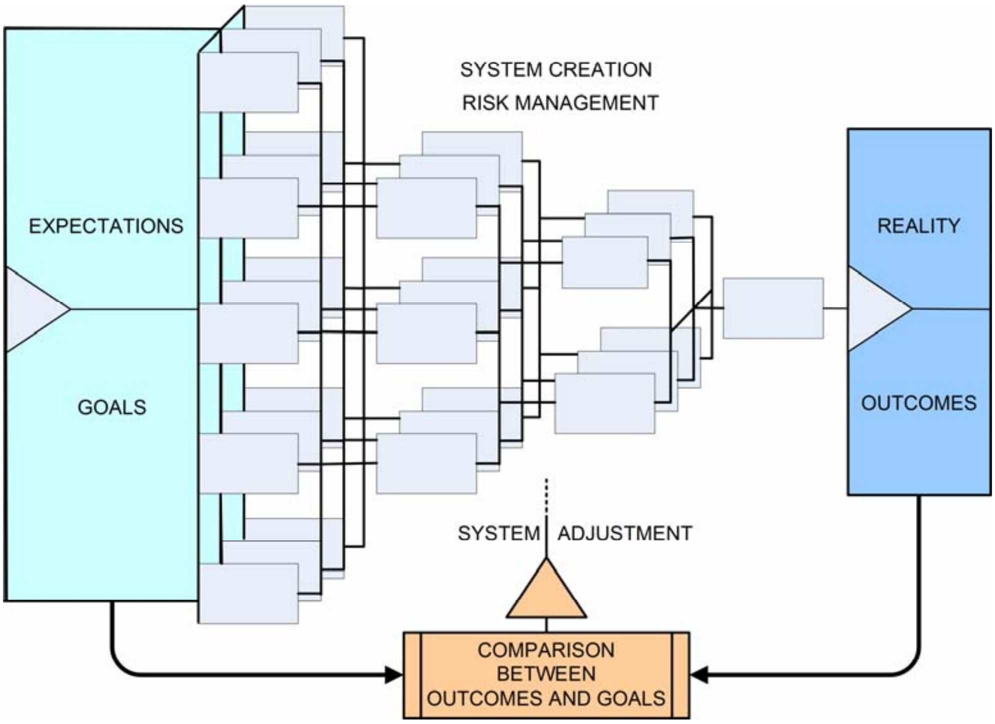
[1] Risk management is the human activity which integrates recognition of risk, risk assessment, developing strategies to manage it, and mitigation of risk. The strategies include transferring the risk to another party, avoiding the risk, reducing the negative effect of the risk, and accepting some or all of the consequences of a particular risk.

Risk in the context of public transport is not a simple technical matter of estimating probability through mathematical calculation. Risk is also dependent on the particular circumstances of the person who has to make a decision in the face of uncertainty (Bernstein, 1998). Different people and different groups within society, for example, those directly affected by a transport accident and those distant from the accident, may ascribe different values to risk. These values may also change with time. ‘Gut feeling’ is a significant factor in risk perception (Bernstein, 1998).

2.3.5 Response to goal deviation

Responses to system goal variation depend on the purposeful use of information capture, storage, transmission, recall, and assessment to control subsystems and system elements. Current information is filtered against a relevance pattern, the irrelevant being discarded, the moderately relevant being averaged and stored in compressed form, the most important being selectively amplified and used in association with current expectations to assess and revise goals. Thus feedback control systems based on sophisticated interpretation of present and past data enables a purposeful response to goal deviations.

Figure 2.1: Schematic showing the relationship between system elements, subsystems, and the goals (expectations) and outcomes (reality) of a system



Feedback control loops operate at all levels within a system, the overall system, subsystems and system elements. The linkages between the system goal comparison function and the system adjustment function are information linkages. Feedback is a necessary, widely called for, process in transport systems to ensure continued safe operation.

> Feedback mechanisms are needed to ensure that the underlying assumptions made during design and certification are continuously assessed in light of operational experience, lessons-learned, and new knowledge. (National Transportation Safety Board (NTSB) Safety Recommendation A-06-36 through A-06-38, May 17 2006)

The Society of Automotive Engineers (SAE) Aerospace Recommended Practice, ARP5150, codifies the high level processes for conducting ongoing safety assessments through a feedback mechanism.

2.4 Aircraft safety-critical subsystems

If the failure of a transport subsystem or system element creates a threat to the wellbeing of operators, passengers and/or bystanders, then it is described as safety critical.

During the design of transport systems, reviews are undertaken to identify safety-critical subsystems and system elements. The reliable performance of a transport system containing safety-critical subsystems is based, in the first instance, on the provision of redundancy[2] for the safety-critical subsystems and system elements. For instances where redundancy cannot be provided, actions including monitoring of safety-critical subsystem/element performance combined with actions to restore performance to design values, the limitation of operational time to a period in which safety-critical subsystem/element deterioration does not exceed design values, and the use of safety factors during safety-critical subsystem/element design, are required to ensure safe operation (Civil Aviation Publication 418, 1990; FAA AC 120-17A, 1978).

The loss of function of a safety-critical subsystem or system element may not always result in the loss of life through an accident. The complexity of transport systems creates the possibility that the loss of function of a safety-critical subsystem or system element may have a different outcome on different occasions – an outcome that may be classified variously as; a reported difficulty, an incident, a serious incident, or an accident.

Because of the number of people that may be affected by a system failure in a large aircraft, a distinction is made for the purpose of airworthiness standards between small and large aircraft. The dividing line between small and large aircraft is based on a long-standing international agreement that large aircraft are those with a maximum take-off weight exceeding 5700kg. Large aircraft are required to be designed and operated in accordance with a fail-safe philosophy, which means that a flight should be capable of being continued to a safe landing in the event of failure of any of the various elements that go to make up the aircraft, other than those justified on a safe-life[3] basis. To take account of a powerplant failure, for example, a large aircraft must have more than one engine. The smaller aircraft are designed

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[2] Redundancy in engineering applications is the duplication of critical components of a system with the intention of increasing reliability of the system, the duplicated system may operate in parallel, sharing loads, but with sufficient capacity to maintain function in the event of one failure (fail safe) or the duplicated system may operate in a standby mode.

[3] Safe-life design philosophy may be used in situations where component properties or system function degrade with continued operation. A specific component or system life, incorporating a safety margin or reserve, is determined during design.

and certificated against a simpler airworthiness code. The concept of fail safe is not so rigorously applied; accordingly engine failure at a critical stage, during take-off, may result in an accident (AAV Inquiry, 1980, p.325).

2.5 References

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3 PROPULSION SYSTEM RELIABILITY

3.1 Introduction

Aircraft propulsion systems must have a high thrust-to-weight ratio. They must also be economical, but above all, they must be reliable.

Propulsion systems that comprise of a reciprocating engine powered propeller provide thrust for low-capacity public transport operations. These propulsion systems are safety-critical systems and depend on the reliable operation of the propeller and reciprocating engine.

The capability of a reciprocating engine to produce the power, specified by the engine manufacturer, reliably throughout flight is a fundamental requirement of safe operation. Conversely, the failure of engines to produce specified power levels or the complete failure of an engine during flight is a threat to safe operation. The expectation of safe operation is expressed, simply, in the design standard for aircraft engines, Federal Aviation Regulations Part 33 Airworthiness Standards: Aircraft Engines.

> Engine design and construction must minimize the development of an unsafe condition of the engine between overhaul periods.

In order to understand the factors that affect reciprocating-engine reliability, it is necessary to develop an understanding of all of the sub-systems that combine to produce the power specified by the engine manufacturer, for the duration of planned flight. It is also necessary to develop an understanding of the hazards created by engine failure and the methods used to prevent engine failure creating a threat to safe aircraft operation.

3.2 Reciprocating-engine systems

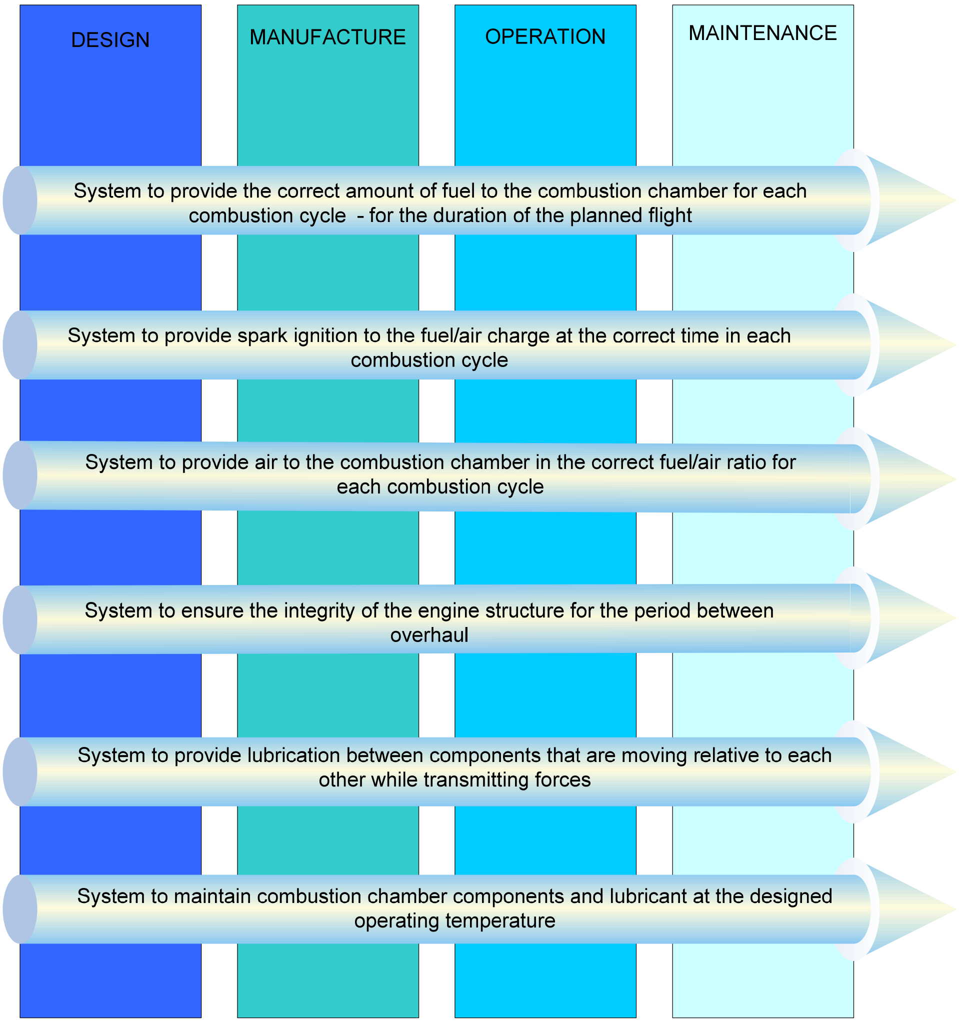
It is important to recognise that, in reciprocating-engine installations, the engine and propeller form an interdependent system. Constant-speed propellers are used in conjunction with high-power reciprocating engines. This combination allows the propeller speed and engine power to be set separately, to obtain the best combination of performance and fuel economy, for all phases of flight.

Just as the engine and propeller form an interdependent system, the engine subsystems (output power setting, structure, fuel/air mixture control, spark ignition, lubrication, and cooling) and fuel consumed in the engine, form an interdependent system. Engine performance and fuel properties are closely linked. The history of spark-ignition engine development has been a process of mechanical refinement to extract the available energy contained in gasoline under controlled combustion conditions and a concurrent refinement of gasoline formulation to allow advantage to be taken of mechanical refinements (Taylor, 1998, vol.1, p.425).

3.3 Reciprocating-engine reliability

Reliability is not a fundamental property of an engine. It is a result of the correct performance of all subsystems through the phases of design, manufacture, operation and maintenance, see figure 3.1.

Figure 3.1: Reciprocating-engine subsystems



The confidence that an aircraft engine will perform reliably and that risks are managed is established by a certification process. The engine design, along with approved instructions for operating limits, lubrication, inspection, component replacement, and testing and adjustment, must pass an extensive testing program.

Reliability may be expressed in qualitative terms or quantitative terms. A correlation between the qualitative and quantitative terms, along with descriptors of failure severity and effect on aircraft and aircraft occupants, is shown in table 3.1. It is normally accepted that a reliable system has a probability of failure of 1 in 10,000,000 (10^{-7}) or that the probability of failure is extremely remote (improbable).

Table 3.1: Relationships between qualitative and quantitative reliability descriptors, severity descriptors, and effects on aircraft and occupants (Smith, Cassell, and Cohen, 1999)

Probability (Quantitative)		1.0	10^{-3}	10^{-5}	10^{-7}	10^{-9}
Probability (Descriptive)	FAR	Probable		Improbable		Extremely Improbable
	JAR	Frequent	Reasonably Probable	Remote	Extremely Remote	Extremely Improbable
Failure condition severity classification	FAR	Minor		Major		Catastrophic
	JAR	Minor		Major	Hazardous	Catastrophic
Effect on aircraft and occupants	FAR	Does not significantly reduce airplane safety (slight decrease in safety margins) Crew actions well within capabilities (slight increase in crew workload) Some inconvenience to occupants		Reduce capability of airplane or crew to cope with adverse operating conditions Significant reduction in safety margins Significant increase in crew workload Severe Cases Large reduction in safety margins Higher workload or physical distress on crew, cannot be relied upon to perform tasks accurately Adverse effects on occupants		Conditions which prevent continued safe flight and landing
	JAR	Nuisance	Operating limitations Emergency procedures	Significant reduction in safety margins Difficult for crew to cope with adverse conditions Passenger injuries	Large reduction in safety margins Crew extended because of workload or environmental conditions Serious or fatal injury to small number of occupants	Multiple deaths, usually with loss of aircraft

FAR; Federal Aviation Regulation (United States of America): JAR; Joint Aviation Regulation (European).

3.3.1 The impact of structural efficiency

Structural efficiency in design is necessary to achieve high power-to-weight ratios. The strength and robustness of engine components and mechanisms, within the defined engine operating limits, is achieved by using materials that comply with standard specifications (to guarantee that the properties of the materials used match those assumed in design).

The engine must be designed and constructed to function throughout its normal operating range of crankshaft rotational speeds and engine powers without inducing excessive stress in any of the engine parts because of vibration and without imparting excessive vibrational forces to the aircraft structure (FAR part 33, subpart C, section 33.33).

A demonstration of the adequacy and robustness of the engine is provided by an endurance test (FAR 33, subpart D, section 33.49). Engines are subjected to blocks of engine operation under a variety of operating conditions to a total of 150 hours of operation. At the conclusion of the endurance test, the condition of components and mechanisms is assessed during a teardown inspection. Each component must retain the functioning characteristics that were established at the beginning of the test.

3.3.2 The impact of combustion abnormalities

Combustion in spark-ignition engines is designed so that a flame front moves across the premixed fuel-air charge in the combustion chamber resulting in a controlled increase in gas pressure. Under certain conditions, rapid oxidation reactions occur at many locations within the unburned charge, leading to very rapid combustion throughout the volume. This essentially volumetric heat release in an engine is called auto-ignition, and the very rapid pressure rise leads to the characteristic sound of engine knock (Turns, 1996, p.6). Within the aviation industry this process of auto-ignition or knock is referred to as ‘detonation’. Detonation can cause mechanical damage through the creation of abnormal loads. It can also cause component overheating and melting through its effect on the mechanism of heat transfer.

Detonation of the fuel-air charge in a reciprocating engine is the principal factor limiting the maximum power that can be produced by an engine. FAR 33, subpart D, section 33.47 requires that:

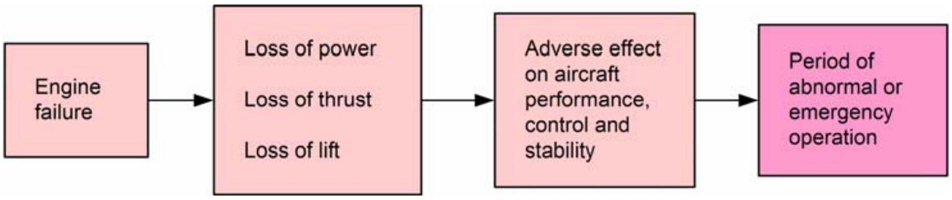
> Each aircraft engine type must be tested to establish that the engine can function without detonation throughout its range of intended conditions of operation.

Avoidance of detonation is achieved primarily by the use of fuel with a known resistance to detonation (octane or performance number rating scales) and specified engine operational limitations, which affect the combustion conditions in each combustion chamber (a function of the engine design). Detonation-free operation is not solely dependent on fuel properties. Factors such as charge temperature, mixture strength, compression ratio and turbocharger boost pressure, ignition timing and spark plug type can also affect the combustion process in an engine. Detonation maps define the combinations of engine power and mixture strength for a variety of limiting conditions (charge and combustion component temperatures) that do not result in detonation.

3.4 Hazards created by reciprocating-engine failure

The failure of an engine powering an aircraft propulsion system can create a hazard during aircraft operation by reducing aircraft performance, adversely affecting aircraft control and stability, and exposing the flight crew to a period of abnormal operation.

Figure 3.2: Engine failure consequence diagram



There are two possible defences for the hazard created by engine failure:

1. Pilot training to respond to the period of abnormal operation
2. Engine reliability.

3.4.1 Pilot response

The UK AAIB investigation of a fatal accident in which a Cessna 404 crashed shortly after takeoff during an attempt to return to the airfield following responses to a set of confusing signs and symptoms related to engine malfunction, discusses the issue of pilot response to engine failure in this class of aircraft (UK AAIB report 2/2001).

The investigation established that accessory gear-train damage in the left engine resulted in the progressive loss of all thrust from the left engine. The right engine showed no evidence of mechanical malfunction, however, the right propeller had been feathered.

The response to an engine failure in a twin-engine aircraft is based on correctly identifying the failed engine, securing it, climbing away if necessary and flying a single-engine approach and landing to a runway. Further, an engine failure after takeoff in a twin-engine aircraft requires immediate, prioritised and accurate corrective action from the handling pilot because of limitations in climb performance.

The affect of an unexpected, complete, engine failure on aircraft behaviour and pilot response is different to the affect of a progressive loss of power and final engine failure.

The AAIB concluded that the handling skills required to successfully overcome an unexpected engine failure, shortly after takeoff, in a twin-engine, aircraft are among the most demanding of skills required by any aircraft pilot and that mishandled turn backs are often fatal (UK AAIB report 2/2001).

A review of accident data for twin reciprocating-engine powered aircraft provides further evidence demonstrating the critical nature of engine failures in this class of aircraft (AVweb, 2003).

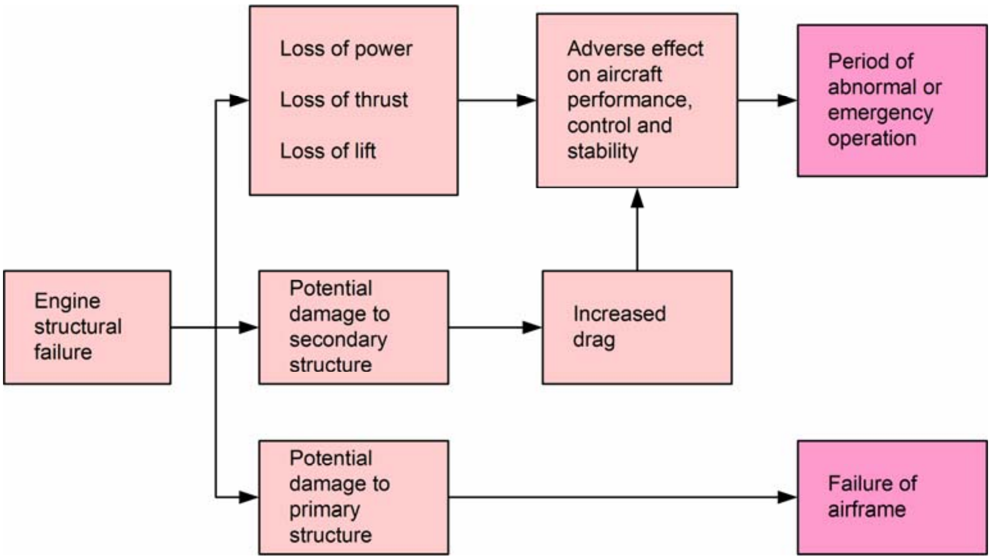
> Between 1972 and 1976, the NTSB investigated the outcome of twin engine crashes and concluded that in the event of an engine failure that resulted in a crash, the likelihood of it being fatal was four times greater than a crash in a single.
>
> Our most recent review of twin accident data tends to support this finding in general, if not to the same decimal point. Typically, in crashes where an engine failed in a twin, the accident was fatal between 20 and 50 percent of the time; in singles, the fatal rate for powerplant failure is lower, on the order of 10 percent, somewhat variable with model.

In light of the potential effect of engine failure on twin-engine, passenger-carrying, aircraft and the lack of thrust-system redundancy for all phases of flight, engine reliability is a critical issue and an important defence for safe operation.

3.4.2 Engine structural failure

The failure of the structure of a reciprocating engine may create additional hazards, increased asymmetric drag and airframe failure. There are no effective defences to these hazards.

Figure 3.3: Engine structural failure consequence diagram



The creation of drag through engine failure is the most critical factor influencing the performance of 8 to 10 seat twin reciprocating-engine air transport aircraft.

The UK AAIB investigation of the Cessna 404 accident states that many aircraft of this class will not sustain a single-engine climb at maximum take-off weight unless the landing gear and flaps are retracted. In the period between takeoff and achieving a suitable climb speed, a forced landing is the only outcome. An unexpected and complete engine failure results in the propeller changing very rapidly from producing thrust to producing drag – it takes time (up to 15 seconds) for a propeller to move to the feather position after the feathering controls have been operated. The reduction in forward thrust for the aircraft is significantly more than 50%. The sudden change in thrust also tends to cause a loss in airspeed while the pilot responds to the problem and takes corrective action. The single-engine rate of climb is highly dependent on airspeed. If, after an unexpected failure, the airspeed drops below the best rate of climb airspeed 'blue line', the aircraft may not climb despite it being correctly configured (UK AAIB report 2/2001).

A greater effect on aircraft performance is the drag created when the engine cowlings are disrupted by the forceful ejection of engine parts or fracture of engine mounts. In this case forced landing is likely to be the only outcome.

Figure 3.4: The effect of the forceful separation of the No.1 cylinder assembly on the engine cowling (occurrence 2000/90)

Examples of accidents and forced landings resulting from the disruption of engine cowlings are present in the literature.

In 1995 a Piper Navajo was forced to ditch near Kennedy Airport following the failure of the left engine while descending into Farmingdale, N.Y.

> The pilot reported that the cowling was open – probably from the departing cylinder that cratered the engine – and the best he could do was a 300 fpm descent into the water. All six exited safely but one passenger died from cardiac arrest. (AVweb, 2003)

The Transportation Safety Board of Canada Aviation Investigation Report A99C0208 details the outcome of the forceful separation of the No. 2 cylinder from the left engine of a Piper Chieftain.

> The Piper PA-31-350 Navajo, C-GHMK, departed from St. Andrews, Manitoba, on a visual flight rules charter flight to Berens River. One pilot and ten passengers, including one infant, were on board, and a dog was stowed in the baggage compartment behind the right, rear seat. At approximately 1530 central daylight saving time (CDT), while the aircraft was at an altitude of about 2500 feet and about 30 nautical miles south of Berens River, the pilot heard a loud sound from the left engine. He saw deformation of the left engine cowling and smoke coming from the engine, and the aircraft yawed to the left. Part of the engine cowling departed in flight. The pilot could not pull the left propeller lever beyond half of its normal travel, nor could he move it into the

> feather position. He set maximum power on the right engine, but the aircraft did not maintain altitude. The pilot advised company dispatch over the radio that he would attempt a forced landing, then force landed in a mossy marsh area. Everybody on board, including the dog, deplaned. Five of the passengers sustained minor injuries during the evacuation. A fire ensued, completely destroying the aircraft except for the empennage aft of the horizontal stabilizers. (TSB Report A99C0208)

Fire created by the failure of engine structures represents an extreme hazard if it exists for a period of time. The reduction of the structural strength of the airframe can result in a catastrophic collapse of a wing. No fire extinguishing systems are provided in this class of aircraft.

The fracture of a connecting rod little end resulted in the forceful separation of a cylinder from the rear of an engine and the fracture of both upper engine mounts. The disruption of the engine mounting system can allow the engine to droop in the airframe and create a high drag condition.

Figure 3.5: The effect of No.6 connecting rod little end fracture on the engine structure (occurrence 2003/2701)

3.5 Reliability measurement

In reality, components of reciprocating-engine systems do fail and flight safety may be threatened by the total loss of thrust, partial loss of thrust, or damage to other structures and systems by the effects of fire or physical impact. Because of the complexity of the systems, the consequences of a component failure may be benign or they may be catastrophic.

While reciprocating-engine reliability is an important factor in flight safety, it is apparent that there is no hard measure of the reliability of these engines, in particular, the horizontally-opposed engines in the 300 to 375 HP class that power the 8 to 10 seat twin-engine air transport aircraft.

The UK AAIB, in the course of its investigation of the Cessna 404 Titan G-ILGW accident (UK AAIB report 2/2001), raised the issue of engine reliability with several regulatory agencies and asked for data on in-flight shut-downs by different models of reciprocating engines. The response from the FAA, and other agencies, was that no reliable data exist for this kind of comparison, largely due to ‘gross under-reporting’ of in-flight shutdown of general aviation piston engines. The FAA assessed the rate as ‘between 1 per 1,000 and 1 per 10,000 flight hours’. This failure rate, qualitatively described as ‘probable’ or ‘reasonably probable’, is well in excess of the ‘improbable’ or ‘extremely remote’ reliability goals expressed in design standards.

Airsafety.Com provided another measure of reciprocating engine reliability in their Information report, December 1, 2002.

> The FAA’s accident/incident data base of 168,272 records was reviewed in order to determine how often a mechanical or system failure was found to be the causal factor in an accident.
>
> Of 34,406 accidents since 1973 involving horizontally-opposed reciprocating engines;
>
> 9,170 (27%) involved a system or mechanical factor (non-operational - something broke or failed).
>
> 5,506 (16%) involved the engine or an engine system (ATA codes 7100 to 8597) (engine fuel, ignition, controls, exhaust, oil, starting, turbocharging).
>
> 1,315 (4% of the accidents, 14% of the mechanical failures, 24% of the engine failures) involved either the engine power sectio (ATA 8520) or the engine cylinder section (ATA 8530).
>
> Considering that there are nearly 500 different ATA codes, ATA codes 8520/30 (engine power and cylinder sections) seem to be disproportionately represented.
>
> A comparison was made between several of the high performance horizontally-opposed reciprocating engine models.
>
> Teledyne Continental Motors (TCM) TSIO-360, 968 accidents
>
> > 492 (51%) system or mechanical factor
> >
> > 266 (27%) engine or engine system
> >
> > 103 (11%) of the accidents, 21% of the mechanical failures, 39% of the engine failures) ATA 8520/30
>
> TCM GTSIO-520, 478 accidents
>
> > 295 (62%) system or mechanical factor
> >
> > 174 (36%) engine or engine system
> >
> > 62 (13% of the accidents, 15% of the mechanical failures, 25% of the engine failures) ATA 8520/30
>
> Lycoming TIO-540, 944 accidents
>
> > 512 (54%) system or mechanical factor
> >
> > 319 (34%) engine or engine system

79 (8% of the accidents, 15% of the mechanical failures, 25% of the engine failures) ATA 8520/30

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4 POWERTRAIN STRUCTURAL RELIABILITY

4.1 Introduction

The structural core of a reciprocating engine is known as the powertrain. The powertrain comprises of the assembly of cylinders, pistons, connecting rods, crankshaft, crankcase, supporting structure, and bearings.

> Of all the problems involved in engine design, that of securing a reliable structure to withstand the heavy loads imposed by gas pressure, inertia forces and thermal expansion, without excessive weight, bulk or cost is the most difficult and basically the most important. Without a sound, reliable and durable structure no amount of refinement of other aspects of design is of any value. (Taylor, 1999, vol.2, p.425)

The dominant design issue for aircraft propulsion systems is the need to minimise bulk, weight and cost for a given power output. The pursuit of high power brings with it the need to, firstly manage the impact of high temperatures developed by the combustion of fuel and, secondly, in concert with the pursuit of minimal weight, manage the impact of high stresses in components of the engine.

Aircraft reciprocating engines have different requirements to automobile reciprocating engines.

Table 4.1: Comparison of the requirements of aircraft and automotive reciprocating engines (Taylor, 1999, vol.2, p.353)

Application	Most Important Requirement	Moderately Important Requirement	Less Important Requirement
Passenger Automobile	Low noise and vibration, reliability, flexibility (smooth and efficient operation over a wide range of engine speeds and loads, low maintenance	Fuel economy, weight, bulk	Long life
Aircraft Propulsion	Light weight, small bulk, high power for takeoff, reliability, fuel economy (brake specific fuel consumption, the mass of fuel an engine uses per horsepower per operating hour), operation over a small engine speed range	Low vibration, low maintenance	Initial cost, long life, noise

The principal issues of aircraft reciprocating-engine reliability centre on the management of component strength, component stress, and component temperature. Excessive component stress and insufficient component strength can threaten reliable operation through component fracture. Excessive component temperature can threaten reliable operation through a loss of strength (softening) or component melting. These threats are addressed through the development and implementation of component failure control plans.

The objective in the design of engine powertrain components is to optimise the desired performance requirements of safe efficient operation relative to cost considerations (cost of materials, design, fabrication, operation and maintenance).

4.2 Powertrain component design

An internal combustion reciprocating engine is an energy conversion machine. The potential chemical energy in the hydrocarbon fuel is converted to a rotational force (turning moment or torque). In the case of an aircraft propulsion system, the torque created by the engine is used to turn a propeller.

> The output power of a spark ignition reciprocating engine is controlled by throttling the air supply. The immediate purpose of opening the throttle is to secure an increase in torque, whether or not an increase in speed follows depends on the nature of the load. With governed engines, the throttle is opened in response to a demand for increased torque, and little change in speed occurs. On the other hand, engines driving fixed pitch propellers or driving vehicles on a level road will respond to opening the throttle with an increase in speed. (Taylor, 1999, vol.2, p.188)

Constant speed propellers act to govern the engine speed by varying the load on the engine. Engine power can be set independently of engine speed.

4.2.1 The relationships between engine parameters

When a gas expands in a cylinder fitted with a moveable piston, work is done by the gas on the piston (Ivanoff, 1994). The relationships between gas pressure, engine capacity, engine speed, engine torque, engine power are summarised in the following mathematical expressions.

$$W = p(V_2 - V_1)$$

W	work done by the gas at constant pressure
P	the actual constant pressure or mean effective pressure
V_1	the initial volume of the gas
V_2	the final volume of the gas

When the piston is connected to a crankshaft, as is the case in a reciprocating engine, the movement of the piston causes the crankshaft to rotate. This turning force is known as torque (T) and the distance the shaft is rotated is known as angular displacement (θ). The work done by torque on a rotating object is a simple function of torque and angular displacement.

$$W = T \times \theta$$

When work is being done continuously over a period of time, the rate of doing work per unit time is known as power. Power (P) produced by a torque in rotational motion is a simple function of torque (T) and angular velocity (ω).

$$P = T \times \omega$$

In the metric system of measurement, the unit of power is a Watt and the unit of torque is a Newton-metre. In the imperial measurement system, the unit of power is horse power and the unit of torque is foot pound. Angular velocity is commonly measured as revolutions per minute. When power is measured at the output shaft of an engine by a brake dynamometer, it is known as brake horse power (bhp).

For a spark-ignition engine, power has been found to be proportional to the engine's air capacity, provided the fuel-air ratio, compression ratio and spark timing are constant (Taylor, 1998, vol.1, p.147). Power is controlled by varying the mass flow of air – throttling the air supply.

$$P = J\dot{M}_a(FQ_c\eta)$$

P	power developed
J	mechanical equivalent of heat
$\dot{M}_a$	mass flow of dry air per unit time, or air capacity
Q_c	heat of combustion per unit mass of fuel
η	thermal efficiency
F	fuel-air ratio

The air capacity of an engine is commonly described by the parameter known as the volumetric efficiency. This parameter is independent of cylinder size and is a measure of the mass of fresh mixture which passes into the cylinder in one suction stroke, divided by the mass of the mixture which would fill the displacement volume of the cylinder.

$$e_v = \frac{2\dot{M}_i}{NV_d\rho_i}$$

$\dot{M}_i$	mass of fresh mixture per unit time
N	number of revolutions per minute
V_d	total displacement volume of the engine
ρ_i	inlet density

The volumetric efficiency of naturally aspirated engines is in the range 0.8 to 0.9. Supercharging or turbo-supercharging is a means augmenting the air pumping capacity of an engine by the use of an external compressor to increase the mass of air inducted into the combustion chamber.

The rating of engines, that is, the specification of rated power, indicates the highest power that is consistent with the specified engine reliability and durability. The rated power of an engine is not the maximum power that may be produced by the engine. The brake mean effective pressure (bmep) and piston speed are normally used in the determination of the operating limits of an engine and assessment of the capabilities of various design options. Brake mean effective pressure (bmep) is a hypothetical quantity that is a measure of the mean pressure in the combustion chamber during the engine cycle without considering the pressure needed to overcome pumping and frictional losses (Repco, 1980, p.5).

Brake horsepower, torque and brake mean effective pressure are related to each other as shown in the following expression (Repco, 1980, p.3).

$$\frac{PLAN}{33{,}000} = b.h.p = \frac{2\pi.n.T}{33{,}000}$$

P	bmep, pounds per square inch
L	stroke, feet
A	area of cylinder, square inches
n	total number of firing strokes per minute
N	revolutions per minute
T	torque, pound-feet

This relationship was originally applied to steam engines. When units that are more appropriate to high-speed reciprocating engines are used; cylinder diameter (*D)* – inches, stroke (*S)* – inches, piston area (*A)* – square inches, number of working strokes per minute (*N)*, engine speed (*n)* in revolutions per minute, mean piston speed (*K)* – feet per minute, brake mean effective pressure (*P)*, horsepower (*bhp)*, torque (*T)* – pounds-feet, the relationships are shown in the following expressions:

$$bhp = \frac{T.n}{5252} = \frac{P.D.^2 K.N}{84,000} = \frac{P.D.^2 n.S.N}{505,000} = \frac{P.A.S.n.N}{396,000}$$

The reciprocating motion of a piston results in cyclic variations in piston velocity and in acceleration. A parameter known as mean piston speed is used as a parameter to evaluate design options. The limiting piston speed is determined by the ability of the reciprocating structure to cope with the mechanical stresses created by inertia (inertia stress increases with the square of piston speed). Limiting piston speed is also determined by the desired fuel economy (Taylor, 1999 vol.2, p378).

$$Mean\ Piston\ Speed = \frac{n.S}{6}$$

n number of revolutions per minute

S stroke, inches

4.2.2 Effect of engine layout

Various arrangements of cylinders around a crankshaft have been used in engine design. These layouts include, inline, vee, horizontally-opposed and radial. The radial layout gives the lowest weight-per-unit displacement because the material in the crankshaft and crankcase is minimised for a given number of cylinders. The ability to maximise power-to-weight resulted in the dominance of this type in large propeller-driven transport aircraft. The horizontally-opposed engine layout gives particular advantages through being short in length, light weight and having a small frontal area for engine powers up to 375 bhp. The horizontally-opposed layout also provides sufficient space between the cylinders for cooling fins and is suited for air cooling, in particular air-cooled installations in smaller aircraft.

A comparison of the key engine parameters of power (bhp), engine speed (rpm), combustion gas pressure (bmep), and piston speed (ft/min) between various aircraft reciprocating engines, automotive engines and a marine engine is presented in table 4.2.

Table 4.2: Comparison of key engine parameters, aircraft, automotive and marine reciprocating engine (Taylor, 1999, vol.2, pp. 410-421)

Engine Layout	Engine Model	bhp	rpm	bmep, psi	piston speed, ft/min	propeller reduction gear ratio	Power/ weight, lb/bhp
Aircraft HO-6	IO-360D Continental	210	2800	165	1760	1	1.4
Aircraft HO-6	TSIO-520-E Continental	300	2700	169	1800	1	
Aircraft HO-6	GTSIO-520-C Continental	340	3200	162	2140	0.75	1.6
Aircraft HO-6	GTSIO-520-M Continental	375	3350	171	2233	1	
Aircraft HO-6	IO-540-D Lycoming	260	2700	141	1969	1	
Aircraft HO-6	IGSO-480 Lycoming	340	3400	165	2200	0.58	1.5
Aircraft HO-6	TIO-540-V2AD Lycoming	350	2600	197	1896	1	1.6
Aircraft HO-6	TIO-540-J Lycoming	350	2575	200	1878	1	
Aircraft Radial	Wright R1820-82A	1525	2800	236	3220	0.563	0.97
Automobile V-8	Mercedes380 SE	155	4750	110	2454		
Automobile V-6	Nissan VG30E turbocharged	160 200	5200	135 168	2834		
Automobile V-8	Chevrolet	390	5200	139	3260		
Automobile V-8	Ford 5L	134	3400	103	1700		
Marine diesel supercharged I-12	Sulzer RTA84	48,360	87	223	1370		74

Engine layout abbreviations: HO-6, six cylinders horizontally-opposed; V-8, eight cylinders in a vee layout; V-6, six cylinders in a vee layout; I-12, twelve cylinders inline.

Engine model abbreviations: IO, injected opposed; T–turbocharged; TS–turbosupercharged, R–radial; 540 etc., engine capacity in cubic inches.

This comparison shows that more power is produced from the same engine (same capacity) at the same or reduced engine speed when the engine air supply is boosted (turbocharged or supercharged) – compare the Lycoming IO-540-D engine with the Lycoming TIO-540-J. It is also clear that a similar power can be obtained from a turbocharged engine operating at different engine speeds by varying the combustion gas pressure (bmep) – compare the Continental GTSIO-520 engines with the Lycoming TIO-540-J engine.

The differences in engine/piston speed and combustion gas pressure between various engine models, is reflected in the criticality of various powertrain components. Higher combustion gas pressures will impose greater stresses on those powertrain components affected by combustion gas pressures, for example, cylinder assemblies, pistons, connecting rods, crankshafts and bearings. Similarly, higher engine/piston speeds will impose greater stresses on those powertrain components affected by inertia loads and friction, for example, bearings, pistons, connecting rods, and crankshafts.

4.3 Powertrain component reliability

Each type of aircraft operation, from recreational using single-engine fixed-gear aircraft to low-capacity regular public transport using multiengine aircraft, imposes special requirements on reciprocating engine design. Typically, the issues of power-to-weight, reliability, simplicity of operation, initial cost and cost of operation, and maintainability, determine the selection of design options. Aircraft performance, through the use of high power-to-weight engines, is important in public transport. Simplicity of operation and ease of maintenance are important for recreation aviation. Engine reliability is important for all types of operation.

The failure of powertrain components has a direct effect on engine reliability, as elements of the propulsion system, they are safety-critical. It is in the nature of reciprocating engines that redundancy cannot be provided for powertrain components.

When considering maintenance requirements for reciprocating engines, it is important to realise that a reduction in failure resistance of powertrain components usually cannot be detected by routine flight crew monitoring or by in-situ maintenance or test. The function of powertrain components is hidden from view. It is also important to realise that there may be an inverse relationship between component age and component reliability.

Powertrain component reliability is achieved by a combination of hard time maintenance actions such as replacement, measurement and overhaul at specified intervals. Powertrain component reliability is not based on the principle of ‘run to failure’ or ‘fit and forget’.

4.3.1 Safety factors

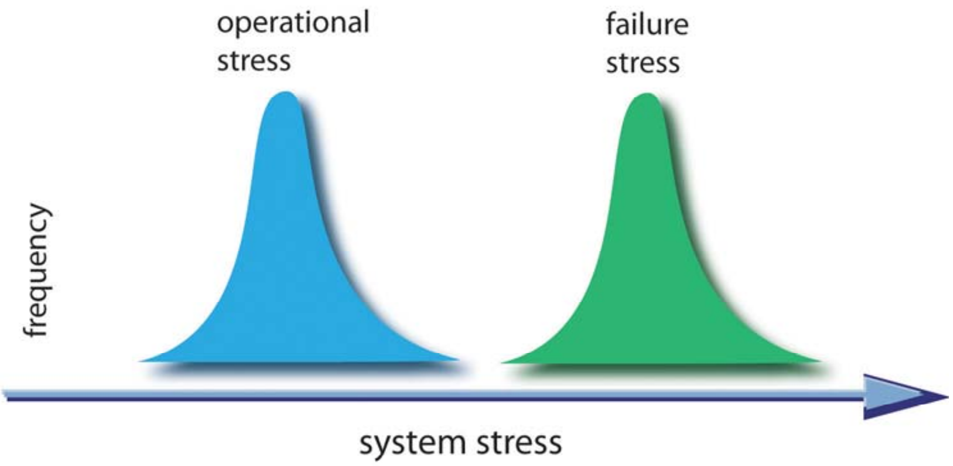
In the most general sense a mechanical system will fail when the stress imposed on the system exceeds the strength of the system. If the system strength is known, then the range of stress that can be applied to the system without resulting in failure is clearly defined.

In reality, system failure stresses and operational stresses cannot be predicted for each component during each moment of operation. Strength can only be determined accurately by testing to destruction and operational stresses can only be determined by continuous measurement. The consequence of uncertainty created by variations in stress and strength is the need to apply safety factors to design values – a design is an approximation, hopefully a conservative approximation, to an effective structure or system.

The effect of uncertainty in operational stress and strength (failure stress) can be shown diagrammatically, see figures 4.1 to 4.5. Structural failure occurs when the operational stress exceeds the failure stress. The probability of failure can be defined as the overlap of the distributions of operational stress and failure stress. It is important to remember that because stress and failure stress are random variables, the identity of particular components that lie in the overlap of the stress and strength distributions, cannot be determined beforehand.

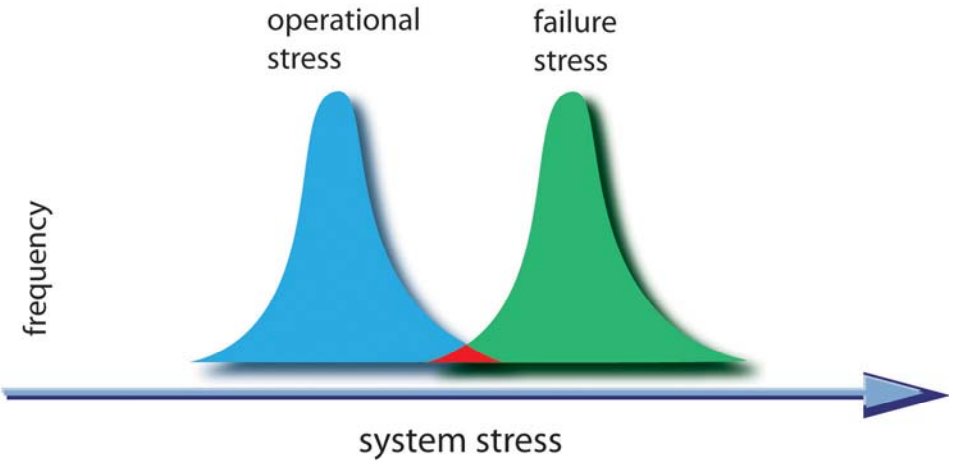
Safety factors are applied to some measure of the distribution of operational stress and failure stress, for example, the mean or either an upper or lower tolerance limit. Variations in the nature of the distributions; from component batch to batch, or between different types of engine operation, may affect the ability of the safety factor to achieve the desired level of component reliability.

Figure 4.1: **Schematic illustration of the probability of failure under conditions of variable operational stress and failure stress – no failure condition.**



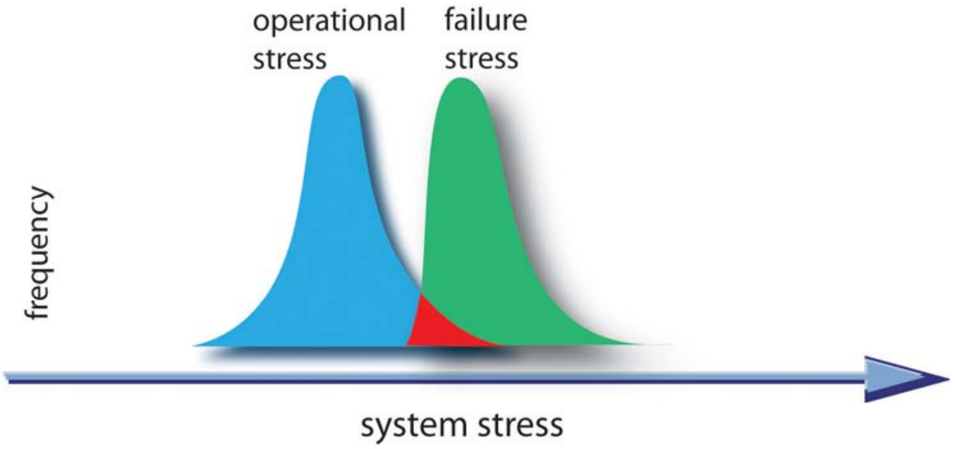
If the distributions of operational stress and failure stress do not overlap, the probability of failure is zero.

Figure 4.2: **Schematic illustration of the probability of failure under conditions of variable operational stress and failure stress – failure condition**



The area of overlap (coloured red) represents the probability of system failure.

Figure 4.3: **Schematic illustration of the probability of failure under conditions of variable operational stress and failure stress – failure condition, the effect of distribution change**



Changes in the nature of distributions, for example, skewing the distribution toward the lower end of the failure stress distribution, will increase the probability of failure – everything else being equal. Similarly, skewing the operational stress distribution toward the higher end of the distribution will also increase the probability of failure.

For the case of components that deteriorate with operational usage, hard time maintenance actions, such as, component replacement are based on a knowledge of the distribution of component failure times and an adequate safety factor

Figure 4.4: **The desired relationship between retirement time and component failure time**

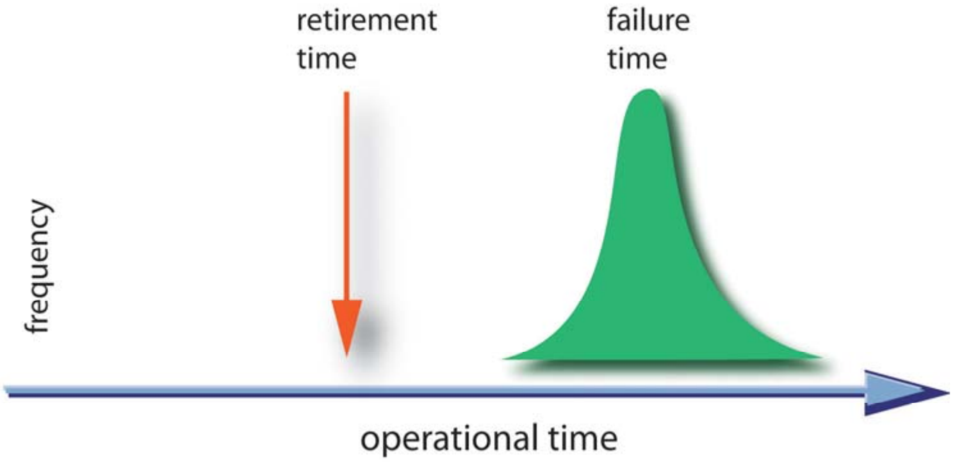
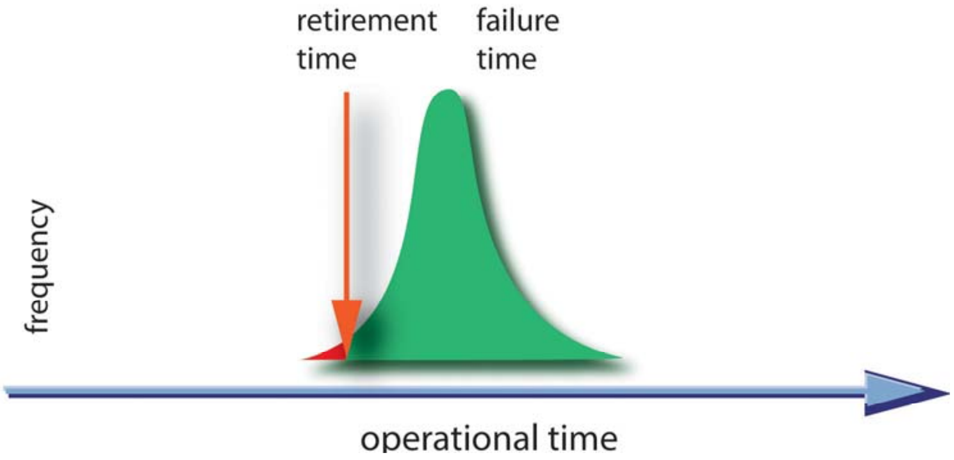


Figure 4.5: **The relationship between retirement time and failure time that results in a number of component failures**



4.4 Powertrain component failure control plans[1]

One of the key questions in developing a failure control plan for any particular component of a machine or structure is determining the magnitude of the margin of safety. The degree of safety and reliability needed (factor of safety) is often specified by code. However, the degree of safety depends on many additional factors such as consequences of failure or loss of redundancy, so it may vary within a generic class of structures or machines. Accordingly, a component failure control plan is developed only for the specific structure or machine under consideration and can vary from one which, in essence, provides assurance of very low probability of service failures, to one which may allow for occasional failures during service.

Structural reliability is a function of the effective operation of structural reliability systems through all phases of the life of a structure - design, manufacture, operation and maintenance. These systems minimise the probability and/or minimise the consequences of component failure.

4.4.1 Component fracture control plans

When loads are applied to a component, fracture may occur through; yielding and plastic collapse or unstable crack propagation from a site of stress concentration (geometric feature or a region of pre-existing crack growth).

The essence of fracture control is ensuring that the mechanical strength of a component is greater than the stress imposed on the component during operation, throughout its designed lifetime (Rolf and Barsom, 1977). While the terms strength and stress may be used in a general manner, the development of a fracture control plan requires the identification of the most critical fracture mechanism or mechanisms and the factors that need to be limited or controlled so that fracture does not occur during operation. It is in the nature of components and applied loads

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[1] Risk assessment methodology used to limit catastrophic failure of an individual component, sub-system or system. Generally, this involves varying degrees of inspection and monitoring, repair, maintenance and eventual retirement. The concept is often initialised early on in the design stage by the manufacturer, but may change depending on experiences encountered during actual service.

that variations from a norm do occur. The success of a fracture control plan depends on the prediction of variation and the development of strategies to cope with uncertainty in prediction.

For the case of yielding and plastic collapse, the critical factors are:

- material properties such as yield and ultimate tensile strengths (tensile, compressive, shear, torsion);
- component stress as determined by component dimension and the nature and magnitude of applied loads;
- potential reduction in material properties due to exposure to the operating environment (e.g. softening resulting from exposure to elevated temperatures); and
- potential increase in component stress due to exposure to the operating environment (e.g. loss of cross-sectional area due to aqueous corrosion).

For the case of unstable crack propagation from a site of stress concentration the critical factors are:

- the critical stress intensity for fracture of the material under the prevailing stress state (plane stress or plane strain) and rate of loading; and
- the stress intensity at the site of stress concentrating features (this is a function of geometric detail and the nature of applied loading).

For the case of unstable extension of a pre-existing crack the critical factors are:

- the critical stress intensity for fracture of the material under the prevailing stress state and rate of loading;
- the nature of subcritical crack growth (e.g. fatigue cracking or stress corrosion cracking) and the operating parameters that affect the initiation of crack growth and the rate of crack growth; and
- the residual strength of the component as a function of crack size.

When fracture from fatigue crack growth is considered to be a threat to the integrity of a component or structure, two options may be considered during design; the specification of component strength and the control of operational stresses to avoid crack initiation (infinite fatigue life), or the development of a plan to retire the component from service after a period of operation (finite life).

A number of strategies have been developed to ensure structural integrity when a component is expected to have a finite life. A component may be removed from service after a predetermined ‘hard time’ period, known as its ‘safe life’. Structural redundancy may be provided in a manner that allows load sharing in the event of component fracture. Note: it is important that redundancy is coupled with repeated inspection for component failure as cracking may initiate and grow in the other elements of the redundant design. Finally, in the damage tolerance approach, the choice of material and design allows non-destructive inspections, at repeated intervals, to detect cracks before they reach a critical size. The component is replaced when a crack is detected.

The nature of reciprocating engines determines that those components subjected to alternating stresses are designed on the basis that their operational life is not limited by fatigue fracture – they are retired from service as a result of wear.

4.4.2 Component melting control plan

Simply, a melting control plan is based on preventing the temperature of a component reaching the melting point of the material. It should be noted that alloys melt over a range of temperatures. The critical temperature from a structural point of view is the incipient melting point.

Control of component temperature requires control of the magnitude of heat energy liberated by a process, the control of heat transfer to the component, and the control of heat removed from the component.

For an air-cooled engine, heat energy is removal from the combustion chamber by air flowing over the exterior of each cylinder head. It is important to note that the cooling system consists of the cylinder-head cooling fins, inter-cylinder baffles and engine cowling. The variable in the cooling system is the air pressure in the cowling – a function of airspeed and cowl flap position, if cowl flaps are fitted.

4.4.3 Bearing surface damage control plan

Plain bearings are used to transmit loads between rotating crankshafts, connecting rods and crankcases. These bearings operate under a hydrodynamic lubrication regime – a high-pressure oil film supports the shaft in the bearing and transmits the applied loads. Hydrodynamic lubrication is created by the slight eccentric rotation of a shaft in the bearing; a converging gap traps oil and results in the development of a localised high-pressure oil film. The critical features for successful bearing operation are; the dimensions and geometry of the shaft and bearing, the surface roughness of the shaft and bearing, and the rotational speed of the shaft in the bearing.

It is common practice for bearings to be created by assembling precision bearing inserts into a bearing housing; this practice allows the bearing surface to be replaced easily following wear.

The nature of hydrodynamic lubrication places two demands on the bearing. Firstly, surface roughness needs to be controlled to prevent oil film disruption. Secondly, a suitable metal surface needs to be provided to minimise friction and wear between the shaft and bearing for the short periods of operation when the rotational speed of the shaft is below the minima for hydrodynamic film formation (boundary lubrication regime). These periods occur at engine start-up and shutdown.

Bearing design and manufacture is governed by the requirements to provide the best bearing surface to cope with short periods of boundary lubrication and contaminants in the oil, while having sufficient strength (load endurance factor) to avoid the break-up of the surface by fatigue cracking. These requirements are met by the creation of multilayer bearing inserts, control of bearing loads, control of bearing temperatures, control of oil temperatures, and control of bearing dimensions.

The load that may be carried by a plain bearing depends on many factors, including the characteristics of the lubricant as well as the bearing. Theoretically, the oil film will not fail if the product of oil viscosity and rotational speed divided the oil film pressure does not fall below a critical value (Taylor, 1999, vol.2, p.513).

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5 FAILURE ANALYSIS METHODOLOGY

5.1 Introduction

The task of analysing engineered-system failure is, essentially, one of reconstructing an event sequence against a background of system design, manufacture, assembly, operation and maintenance (Romeyn, 2002, 2004, 2006).

Traditionally, investigations of engineered-system failure have involved the gathering of facts; what happened, what failed, how did it happen, how did it fail? More recently, there has been a greater emphasis placed on determining why failures occur. The issue of determining why is easy to say but is it easy to do? What do we need to learn and how do we learn it? How do we know when we have learnt it? How do we achieve system correction? Finally, why do failures continue to occur?

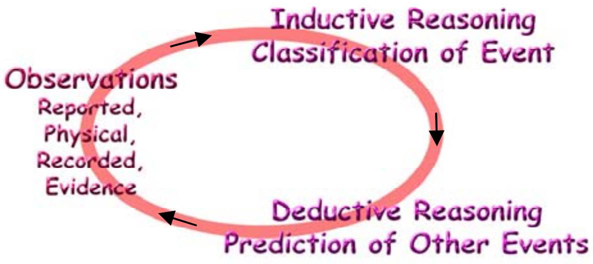
Failure analysis, in the context of transport systems, is the descriptive term for the process of feedback that aims to correct safety-critical subsystems and system elements to achieve the system goal of safe operation. In keeping with all other feedback processes, it operates through information linkages. These linkages are human-based and involve the processes of information capture, information processing, and interaction with others who may be required to change subsystems or system elements.

5.2 Methodology

In keeping with many other fields of study and pursuits of learning, a method is used to provide the framework for failure analysis.

For occasions where learning is initiated by a past event, analysis begins with observations (physical, recorded and reported evidence), followed by the development of more general statements regarding patterns of behaviour or classification of events into groups that have similar characteristics and mechanisms of behaviour, before developing a hypothesis and drawing conclusions. This method is commonly used in science and employs inductive reasoning in the initial stages. It is different to another research method that seeks to establish if a theory applies to a particular circumstance or behaviour through a process of hypothesis development and testing.

Figure 5.1: Relationships between observation and reasoning



5.3 Information gathering

Information gathering (information capture and processing) can be divided further into the processes of seeing, classifying, communicating, evaluating, and analysing.

5.3.1 Seeing

The most important features of seeing are the mental images created in response to sensory input. Seeing is much more than the physical process of image formation. Features in our environment are brought to our sense of sight for recognition and quantification through a variety of tools; simple lens, electron microscope, thermometer, and all manner of instrumentation.

All day and every day we are receiving information from our sensory organs. The decisions and judgements we make are based on the information received and the ways in which we adapt to, and deal with, new information. Some information is sensed as immediately useful and is acted on. Much is sensed as not immediately useful; we are aware of receiving it but we do nothing about it. Other information is received without any conscious awareness. Successful detectives differ from less successful ones in their ability to perceive the relevance of information, which the rest of us ignore, regard as irrelevant, or do not see, to the solution of their problem (Johnson Abercrombie, 1969). It is important to be able to see the detail of system element construction and behaviour as well as the construction and behaviour of subsystems in the context of an overview of system expectations and reality; goal – output matching.

The process of seeing is dependent on individual traits and abilities. These traits and abilities give rise to variability in information gathering that extends to variability in the effectiveness of feedback control. The success of analyses depends on the mental processes and knowledge of the analyst.

> What one sees or observes depends on what one knows and understands (Hull, 1999).
>
> And the new object presented to Sense, or a new idea presented to Thought, must also be soluble in old experiences, be re-cognized as like them, otherwise it will be unperceived, uncomprehended (Lewes, 1879).

5.3.2 Classifying

Every person has a store of information. As a result of seeing, listening, reading, reflecting on our experiences, and reasoning, we acquire both information and misinformation. Every person also has persistent deep-rooted ways of classifying information, thinking, perceiving, and behaving. The process of classifying is the process of matching observations with our prior store of information. The effect of personal assumptions, bias, and preconceptions can lead to classifications that differ from those made by others.

The strength of the process of classification is in its ability to tap into knowledge developed in other places and at other times. It also allows logically valid inferences to be made on the basis of experiences from the operation of other systems and the conduct of prior, controlled, experiments.

Classification of event significance is a process that creates a dilemma. Classification for significance is conducted against a relevance pattern that may be an individual norm, an industry norm, or a societal norm. If an event is considered to be of low significance, the information is discarded. If an event is considered to be of moderate significance, the information is averaged and stored in compressed form. If an event is considered to be of high significance, the information is selectively amplified and used immediately to assess and revise subsystem and system element performance.

In a complex system, such as a transport system, the presence of redundancy and other strategies to minimise the effect of critical subsystem or system element failure on system safety, creates a dilemma of significance. Subsystem or system element failure with no catastrophic outcome may be viewed as a measure of the robustness of the system, or it may be viewed as an example that the system is operating in ways not anticipated during its creation. Additionally, in a complex system with multiple strategies to minimise the effect of safety-critical subsystem system or system element failure, an immediate threat to wellbeing is not always created through subsystem or system element failure. However, it has been well recognised that lesser events can, in combination with other events and circumstances that may be extremely difficult to predict, create a threat to wellbeing at some other time (O’Hara, 2004). There is value in acting to prevent system failure through correcting subsystem and system element failure rather than reacting to system failure.

> In judging the severity of the event, it is important to understand the actual consequences that the observed event had on airplane operation. It is even more important, however, to understand the potential consequences if the event had occurred in more vulnerable circumstances. (SAE ARP5150)

The classification of solid rocket booster O-ring erosion and external fuel tank foam strike damage as nagging issues, of seeming little consequence, was initially taken as evidence that the Space Shuttle design was capable of operating successfully with these design deviations. They were not taken as signals of potential danger. The significance of O-ring erosion, and 17 years later, foam debris strikes, became clear in retrospect, after lives had been lost (Columbia Accident Investigation Board, 2003).

5.3.3 Communicating

Knowledge and understanding are gained through interactions between other analysts, designers and operators of systems, and other members of society with specialised knowledge. The critical issue is about gathering proper answers to the right questions. Formulating the right questions requires a broad knowledge of system structures, interactions and control hierarchies, and a common technical language. The use of technical descriptors can be a source of confusion when different meanings are attached to the same descriptor.

Effective feedback is dependent on the creation of an information linkage, through oral and written communication between the analysts, designers, and operators of engineered systems. The dependence on oral and written communication is a potential barrier to effective feedback. Communication across professional groupings and disciplines is affected by the culture, preconceptions and, possibly bias, of each grouping.

5.3.4 Evaluating

Evidence associated with an event needs to be evaluated from the viewpoint of the system structural and control hierarchies in order to resolve what subsystem or system element failure led to the threat to safe operation.

Successful evaluation comes from the conscious consideration of many possible cause and effect linkages rather than jumping to a conclusion without considering the evidence for alternate cause and effect linkages. Important discoveries in science provide clear examples of making use of information that had previously been regarded as unimportant or useless. The ability to address new problems depends on the ability to make new associations between information where, previously, there have been no conventional or traditional relationships.

5.3.5 Analysing

Cause and effect linkages associated with an event need to be analysed to determine what designed subsystem or system element controls and limits were ineffective, inoperative, or not present. Analysis requires knowledge of the normally hidden internal variables within a system and a deeper knowledge of subsystem and system element behaviours that are normally treated as black-box abstractions.

Analysis is a process of learning. Learning implies the gaining of knowledge; in the case of failure analysis, the gaining of knowledge that allows a system to continue to achieve the goal of safe operation. The process of learning is a key variable in achieving effective feedback control.

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6 POWERTRAIN FAILURE OCCURRENCES – 2000-2005

6.1 Introduction

During the period, January 2000 to December 2005, 20 in-flight engine failures occurred in Australia. Each in-flight engine failure was caused by the structural failure of a powertrain component. An overview of both the frequency and nature of these occurrences is shown in figure 6.1.

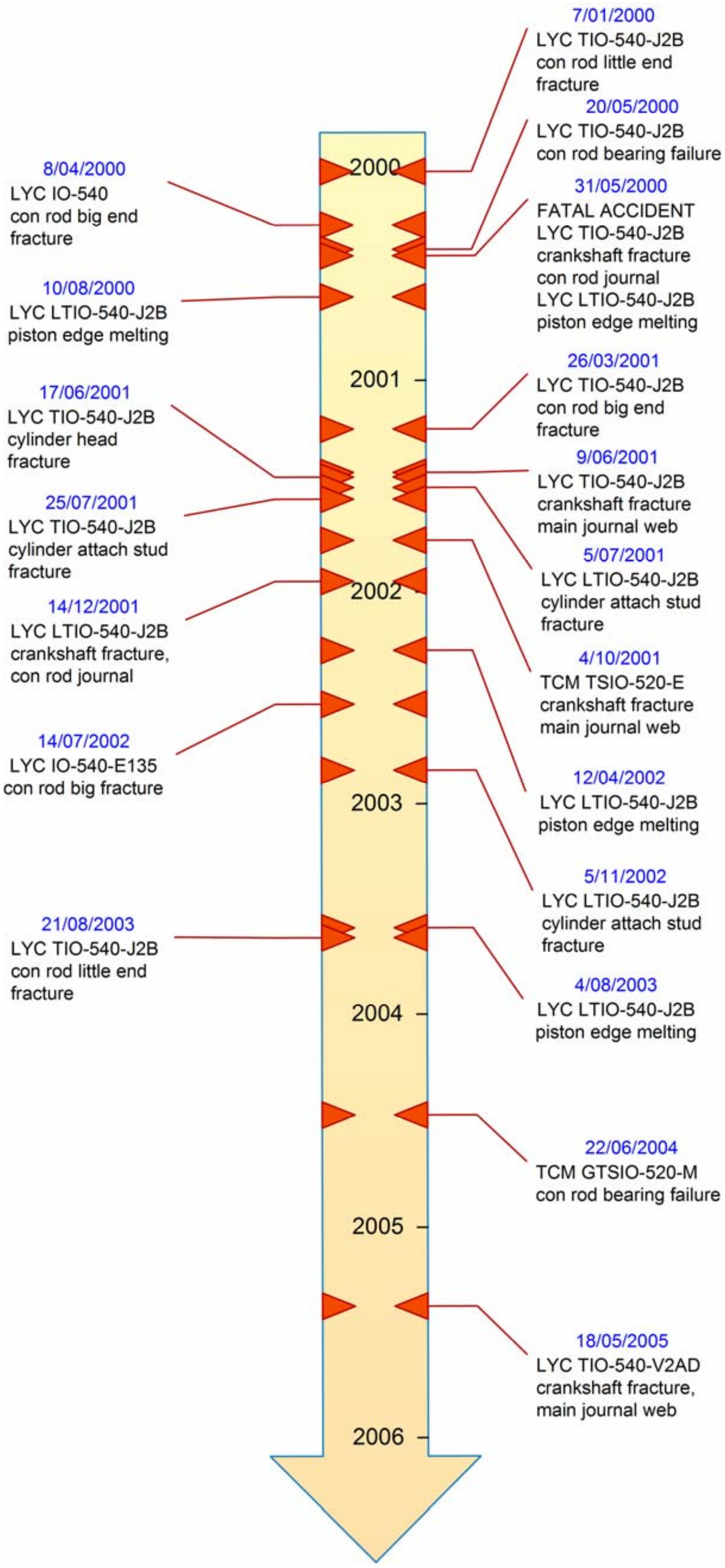
The distribution of reported powertrain failure occurrences over the six-year period was not uniform. There were five occurrences in 2000 (one involved the structural failure of both engines), seven occurrences in 2001, three occurrences in 2002, two occurrences in 2003, one occurrence in 2004, and one occurrence in 2005.

Sixteen of the 20 failures involved Lycoming TIO-540-J2B(D) engines fitted to Piper Chieftain aircraft, two failures involved Lycoming IO-540 engines, one fitted to an Aero Commander and one fitted to a Piper PA32, one failure involved a Teledyne Continental Motors TSIO-520-E engine fitted to a Cessna 402B, and one failure involved a Teledyne Continental Motors GTSIO-520-M engine fitted to a Cessna 404.

It is also evident from the reported occurrences that structural failure was not restricted to a particular powertrain component. The failures involved cylinder head fracture, piston edge melting, connecting rod little-end fracture, connecting rod big-end fracture, cylinder attachment stud fracture, bearing failure, and crankshaft fracture.

For each reported occurrence of powertrain structural failure, the available evidence is examined to identify the key event in the failure sequence and classify the structural failure mechanism. The occurrences are grouped according to the structural subsystems affected, combustion chamber, connecting rod, crankshaft, bearings. The evidence examined for each occurrence consists of; reported evidence (pilot statements, witness reports and maintenance records), physical evidence (an examination of engine components), and where available, data relating to engine and aircraft performance that had been recorded electronically.

Figure 6.1: Timeline of powertrain structural failure occurrences for the period January 2000 to December 2005



6.2 Combustion chamber assembly failures

The typical form of combustion chamber structures for air-cooled aircraft reciprocating engines is a cast aluminium alloy cylinder head connected to a steel barrel, with an aluminium alloy piston. The cylinder barrel is attached to the crankcase by a number of threaded fasteners.

The discontinuous nature of combustion in a reciprocating engine and the heating and cooling that accompanies each period of engine operation (start/stop cycle), creates cyclic stresses in various elements of the combustion chamber structure. Cyclic stresses, developed through cyclic pressures and cyclic, differential, expansion and contraction, create a threat to structural integrity through the possibility of fatigue crack initiation and propagation.

Because heat is liberated during combustion, a mechanism to transfer heat away from the combustion chamber is required in order to maintain the temperature of structural elements to design-allowable temperatures. The failure to transfer heat effectively creates a risk of material softening or melting.

Table 6.1: Combustion chamber failure occurrences, period 2000 to 2005

Occurrence Number	Occurrence Date	Aircraft Registration (Engine type)	Component Failure
2000/2157	31 May 2000	VH-MZK (right) Lyc LTIO-540-J2B	No.6 Cylinder head and piston melting
2000/3675	10 Aug 2000	VH-NPA Lyc LTIO-540-J2B	No.6 Piston melting
2001/2885	17 Jun 2001	VH-MJA Lyc TIO-540-J2B	No.1 Cylinder head fracture
2001/3357	5 Jul 2001	VH-RNG Lyc LTIO-540-J2B	No.4 Cylinder attachment stud fracture
2001/3251	25 Jul 2001	VH-FIA Lyc TIO-540-J2B	No.2 Cylinder attachment stud fracture
2002/2059	12 Apr 2002	VH-LTW Lyc LTIO-540-J2B	No.3 Piston melting
2002/5129	5 Nov 2002	VH-TZY Lyc LTIO-540-J2B	No.4 Cylinder attachment stud fracture
2003/3532	4 Aug 2003	VH-HJS Lyc LTIO-540-J2B	No.5 piston melting

6.2.1 Occurrence 2000/2157 VH-MZK (right engine)

Reported evidence

VH-MZK was forced to land on water, at night, following the failure of both engines. All passengers and crew were fatally injured.

Time since overhaul: 1,395 hours

Physical evidence

Examination of the right engine revealed that melting of a region of the No.6 piston edge allowed combustion gases to bypass the piston rings, see figure 6.2.

Figure 6.2: No.6 piston, MZK right, overview of the piston crown and a detailed view of the region of localised melting

In addition to the melting of the piston edge, localised melting had affected a localised region of the cylinder head, see figure 6.3. Melting occurred in the region between the upper spark plug hole and the edge of the exhaust valve. Heat transfer from this region is affected by the presence of the port between the exhaust valve and cylinder head exhaust flange. The separation of this region from the air-cooled surfaces of the remainder of the cylinder head, results in a higher temperature in this region of the cylinder head. When cylinder head temperatures are increased generally, the region between the upper spark plug and exhaust valve will be first to reach the melting point of the cylinder head alloy.

Figure 6.3: No.6 cylinder head, MZK right, overview of the combustion chamber surface and a detailed view of the region of localised melting

Examination of the remaining five pistons from the engine revealed that the No.5 piston displayed evidence of piston edge distress from exposure to high temperatures, see figure 6.4.

Figure 6.4: No.5 piston, MZK right, region of edge distress (arrowed) and a metallographic section taken through the piston edge

The metallographic section is oriented with the piston crown to the right and the piston side to the top. The microstructural features indicate that material is breaking away from the piston edge as a result of extensive softening of the edge and the forces developed during engine operation.

Recorded evidence

Evidence of aircraft performance was limited to that derived from recorded radar data and recorded voice transmissions between the pilot and ground stations. This class of aircraft is not required to be fitted with a flight data recorder or a cockpit voice recorder. While the data relating to aircraft operation and flight performance is limited, useful data on the performance of the aircraft propulsion system was obtained.

The takeoff, climb, and the cruise phases of flight were recorded by two radar sensors – Adelaide and Summertown. Altitude, aircraft heading and groundspeed data was recorded every 3.6 seconds – the period relates to the period of radar sensor rotation. This frequency of data collection is sufficient to establish performance trends, such as, rate of climb, but insufficient to detect changes in performance parameters over periods of less than, approximately, 12 seconds.

During radio transmissions between the pilot and ground stations, other sounds in the cockpit will be transmitted when the pilot's microphone is keyed. One background sound that is of use to the investigation of propulsion system performance, is the sound created by the aircraft's propellers. The sound created by propellers is characterised by discrete frequencies occurring at harmonics of the blade passing frequency, a function of the number of blades and the propeller speed (Lan and Roskam, 1988). The sound level, for a particular propeller design, increases with absorbed power and increased tip speed. Data on propeller/engine speed obtained from audio analysis relates, only, to the period that the pilot's microphone is open – the data relates to short intervals of flight.

A comparison was made between the flight performance, as recorded by radar, of several Piper Chieftain (PA 31-350) aircraft, departing Adelaide airport, prior to and following the flight where both propulsion systems failed on MZK.

A plot of altitude versus flight time is shown in figure 6.5. The ground track of each aircraft is shown in figure 6.6. The details of each flight are:

- MZK departing Adelaide at 0530 UTC, 31 May 2000, for Port Pirie – VH-MZK YPAD-YPIR
- MZK departing Adelaide at 0850 UTC, 31 May 2000, for Whyalla (accident flight) – VH-MZK YPAD-YWHA
- NPB departing Adelaide at 1030 UTC, 31 May 2000, for Port Pirie – VH-NPB YPAD-YPIR
- AZJ departing Adelaide at 2140 UTC, 31 May 2000, for Leigh Creek – VH-AZJ YPAD-YLEC

Note: local time in Adelaide was Australian Central Standard time (Australian Central Standard time is 0930 hours ahead of Coordinated Universal time, UTC).

It is evident that the takeoff and climb phase of flight for the accident flight (MZK YAD-YWHA) was normal and comparable to climb phases for the other flights, given variations in aircraft weight. The rate of climb was constant to cruising altitude. Climb performance is a direct function of propulsion system performance. Any pilot-commanded change in propulsion system settings or any propulsion subsystem/component loss of function will be reflected by a change in the rate of climb.

Figure 6.5: **Altitude versus flight time profiles to the limit of radar coverage, radar data recorded for Piper PA31-350 aircraft operating out of Adelaide (31 May 2000)**

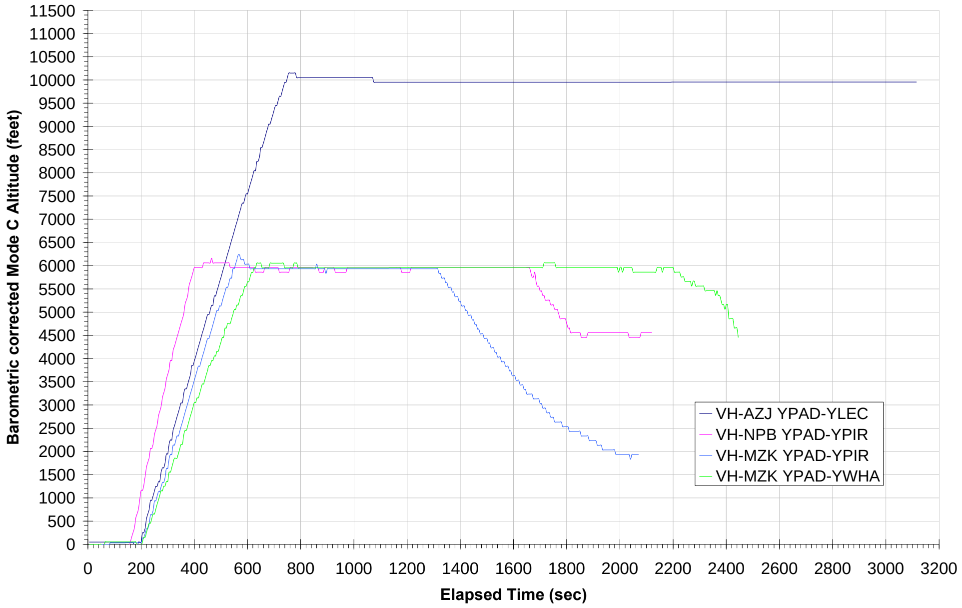
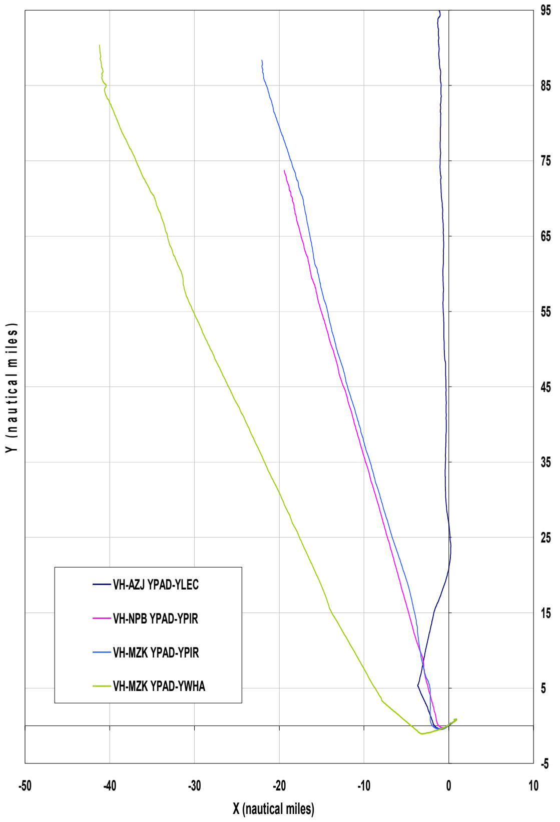


Figure 6.6: **Ground tracks, radar data recorded for Piper PA31-350 aircraft operating out of Adelaide (31 May 2000)**



A detailed examination of the parameters of altitude, ground speed and heading for the accident flight (MZK) indicated that the initial section of the cruise phase of flight was normal. However, it is evident that, 17 minutes after top-of-climb, there was a short-term deviation in heading (approximately two minutes) accompanied by a sustained drop in ground speed. The event responsible for the deviation in heading and reduction in ground speed may have been the sudden failure of one engine. It is important to note that the deviation in heading does not represent the direction of aircraft yaw that would be expected to accompany a sudden engine failure in a twin-engine aircraft. The deviation in heading may be a consequence of a control response to an engine failure, and may be an under or over correction.

Analysis of the available audio transmissions indicated that during climb the propeller speed was 2,400 rpm, the normal propeller speed for climb. During cruise four minutes after the top-of-climb, the propeller speed was 2,200 rpm, the normal propeller speed setting for cruise. However, eight minutes after the event that initiated the heading deviation and ground speed decrease, audio analysis indicated that the propeller speed was 2,400 rpm, an abnormal propeller speed for the cruise phase of flight.

Figure 6.7: Altitude, ground speed, and heading for VH-MZK, accident flight

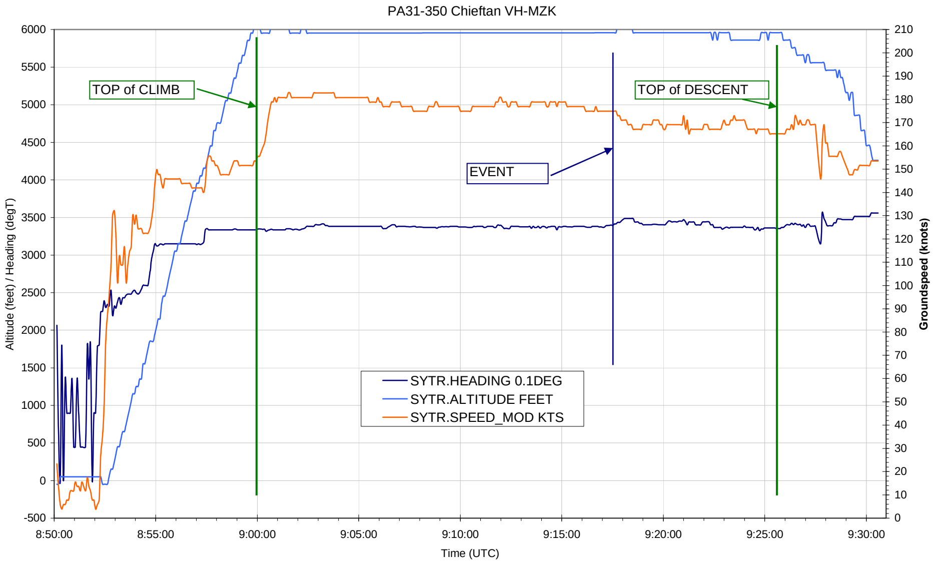
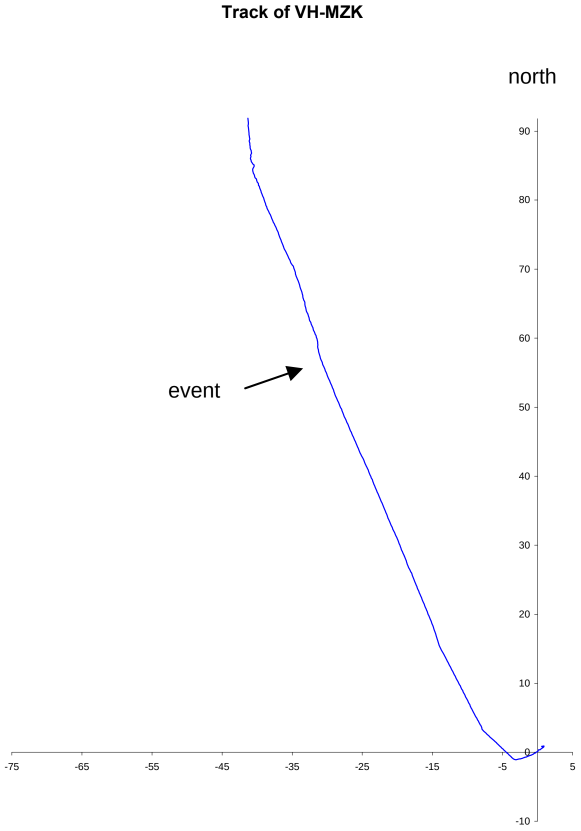


Figure 6.8: Ground track for VH-MZK, accident flight, polar plot



Fourteen minutes after the event that resulted in a deviation in heading and a reduction in groundspeed, the pilot made a Mayday transmission – ‘both engines failed’.

The failure of the left engine involved:

- the separation of the destruction of the No. 6 connecting rod big-end bearing inserts;
- the fatigue fracture of the No. 6 connecting rod big-end bearing housing;
- a forceful collision between the No. 6 piston and the cylinder head;
- the collision between the No. 6 connecting rod and the camshaft leading to the fracture of the pneumatic pump drive coupling and holing of the crankcase; and
- the fatigue fracture of the No. 6 connecting rod crankshaft journal.

See pages 78-85 of this report.

6.2.2 Occurrence 2000/3675 VH-NPA

Reported evidence

The pilot noted that the right-engine oil pressure was low and decreasing, the engine oil temperature had increased during the course of recording engine instrument readings for trend monitoring (cruise phase of flight). Oil was observed to be streaming from the engine nacelle skin joints and vent. The right propeller was feathered and the engine shutdown.

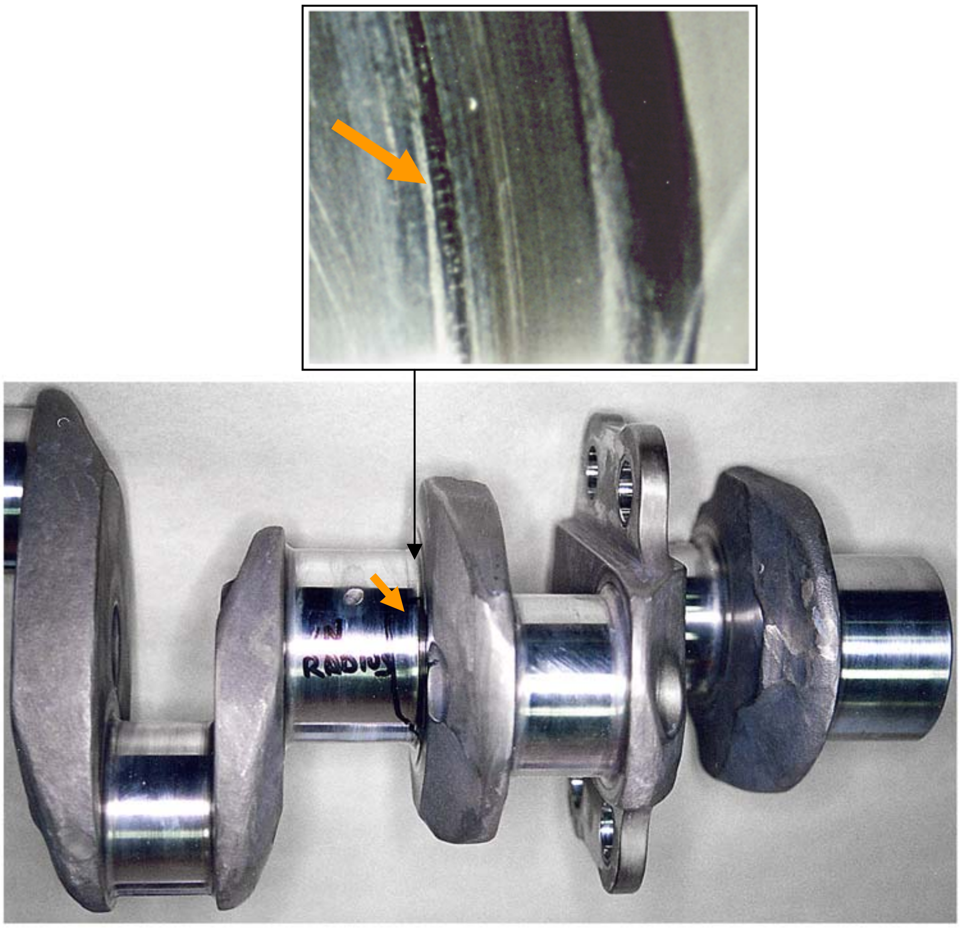
Physical evidence

Examination of the engine revealed that the engine had malfunctioned and lost power because of the loss of piston sealing through the melting of a section of the No.3 piston edge, see figure 6.9. In addition, localised melting of the cylinder head had occurred in the region between the upper spark plug and exhaust valve.

Figure 6.9: No.3 Piston and cylinder head, NPA, showing the regions of localised melting

During an inspection of the remaining components of the engine, the presence of cracking in the No.4 main bearing journal fillet radius of the crankshaft was discovered. The cracking comprised of a series of short cracks, oriented parallel with the journal axis, in the fillet between the journal and the No.4 main/No.5 connecting rod web, see figure 6.10. Cracking of this nature occurs as a result of sliding contact between the main bearing inserts and the journal fillet radius, following the displacement of the inserts from their normal position in the main bearing housing during engine operation.

Figure 6.10: Cracking in the fillet between the No.4 main bearing journal and the No.4 main/No.5 connecting rod web



The location of cracking is arrowed. The nature of cracking is shown in the inset.

6.2.3 Occurrence 2001/2885 VH-MJA

Reported evidence

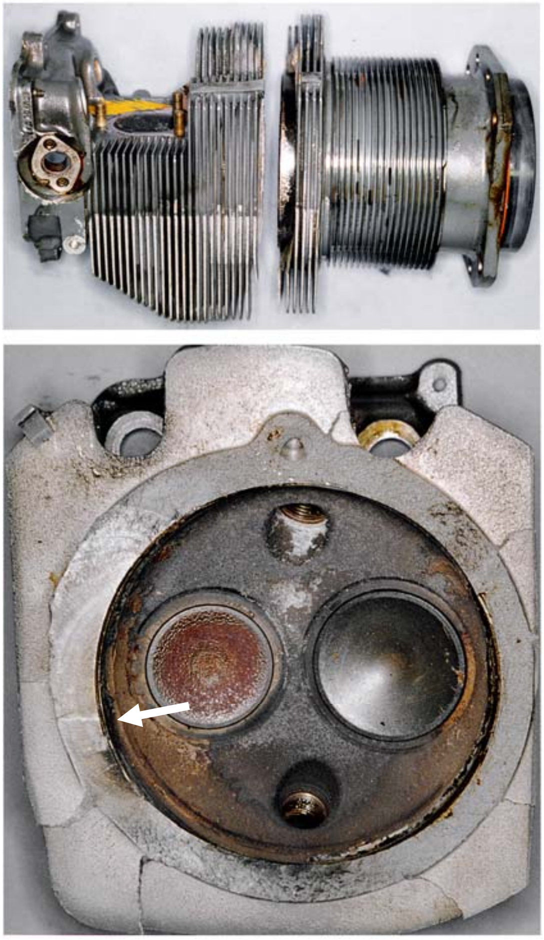
The left engine of a Piper Chieftain malfunctioned approximately 4 minutes after takeoff. The pilot heard a 'thud' from the left engine and sensed a slight yaw to the left. A reduction in manifold pressure was observed. However, no signs of smoke or oil loss were observed. The engine was not shutdown following the malfunction or during the return to the airfield.

Time since overhaul: 1,352 hours

Physical Evidence

Inspection of the engine revealed that the head of the No.1 cylinder had separated from the cylinder barrel, figure 6.11. The fracture of the cylinder head occurred as a result of fatigue crack propagation through the cylinder head wall from the location of the threaded connection between the head and barrel on the exhaust valve side of the cylinder.

Figure 6.11: The fractured No.1 cylinder, the site of fatigue crack initiation is arrowed



6.2.4 Occurrence 2001/3357 VH-RNG

Reported evidence

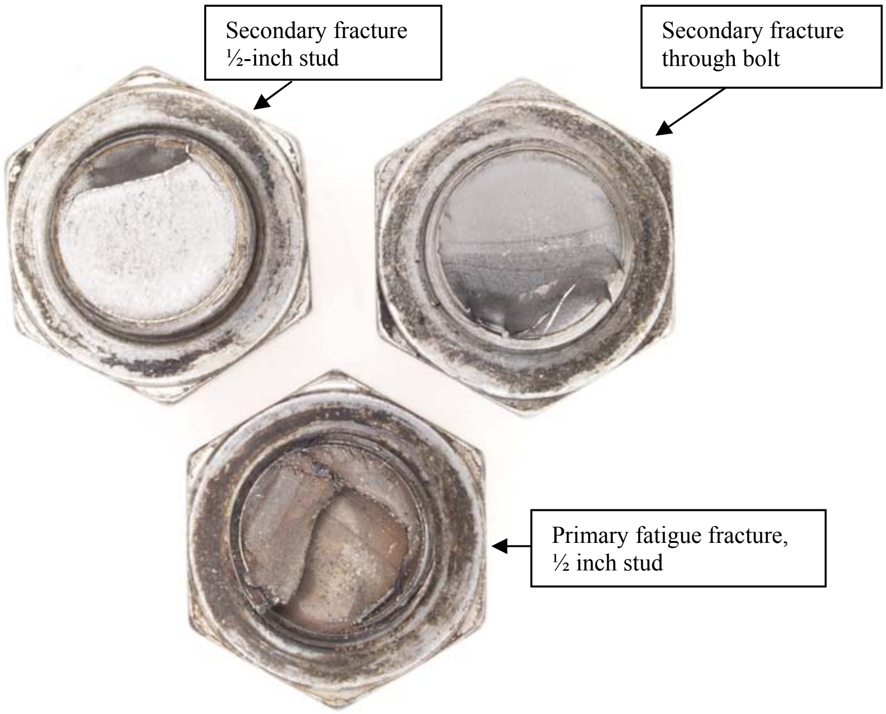
Shortly after takeoff, the right engine of a Piper Chieftain malfunctioned. The pilot observed a drop in the manifold pressure in the right engine and oil streaking on the engine cowl. The engine was shutdown and the aircraft returned to land at the airfield.

Time since overhaul: 623 hours

Physical evidence

Examination of the engine revealed that the No.4 cylinder had partially separated from the crankcase following the fracture of seven of the cylinder hold down fasteners, see figure 6.12. The sequence of fastener fracture commenced with the initiation and propagation of fatigue cracks in one of the two ½ inch studs. Fatigue cracking initiated at the root of the first thread in from the face of the nut and, subsequently, at the root of the thread adjacent to the face of the nut, figure 6.12.

Figure 6.12: The two fractured ½-inch studs and the fractured through-bolt



The remaining ½-inch stud and, one of the two ½-inch through bolts, fractured as a result of fatigue crack growth and fastener load redistribution following the initial ½-inch stud fracture. The smaller, ⅜-inch, studs fractured as a result of fastener load redistribution, figure 6.13. The second through-bolt remained intact.

Figure 6.13: General view of the recovered cylinder base attachment fasteners

6.2.5 Occurrence 2001/3251 VH-FIA

Reported evidence

During climb through 1,200 ft, the pilot noticed a reduction in power in the left engine. A visual inspection of the left engine from the cockpit revealed oil streaking on the engine cowl. The engine was shutdown and the aircraft returned to the airfield.

Physical evidence

Examination of the engine revealed that the No.2 cylinder assembly had become detached from the crankcase following the initiation and propagation of fatigue cracking in both ½-inch studs. Fatigue cracking was extensive, extending to approximately 80% of the diameter of each stud, figure 6.14. The four ⅜-inch studs fractured as a result of fastener load redistribution following the fracture of the ½-inch studs.

Figure 6.14: The two fractured ½ inch studs

Figure 6.15: The four fractured ⅜ inch studs

6.2.6 Occurrence 2002/2059 VH-LTW

Reported evidence

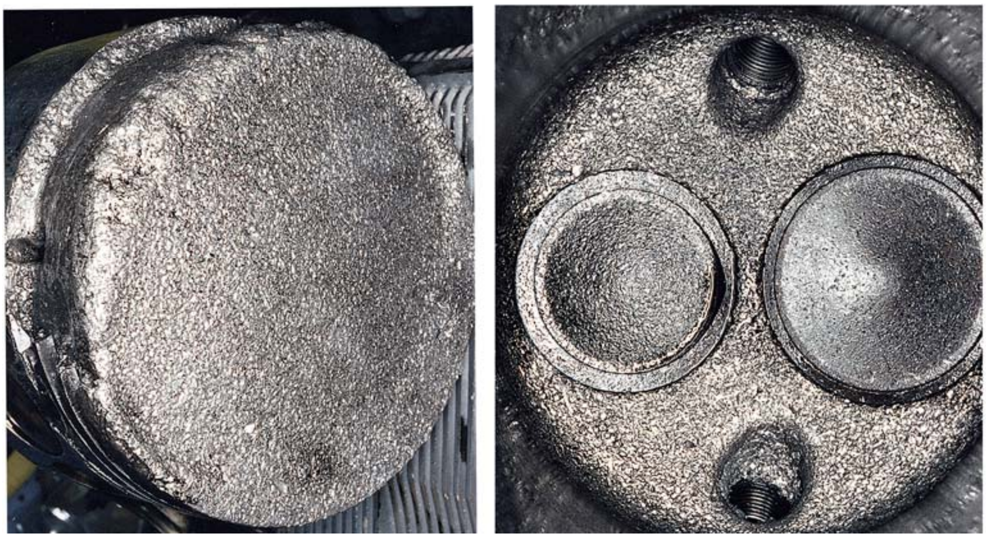
The pilot of a Piper Chieftain became aware of a slight engine vibration during climb, passing through 2,500 ft. The engine instruments were checked and readings were found to be within the normal operating range. Approximately one minute later the right engine surged and the manifold pressure decreased to approximately 26 inches of mercury. No change in engine performance occurred when the throttle was opened fully, the mixture adjusted to rich and the propeller speed increased to give a fine pitch. A decision was made to return to the airport (seven minutes flight time by GPS). On descent, the right engine manifold pressure fluctuated between 26 and 31 inches of mercury. During the completion of pre-landing checks it was noted that the right engine oil temperature was above the maximum allowed and the oil pressure below minimum allowed. The right engine cylinder head temperature was normal. The propellers could not be synchronised. After landing, the smell of burning oil was noted and oil staining on the right engine cowls was observed. Once clear of the runway, both engines were shutdown following the normal checklist procedures.

Physical evidence

Examination of the engine revealed that the edge of the No.3 piston crown had melted and the piston rings had fractured into many small pieces, figure 6.16. Approximately 1 litre (1.06 US Quarts) of engine oil remained in the engine sump – the maximum capacity of the engine is 11.4 litres (12 US quarts) and the minimum safe quantity is 2.6 litres (2.75 US quarts). The No.3 fuel injector nozzle was examined and found to be free of any obstruction.

Figure 6.16: The No.3 piston, as removed from the engine

Figure 6.17: **The No.3 piston and cylinder head showing the extent of damage created by the fragmented piston rings**



6.2.7 Occurrence 2002/5129 VH-TZY

Reported evidence

The pilot of a Piper Chieftain observed a small drop in manifold pressure in the right engine during climb. Visual inspection of the engine from the cockpit revealed oil streaking on the engine cowl.

Time since overhaul: 1699 hours

Physical evidence

Examination of the engine revealed that seven of the eight cylinder base attachment fasteners on the No.4 cylinder had fractured. The primary fracture was caused by the initiation and growth of a fatigue crack in one of the two ½-inch studs (upper left figure 6.18) Fatigue propagated to approximately 80% of the stud diameter. The remaining ½-stud and one through bolt fractured as a result of fatigue cracking under conditions of increased alternating stress developed by load redistribution after the primary fracture.

Figure 6.18: The fractured ½ inch studs (top – the primary fatigue fracture is on the left) and the fractured through bolt (bottom)

6.2.8 Occurrence 2003/3532 VH-HJS

Reported evidence

The pilot of a Piper Chieftain observed that, while leaning in cruise, the right engine manifold pressure and oil pressure dropped accompanied by increase in the exhaust gas temperature. The pilot also noticed that the engine was ‘smoking’. The engine was shutdown.

Time since overhaul: 1,135 hours

Physical evidence

Examination of the engine revealed that the edge of the No. 5 piston had melted to an extent that combustion gases could bypass the piston seal, figure 6.19. No localised melting of the cylinder head in the region between the upper spark plug and exhaust valve had occurred.

Figure 6.19: The No. 5 piston and cylinder head

6.3 Connecting rod assembly failures

6.3.1 Introduction

Connecting rods provide the means of transferring the reciprocating motion of the pistons to the rotary motion of a crankshaft. The primary loads imposed on a connecting rod during engine operation are related to combustion gas pressures and inertia forces.

Because loads are being transferred between components moving relative to each other – the connecting rod little-end oscillates about the piston pin, and the crankshaft journal rotates within the connecting rod big-end – bearings are needed at both ends of the connecting rod.

The bearings used in aircraft reciprocating engines are plain bearings. Two types of plain bearing are used in engines with a horizontally-opposed cylinder layout. A bronze bush is used to provide the bearing surface between the piston pin and the connecting rod. A precision insert, comprising of a number of bonded metallic layers, is used to provide the bearing surface between the connecting rod and the crankshaft. The differences in bearing type and size relate to the differences in sliding speed and the constraints imposed by engine assembly.

Table 6.2: Summary of occurrences involving connecting rod failure

Occurrence Number	Date of Occurrence	Aircraft registration and Engine Type	Component Failure
2000/90	7 Jan 2000	VH-MZK Lyc TIO-540-J2B	No.1 con rod little-end fracture
2000/1327	8 Apr 2000	VH-BNN Lyc IO-540	No.4 con rod big-end fracture
2001/1405	26 Mar 2001	VH-LTW Lyc TIO-540-J2B	No.2 con rod big-end fracture
2002/3474	14 Jul 2002	VH-ACZ Lyc IO-540-E135	No.4 con rod big-end fracture
2003/2701	21 Aug 2003	VH-OCF Lyc TIO-540-J2B	No.6 con rod little-end fracture

6.3.2 Occurrence 2000/90 VH-MZK (left engine)

Reported evidence

During the cruise phase of flight, the pilot heard a bang from the left engine. The left engine then stopped and the propeller feathered. A visual inspection of the engine from the cockpit revealed that the engine cowling had been damaged. The aircraft was forced to land.

Time since overhaul: 1,673 hours

Figure 6.20: The extent of damage to the engine cowling caused by the forceful separation of the No.1 cylinder assembly

Physical evidence

Examination of the engine revealed that the No.1 cylinder had separated from the crankcase. An internal examination revealed that the No.1 connecting rod little-end had fractured.

Figure 6.21: The No.1 cylinder 'as recovered'

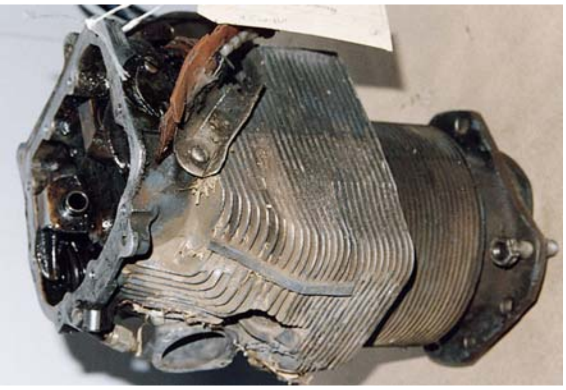


Figure 6.22: The No.1 connecting rod showing the fractured little-end housing

While the remnant of the little-end housing had been damaged extensively and the rest of the housing was lost during the engine failure, it is evident that the nature of the failure is consistent with the development of fatigue in the housing.

It is unlikely that the failure of the little-end housing was the result of a single load application. The fracture occurred during cruise, a phase of flight during which the inertia forces imposed on the little-end housing are lowed through the reduction in engine speed from the engine speeds used during takeoff and climb.

There is evidence that the little-end bearing had been destroyed during a period of engine operation prior to the fracture of the housing. Galling (adhesive wear) was present on the surface of the No.1 piston pin in the region where it bears against the little-end bearing. Galling occurs when the steel piston pin bears against the steel inner surface of the housing. The surface damage created by galling is known to be a potent initiator of fatigue cracking.

Figure 6.23: **Galling (adhesive wear) on the No.1 piston pin**

An overview of piston pin wear, with the piston in situ in the No.1 piston, is shown at the top of the figure. Detailed views of two regions of galling are shown at the bottom of the figure.

6.3.3 Occurrence 2000/1327 VH-BNN

Reported evidence

During the cruise phase of flight, the pilot of the single-engine aircraft (Piper Lance) noticed that the vacuum pump warning light had illuminated and the vacuum gauge reading had dropped to zero. The pilot also reported that the engine started to vibrate. While completing troubleshooting checks the propeller stopped. The aircraft was forced to land on a suburban beach.

Time since overhaul: 1,300 hours

Physical evidence

Examination of the engine revealed that the No.5 connecting rod big-end had fractured.

Figure 6.24: The remnants of the No.5 connecting rod recovered form the engine

The recovered fragments of the big housing (top left), some of the larger fragments of the bearing inserts (top right), detailed view of both housing fractures at the transition to the rod 'I' beam (bottom). The sites of fatigue initiation are arrowed.

It is evident that the initial fracture of the big-end housing occurred as a result of fatigue crack growth from the outer surface to the inner surface of the housing. The sites of fatigue crack initiation are associated with the regions of reduced cross-section created by the counterbore at the transition between the housing and the connecting rod 'I' beam.

It is also evident that the big-end bearing inserts had been destroyed prior to the fracture of the housing. There are two significant features of the bearing insert destruction. Firstly, the separation and fragmentation of the aluminium-tin/lead-tin bearing alloy layer from the steel backing. Secondly, the steel backing of the inserts had been uniformly reduced in thickness through a process that involved the extrusion of the steel backing through the gap between the big-end housing and crankshaft journal.

6.3.4 Occurrence 2001/1405 VH-LTW

Reported evidence

The pilot became aware that the left engine was running ‘roughly’ at the top-of-descent. An initial check of the engine instruments showed no abnormal readings, however, within 30 seconds of the indication of rough running, the engine failed. The engine was shutdown and the propeller feathered in accordance with emergency procedures.

Time since overhaul: 1,035 hours

Physical evidence

Examination of the engine revealed that the No.2 connecting rod big-end had fractured.

Figure 6.25: The recovered No.2 connecting rod and piston

Detailed views of both fractures in the big-end housing, at the transition between the housing and rod ‘I’ section (bottom). The sites of fatigue crack initiation are arrowed.

It is evident that the initial fracture of the big-end housing occurred as a result of fatigue crack growth from the outer surface to the inner surface of the housing. The sites of fatigue crack initiation are associated with the regions of reduced cross-section created by the counterbore at the transition between the housing and the connecting rod ‘I’ beam.

It is also evident that the big-end bearing inserts had been destroyed prior to the fracture of the housing. The aluminium-tin/lead-tin bearing alloy layer had separated from the steel backing. The steel backing of the inserts had been uniformly reduced in thickness through a process that involved the extrusion of the steel layer through the gap between the big-end housing and crankshaft journal.

6.3.5 Occurrence 2002/3474 VH-ACZ

Reported evidence

The pilot noticed that the left engine was vibrating with increasing intensity during cruise. The engine malfunction culminated in a loss of power and yaw, at which point, the pilot shutdown and secured the left engine.

Time since overhaul: 157 hours

Physical evidence

Examination of the engine revealed that the No.4 connecting rod big-end had fractured.

Figure 6.26: The No.5 connecting rod recovered from the engine

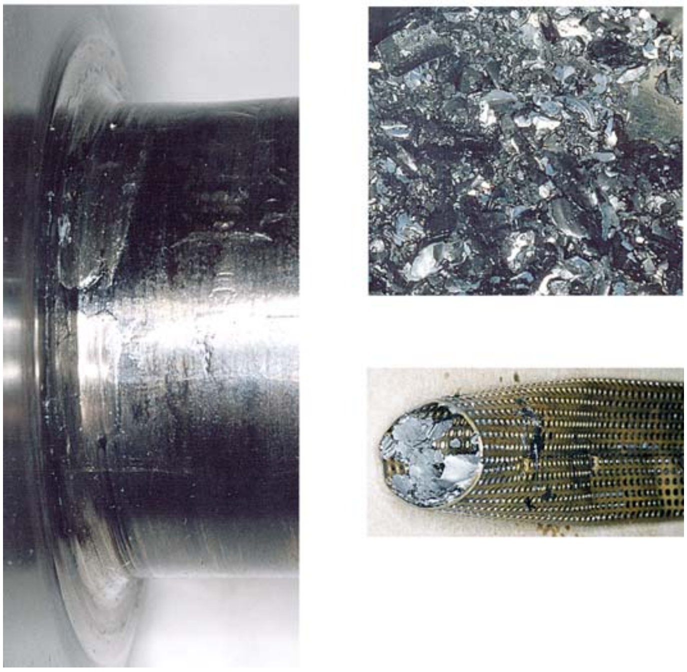
Some of the larger fragments of bearing inserts recovered from the debris in the engine sump are shown (bottom right).

Figure 6.27: **Detailed views of the fractures in the big-end housing at the transition between the housing and rod ‘I’ section**

It is evident that the initial fracture of the big-end housing occurred as a result of fatigue crack growth from the outer surface to the inner surface of the housing. The sites of fatigue crack initiation are associated with the regions of reduced cross-section created by the counterbore at the transition between the housing and the connecting rod ‘I’ beam.

It is also evident that the big-end bearing inserts had been destroyed prior to the fracture of the housing. The aluminium-tin/lead-tin bearing alloy layer had separated from the steel backing. The steel backing of the inserts had been uniformly reduced in thickness through a process that involved the extrusion of the steel layer through the gap between the big-end housing and crankshaft journal.

Figure 6.28: **Detailed views of the crankshaft, No.5 connecting rod journal and debris recovered from the sump**



6.3.6 Occurrence 200303701 VH-OCF

Reported evidence

The pilot first became aware of a malfunction in the left engine through a series of ‘explosions’ followed by severe vibrations and flames, during an approach to land. The engine was shut down immediately and the propeller was feathered. The fire went out after the engine was shutdown.

Time since overhaul: 1,640 hours

Physical evidence

Examination of the engine revealed that the little end of the No.6 connecting rod had fractured. The separated end of the connecting rod had collided with the underside of the No.6 piston resulting in the fracture of the No.6 cylinder attachment fasteners, the separation of the No.6 cylinder from the crankcase. In addition, the crankcase structure surrounding both upper engine mount attachment points was fractured during the forceful separation of the cylinder and by the flailing of the connecting rod. The engine remained supported only by the two lower mounts.

Figure 6.29: The damage to the crankcase and upper mounts

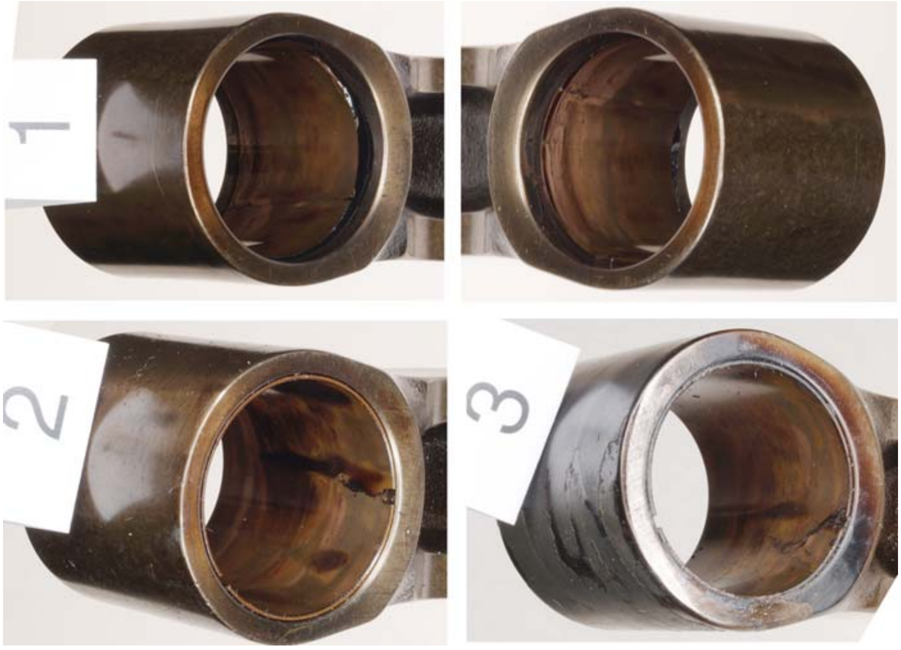
Figure 6.30: The fractured little-end housing of the No.6 connecting rod

A sample of debris from the little-end bearing, recovered from the sump and filters is shown bottom left.

It is evident from the nature of the little-end bearing remnants recovered from the engine sump and oil filters that the little-end bearing had been destroyed during a period of engine operation prior to the fracture of the housing. Galling (adhesive wear) and surface cracking were present on the inner surface of the housing. This type of surface damage occurs when the steel piston pin bears against the steel inner surface of the housing in the absence of the leaded bronze bearing.

Examination of other connecting rods from the left engine revealed that the process of little-end bush destruction was not restricted to the No.6 connecting rod, figure 6.31.

Figure 6.31: The condition of little-end bearings from other connecting rods from the left engine



Cracking and edge breakaway is evident at both ends of the No.1 rod little end bearing (top), cracking is evident in the bearings from the No.2 and No.3 connecting rods.

Similar connecting rod little-end bearing deterioration was discovered during the disassembly of the right engine at a later time, figure 6.32.

Figure 6.32: Cracking and edge breakaway in the No.1 connecting rod little bearing, VH-OCF right engine

6.4 Crankshaft failures

6.4.1 Introduction

The crankshaft is the component that converts the reciprocating action of the piston/connecting rod into rotational power – for a direct drive engine, the rotational power is provided at the end flange of the crankshaft. In a multi-cylinder engine, the crankshaft combines the combustion forces created in each cylinder assembly. While the crank form (a short section of the shaft displaced parallel to the main axis of the shaft) is common to all crankshafts, the overall form of the shaft depends on the layout of the cylinders, for example, inline, vee, horizontally opposed, or radial.

During engine operation, the crankshaft is subjected to alternating stresses created by the discontinuous gas pressure loads from each cylinder and the inertia loads associated with the reciprocating action of the pistons and rotation of unbalanced masses. Because the crankshaft is an elastic member, these alternating stresses create deflections in the plane of rotation, giving rise to torsional vibrations, and in the plane of the axis of the crankshaft, giving rise to longitudinal vibrations.

The crankshaft is supported in the engine crankcase by several main bearings. For six-cylinder horizontally-opposed aircraft engines, the crankshaft is supported by a main bearing at each end of the shaft and two intermediate main bearings, one between each of the two connecting-rod journals.

Table 6.3: Summary of occurrences involving crankshaft fracture

Occurrence Number	Date of Occurrence	Aircraft registration and Engine Type	Component Failure
2000/2157	31 May 2000	VH-MZK left Lyc TIO-540-J2B	No.6 con-rod journal fracture plus big-end housing fracture
2000/2276	20 May 2000	VH-ODE Lyc TIO-540-J2B	No.1 con-rod bearing breakdown
2001/2544	9 Jun 2001	VH-TTX Lyc TIO-540-J2B	Main bearing crankweb fracture No.4 main/No.4 rod
2001/4799	4 Oct 2001	VH-BEM TCM TSIO-520-E	Main bearing crankweb fracture
2001/5866	14 Dec 2001	VH-JCH Lyc LTIO-540-J2B	No.6 con-rod journal fracture plus big-end housing separation
2004/2291	22 Jun 2004	VH-VEC TCM GTSIO-520-M	No.3 con-rod bearing breakdown
2005/02231	18 May 2005	VH-IGW Lyc TIO-540-V2AD	Main bearing crankweb fracture, No.4 main/ No.4 rod journal

6.4.2 Occurrence 2000/2157 VH-MZK (left engine)

Reported evidence

VH-MZK was involved in a fatal accident following the failure of both engines and a ditching at night.

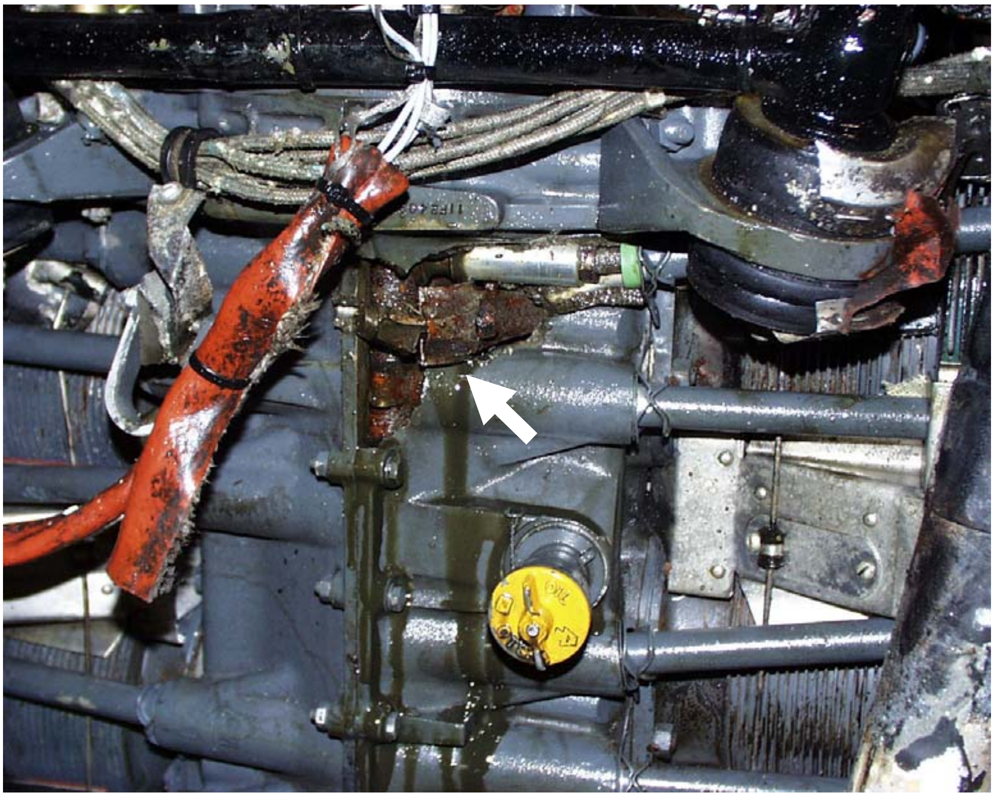
Time since overhaul: 262 hours

Physical evidence

The engine was recovered with the aircraft wreckage from the bottom of Spencer Gulf. It had been immersed in seawater for several days.

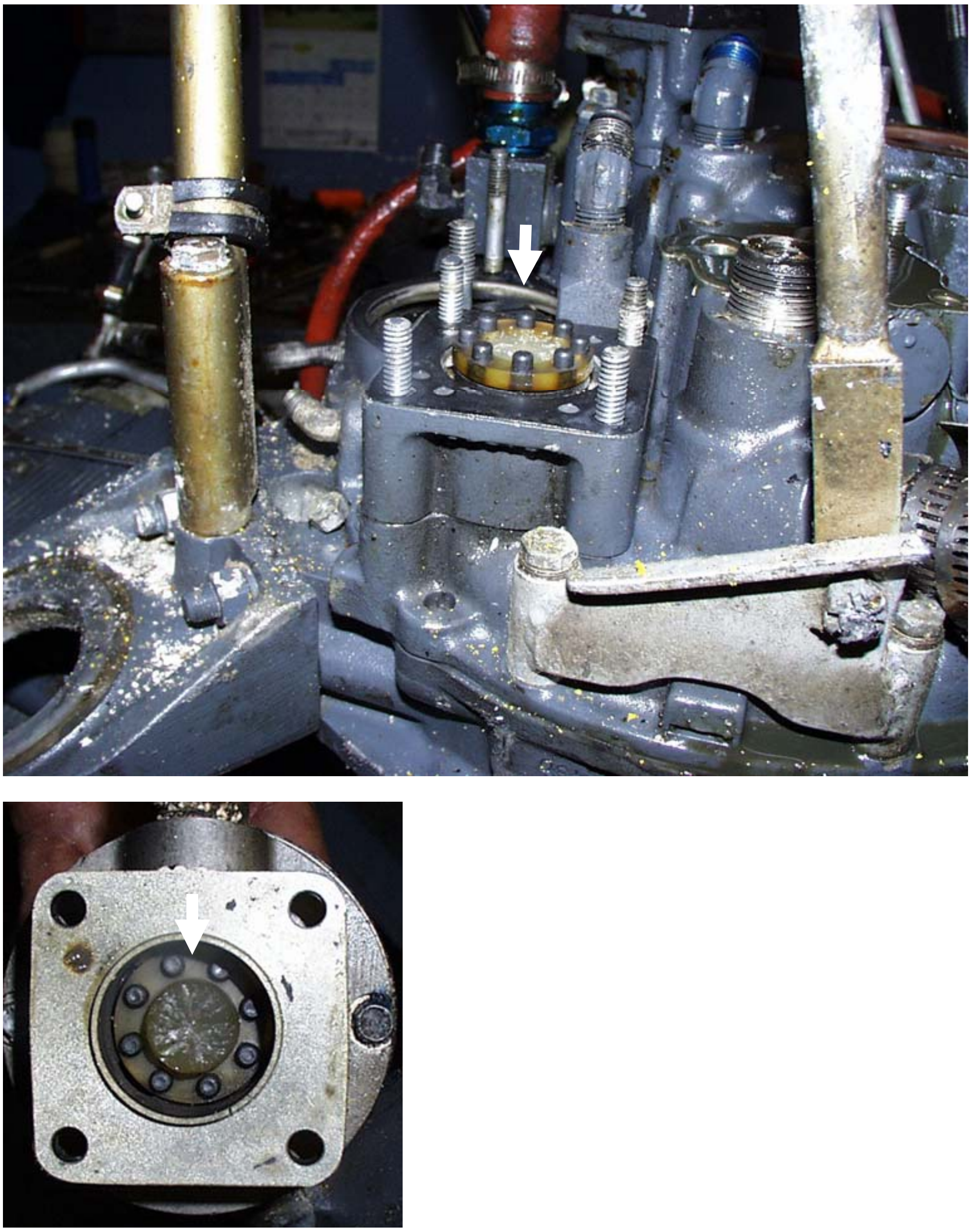
During the initial examination of the engine, it was apparent that the No.6 connecting rod had separated from the crankshaft journal, collided with the camshaft, and collided with the top of the left crankcase half. The collision with the crankcase ruptured a major oil gallery, see figure 6.33. The impulse transmitted through the camshaft to the accessory drive train, resulted in the fracture of the pneumatic pump drive coupling, see figure 6.34.

Figure 6.33: The left engine, MZK, as recovered



The site of crankcase rupture is arrowed.

Figure 6.34: Pneumatic pump coupling fracture, left engine, MZK



The fractured pneumatic pump drive coupling is arrowed.

Detailed examination of the No.6 connecting rod revealed that the fracture of the big-end housing did not occur as the result of a single load application. The big-end housing fractured as a result of fatigue cracking that initiated on the outside of the big-end cap at the regions of reduced cross-section created by the counterbore, figures 6.35 and 6.36. When final fracture of the big end occurred, the piston was released with sufficient speed to impact the cylinder head and deform the edge of the piston, figure 6.37. This type of damage is an indicator that the big-end housing fractured while the engine was operating in its normal speed range.

Figure 6.35: The No.6 connecting rod, as recovered

Several fragments of the big end bearing inserts are shown at the bottom of the figure.

Figure 6.36: The location and extent of fatigue cracking in the No.6 connecting rod cap

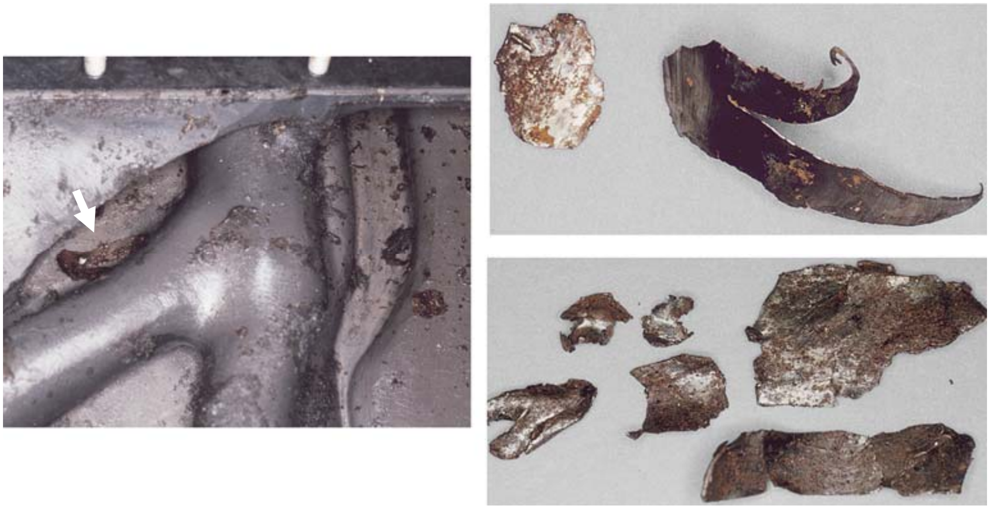
The sites of fatigue crack initiation are arrowed. Fatigue crack growth, in the region identified as ‘fracture 1’, extended over the full extent of the cross-section.

Figure 6.37: The nature of piston edge deformation created by the impact of the No.6 piston against the No.6 cylinder head

The deformation of the edge of the piston and the region of contact between the piston and cylinder head are arrowed.

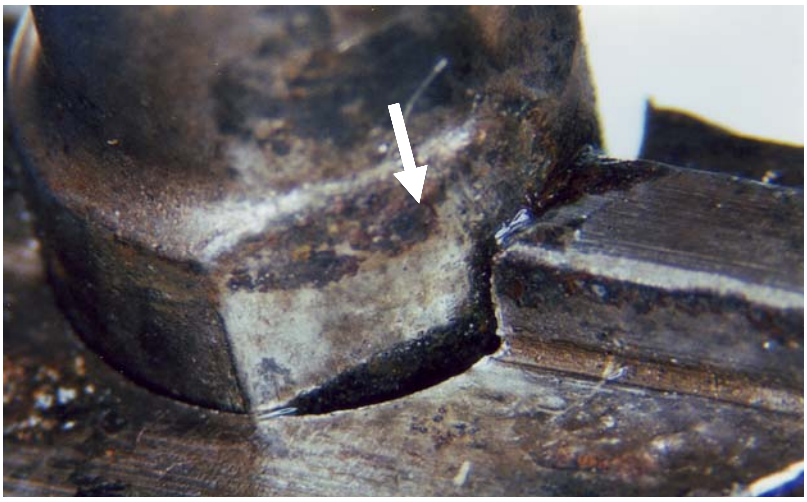
The No.6 big-end bearing inserts had been reduced to fragments of insert steel backing that had been reduced uniformly in thickness while lubricating oil was supplied to the bearing, figure 6.38. There was no evidence of overheating of the big-end bearing associated with a loss of lubrication. It is evident from wear between the crankshaft journal and the inner surface of the big-end housing, and the guide section of the housing bolts, that the crankshaft continued to rotate with an intact housing for a period of time following the destruction of the bearing inserts, see figure 6.39.

Figure 6.38: Fragments of the No.6 big end bearing inserts recovered from the engine sump



A fragment of the steel backing from the No.6 connecting rod bearing insert remained in the sump, arrowed left.

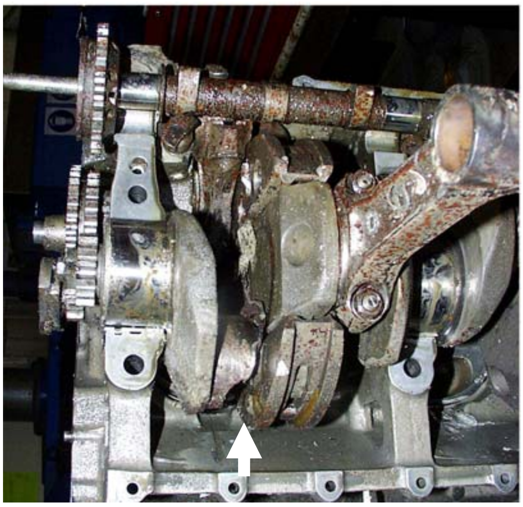
Figure 6.39: **No.6 connecting rod, big end housing bolt. Bolt guide section wear**



The design of the connecting rods fitted to Lycoming TIO-540-J2B engines is such that the guide section, (the increased diameter at the centre of the bolt), protrudes beyond the housing inner surface into a recess machined in the rear surface of the bearing inserts.

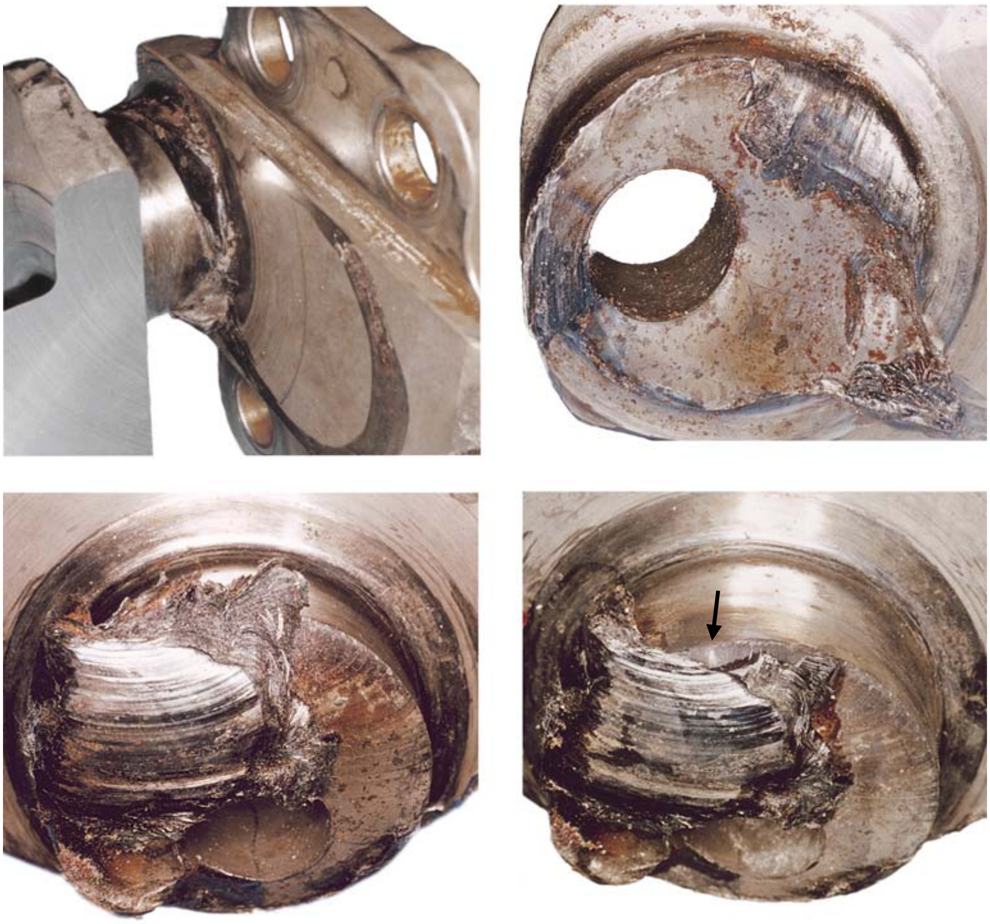
Upon disassembly of the engine, it was clear that the crankshaft had fractured at the No.6 connecting rod journal, figure 6.40.

Figure 6.40: **The fractured No.6 connecting journal, in situ**



Fracture was caused by fatigue crack initiation and growth. Fatigue cracking initiated at the transition between the journal and the crankweb fillet, figure 6.41. Distinctive fatigue ‘progression’ marks were present on the fatigue fracture surface. These marks are created by major changes in the alternating loading spectrum. Typically, for engine crankshafts, they are associated with engine start/stop cycles. It was estimated that fatigue crack growth had occurred over a period of at least fifty engine start/stop cycles.

Figure 6.41: Detailed views of the No.6 connecting rod journal



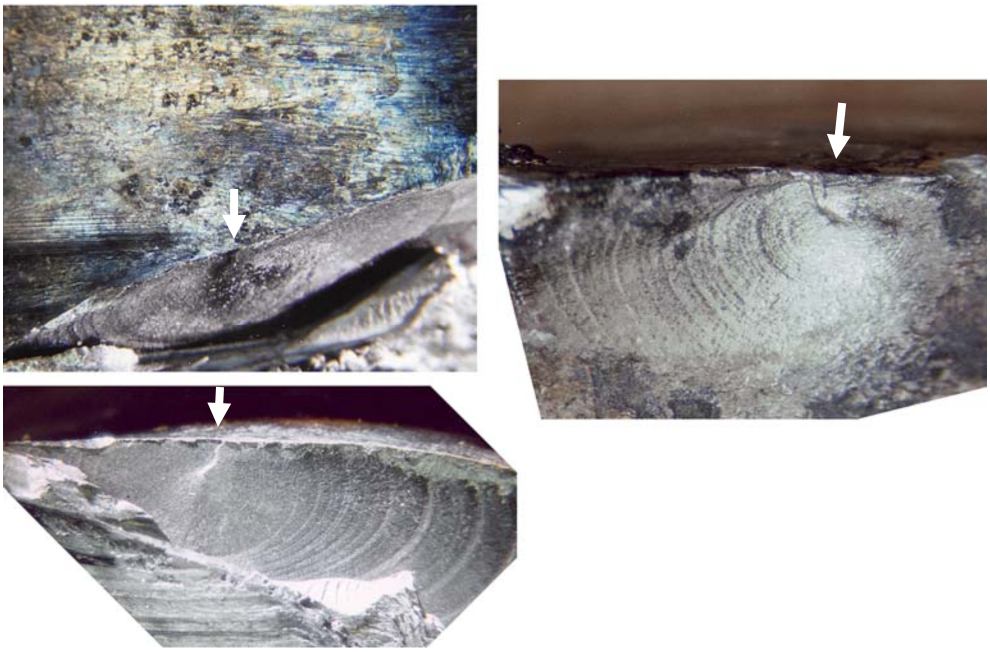
The lower two photographs show the fracture surface of the rear crankshaft section in the 'as received' condition (left) and after some of the deformed material had been broken away to reveal the initiation site of fatigue cracking.

Because the plane of fatigue cracking was inclined at an angle to the axis of the journal and crack growth extended into the crankweb, rotational forces could be transmitted between the two halves of the crankshaft for a period of time after the final fracture of the journal.

It is evident that with continued engine operation and crankshaft rotation, that deformation of the interlocking parts of the crankshaft halves occurred progressively. Continued operation with progressive deformation of the fracture surfaces will have an effect on engine timing, and as such, engine performance. It is a design feature of the horizontally-opposed engine that ignition and valve timing for all cylinders is indexed to the position of the crankshaft through a gear train driven from the rear of the crankshaft. Correct ignition timing for each cylinder relies on the location of the connecting-rod journal with respect to the ignition timing gear train.

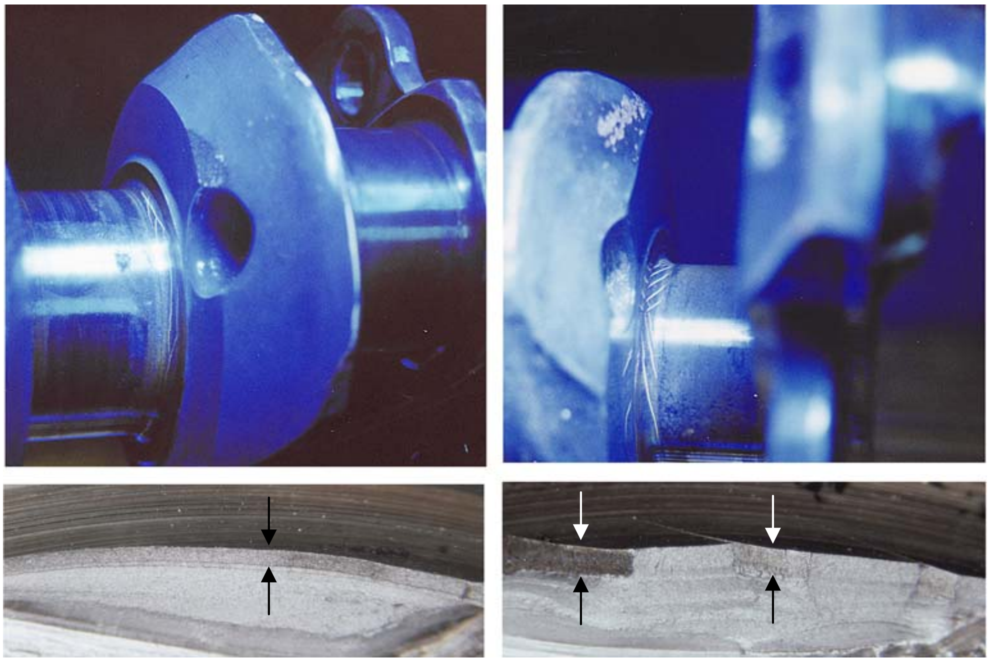
Fatigue cracking initiated at a site below the journal surface. This region of the fatigue fracture surface had been affected by heating and localised deformation. It is noticeable that a 'steplike' feature extended from the site of initiation to the surface.

Figure 6.42: **The initiation site of fatigue cracking**



Further evidence, that the engine had continued to operate and the crankshaft had continued to rotate, is provided by the presence of fatigue cracking in the fillet of the No.5 connecting rod journal and the fillet of the No.4 main journal.

Figure 6.43: **Magnetic particle inspection indication of fatigue cracking in the No.5 connecting rod journal and the No.4 main journal**



No.4 main journal is shown on the left, No.5 connecting rod journal is shown on the right. Examples of fatigue crack growth extending from the surface of the journals, associated with magnetic particle indications are shown below the photographs of the journals. The extent of fatigue cracking from the journal surface is arrowed.

The failure of the left engine of VH-MZK is characterised by several processes of wear, crack growth, progressive deformation, affecting a number of components over varying periods of operational time before the final engine stoppage.

Recorded evidence

Detailed analysis of recorded radar data and voice transmissions between the pilot and ground stations, indicated that the performance of the propulsion systems were normal until 17 minutes into the cruise phase of flight, see pages 48-52.

6.4.3 Occurrence 2000/2276 VH-ODE

Reported evidence

During cruise, the pilot noticed a loss of propeller synchronisation. A short time later it was noticed that the left engine manifold and oil pressures were decreasing while the oil temperature was increasing. The engine was shutdown.

Time since overhaul: 835 hours

Physical evidence

Examination of the engine revealed that the big-end bearing inserts in the No.1 connecting rod were in state of partial destruction.

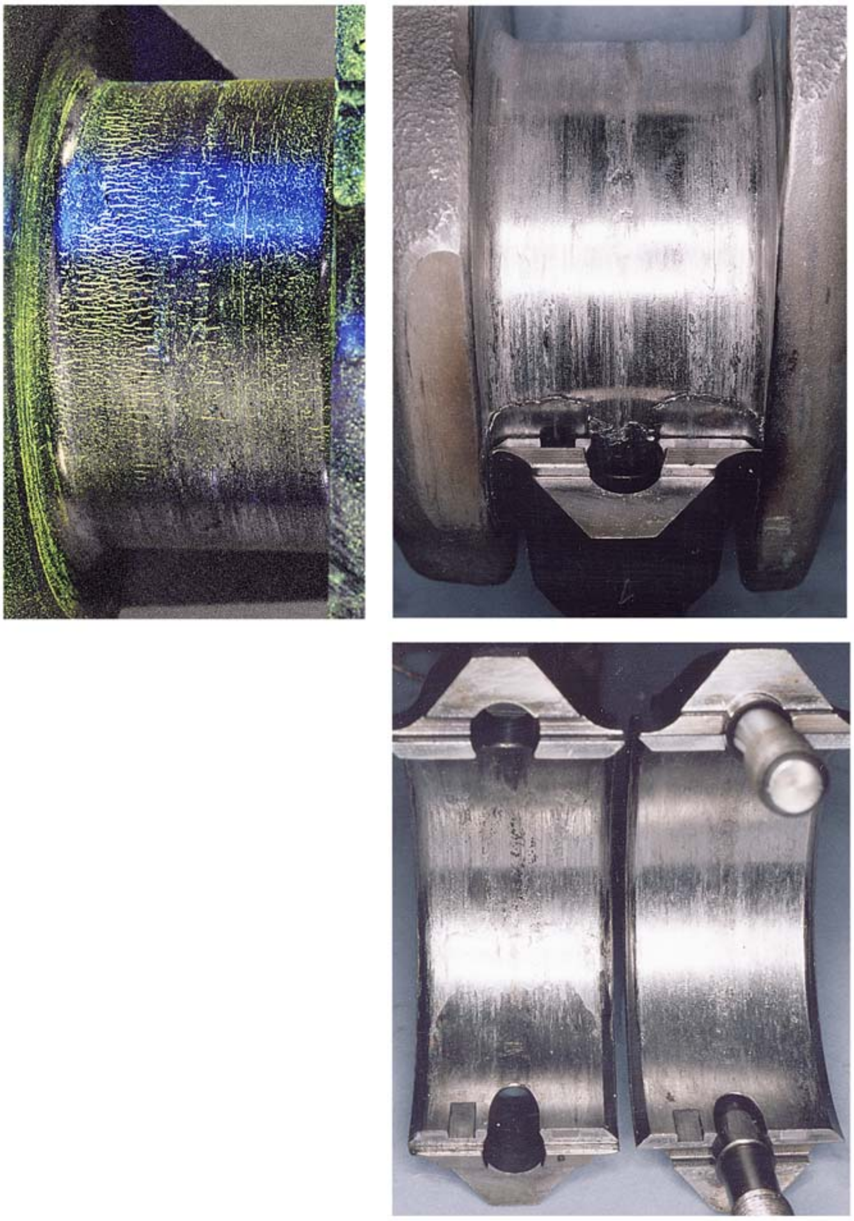
Figure 6.44: The extent of damage to the No.1 connecting rod big end bearing inserts

Bearing breakdown was characterised by the separation of the aluminium-tin and lead-tin bearing alloy layers. The steel backing was in various states of destruction:

generally, the backing had been reduced in thickness and broken up through rotation against the section of the housing bolts that protrude into the housing; some of the backing had been extruded through the gap between the housing and crankshaft journal. The bearing inserts, p/n 74309-M03, were 0.003 of an inch oversize to allow for a reduction in journal diameter following maintenance actions designed to restore the condition of worn crankshaft journals. The crankshaft was identified as p/n 13F27735, s/n V53794017 M03P (M03P refers to the reduction in the diameter of the connecting-rod journals of 0.003 of an inch).

During engine disassembly, it was found that small sections of the bearing alloy layers had broken away from other big-end bearing inserts, see figure 6.71.

Figure 6.45: The condition of the No.1 crankshaft journal and surface of the big end housing



Extensive ‘thermal’ surface cracking of the journal is evident in the magnetic particle inspection indications (top left).

6.4.4 Occurrence 2001/2544 VH-TTX

Reported evidence

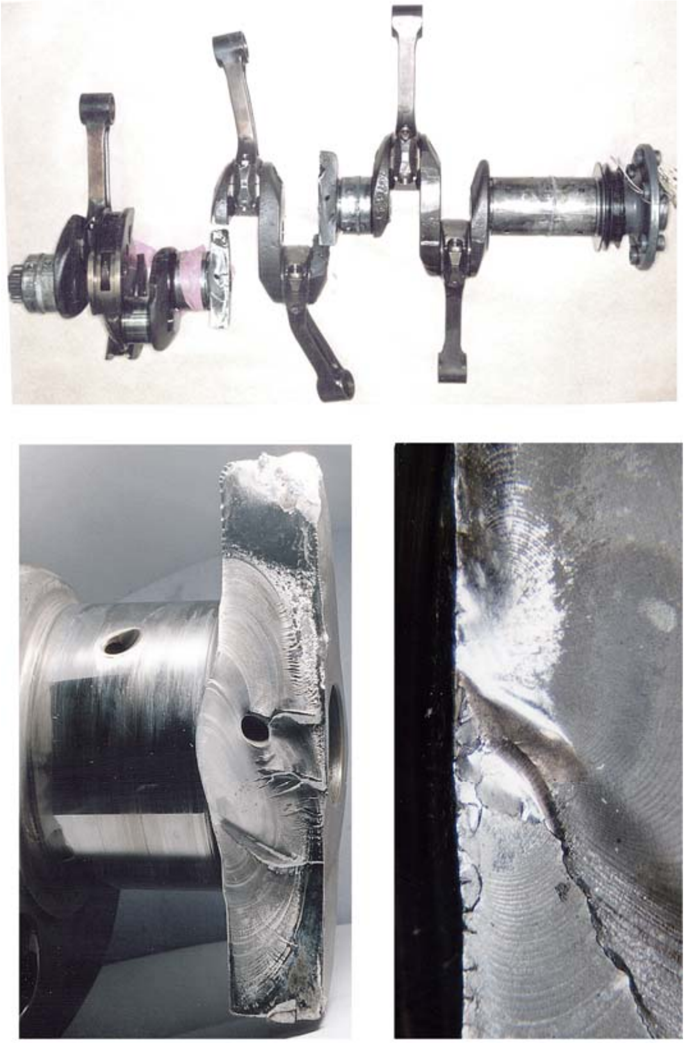
The left engine failed during climb at approximately 600 feet. The pilot completed the engine failure checklist and returned to land.

Time since overhaul: 1,300 hours

Physical evidence

Examination of the engine revealed that the crankshaft had fractured in two locations between the two centre main-bearing journals as a result of fatigue cracking. The primary fatigue fracture was located at the forward fillet radius of the No.4 main bearing journal, figure 6.46.

Figure 6.46: The primary fatigue fracture, No.4 main bearing/No.4 connecting rod crankweb



It is evident that fatigue cracking initiated in the crankweb between the No.4 main-bearing journal and the No.4 connecting-rod journal as a result of damage created by contact between the No.4 main-bearing inserts and the No.4 main-bearing journal fillet radius, figure 6.47.

Figure 6.47: The nature of No.4 main bearing journal fillet radius damage

Contact between the rotating crankshaft and bearing inserts created two types of journal damage: circumferential scoring; and a series of short cracks created by localised thermal expansion of the journal surface. The circumferential scoring changes the geometry of the fillet radius and increases the level of local stress concentration. The series of ‘thermal’ cracks, oriented parallel to the journal axis, create discontinuities in the surface hardened zone of the journal and also act to increase local stress concentration levels.

Because of the orientation of the plane of fatigue fracture through the No.4 main/No.4 connecting-rod crankweb, rotational forces could be transferred between the two halves of the crankshaft following final fracture. However, continued engine operation following the fracture of the No.4 main/No.4 connecting-rod crankweb, creates a condition of high alternating stress at the fillet between the No.3 main journal and the No.3 main/No.3 connecting-rod crankweb. The effect of increased alternating stress in this location, results in rapid fatigue crack initiation and crack growth. The engine ceased to function following the fracture of the No.3 main/No.3 connecting-rod crankweb.

Figure 6.48: Crankshaft secondary fracture, No.3 main/No.3 connecting rod crankweb

The crankshaft was marked with the following identifiers, part number LW 10346, serial number 87928.

6.4.5 Occurrence 2001/4799 VH-BEM

Reported evidence

Shortly after commencing descent, the pilot reported that the left engine started to shudder, before it stopped suddenly with the propeller in the unfeathered position. A visual inspection of the engine from the cockpit revealed oil streaming from the engine cowling. It was also reported that the leads between spark plugs in the No.3 and No.1 cylinders, had been transposed for a period of time before the engine failure.

Time since overhaul: 298 hours

Physical evidence

Examination of the engine revealed that the crankcase had been holed near the No.5 cylinder and the crankshaft had fractured. The mechanism of fracture was fatigue cracking. Fatigue cracking initiated below the surface of the fillet radius between the No.3 main-bearing journal and the No.5 connecting-rod journal, and cracking propagated through the No.3 main/No.5 connecting-rod crankweb.

Note: Teledyne Continental Motors number cylinders, journals and bearings from the rear of the engine, in contrast to Lycoming engines, which are numbered from the front of the engine.

Figure 6.49: The fracture through No.3 main/No.5 connecting-rod crankweb

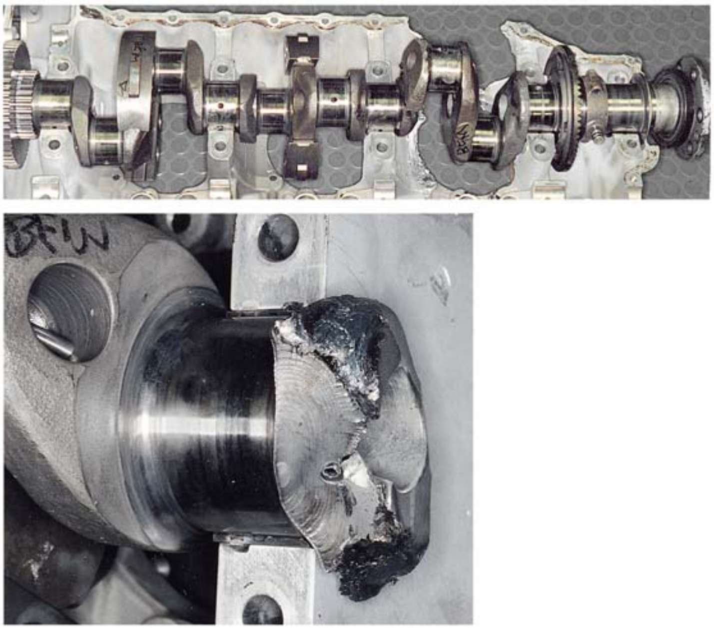
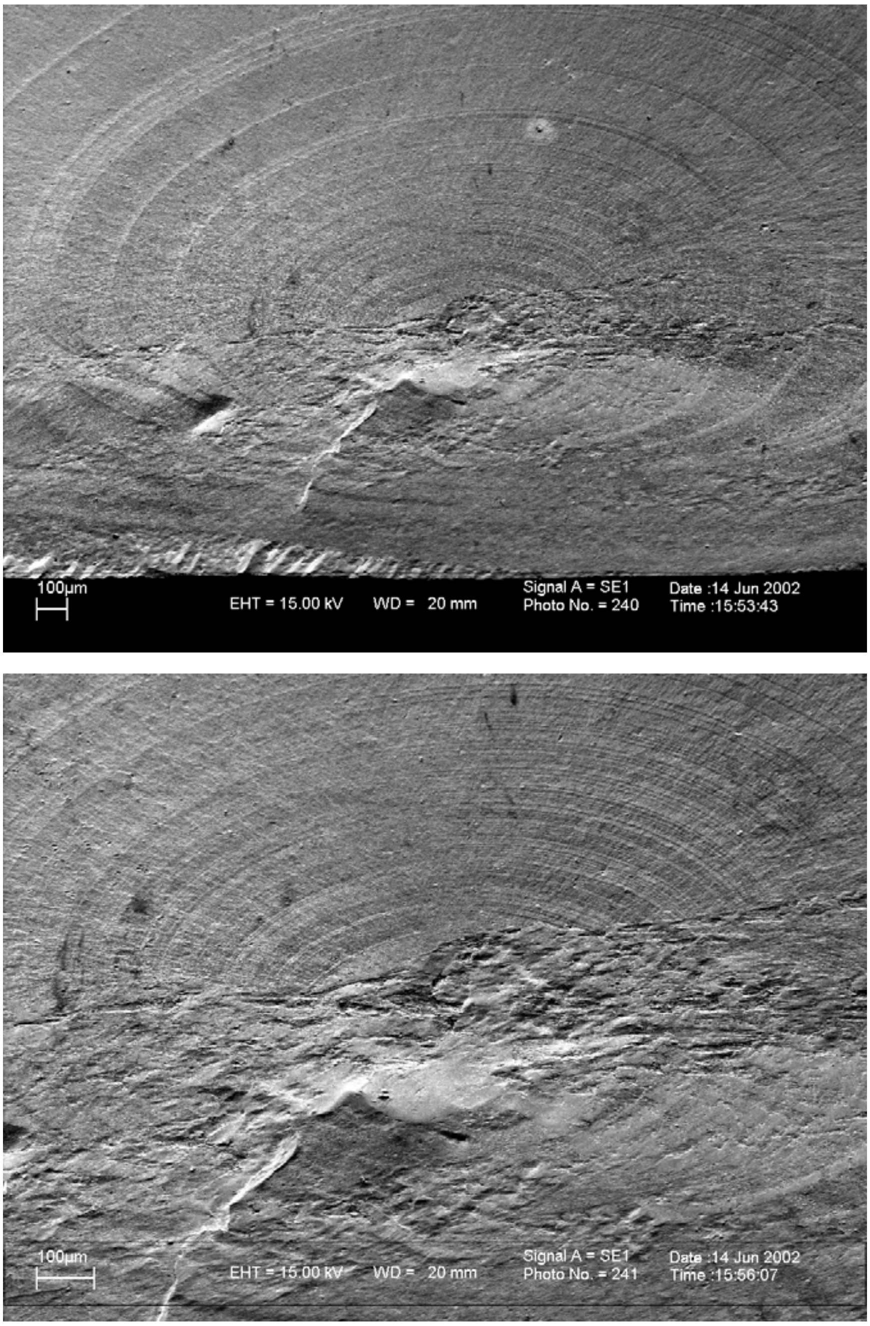


Figure 6.50: Detailed views of the site of fatigue crack initiation, scanning electron micrographs



6.4.6 Occurrence 2001/5866 VH-JCH

Reported evidence

Approximately 10 minutes after entering the cruise phase of flight, the flight crew became aware of a developing engine problem when the propellers ‘dropped out of synchronisation’. The following observations were noted by the flight crew:

> Gyro pressure gauge ‘spiked’ and dropped to approximately four inches (lower limit), pneumatic ‘inop’ light was on, the right-engine oil temperature was 245˚F (max), right-engine cylinder-head temperature was in the normal range, right-engine oil pressure was approximately 65 psi and falling.

Finally, the speed of the right engine fluctuated up and down, approximately 100 rpm. At this point, the crew elected to shut the engine down in accordance with the engine-securing checklist.

Time since overhaul: 1,055 hours

Physical evidence

During the initial examination of the engine, it was apparent that the No.6 connecting rod had separated from the crankshaft journal and had collided with the camshaft, figure 6.51. The impulse transmitted through the camshaft to the accessory drive train resulted in the fracture of the pneumatic pump coupling, figure 6.52.

Figure 6.51: The No.6 connecting rod, as recovered

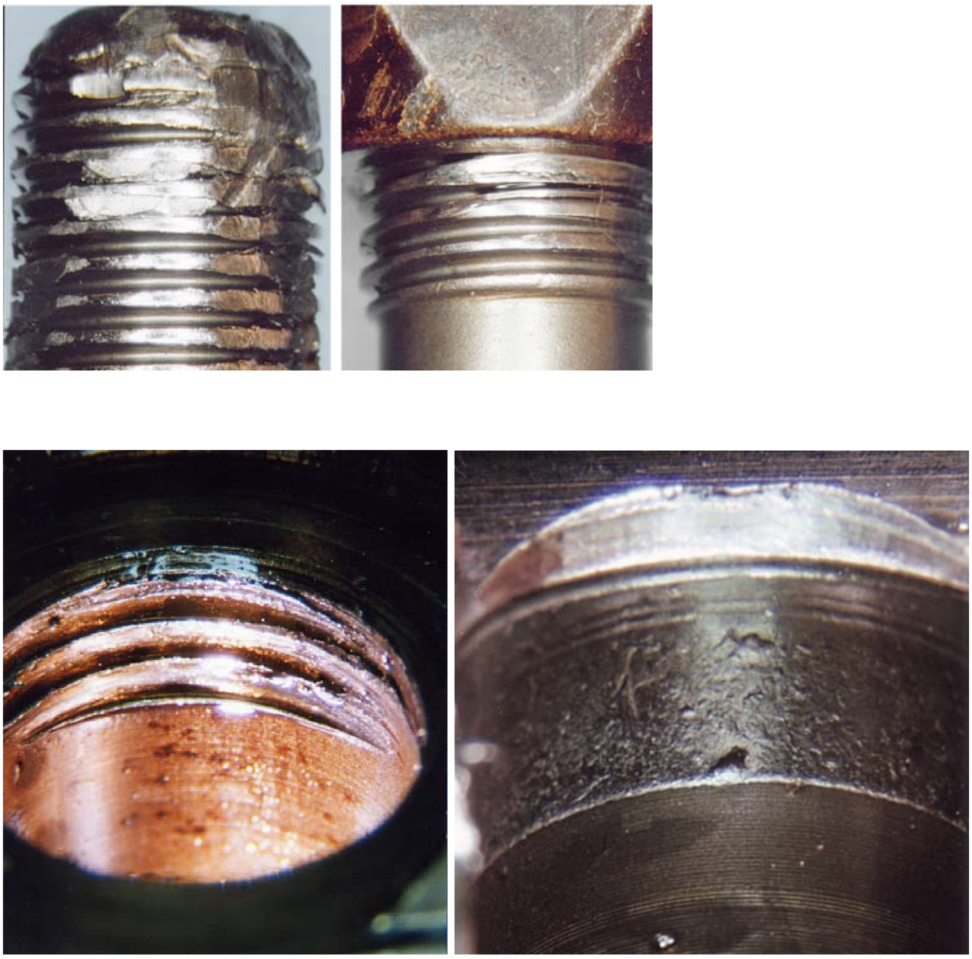
Figure 6.52: Pneumatic pump coupling fracture, right engine JCH

Separation of the No.6 big-end housing allowed the piston to strike the domed surface of the combustion chamber with sufficient force to deform the edge of the piston crown, see figure 6.53.

Figure 6.53: The nature of piston edge deformation created by the impact of the No.6 piston against the No.6 cylinder head

The separation of the No.6 big-end housing involved the loosening of nuts installed on the big-end housing bolts and the eventual loss of one nut. Evidence of nut loosening is provided by the fretting wear damage on the bolt threads and those regions of the boltholes that contact the bolt thread or guide surface, see figure 6.54.

Figure 6.54: Examples of No.6 connecting rod big-end bolt thread and bolthole damage



While it is clear that both parts of the connecting rod big-end housing (rod and cap) had remained intact (figure 6.55), it is evident that the inner surface of the housing had been damaged by rotational contact with the crankshaft journal in the absence of the big-end bearing inserts. The damage was sufficient to initiate fatigue cracking in the centre of the cap, figure 6.56.

The No.6 big-end bearing inserts had been reduced to fragments of steel backing. The fragments had been reduced uniformly in thickness while lubricating oil was supplied to the bearing, figure 6.57. There was no evidence of overheating of the big-end bearing associated with a loss of lubrication.

Figure 6.55: **The No.6 connecting rod big-end, as recovered**

Figure 6.56: **The location of fatigue cracking, extending from the inner surface of the No.6 connecting rod big-end cap**

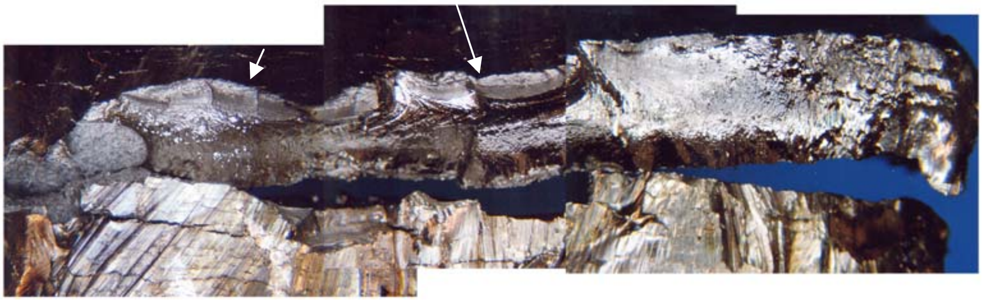
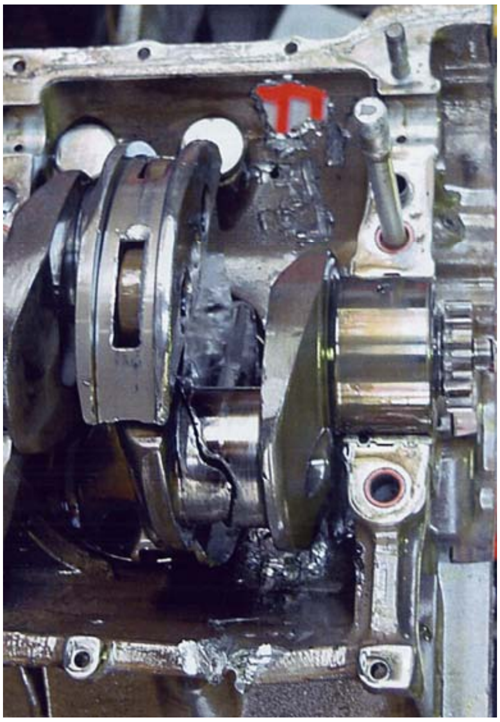


Figure 6.57: **Fragments of the No.6 big-end bearing inserts recovered from the engine sump**

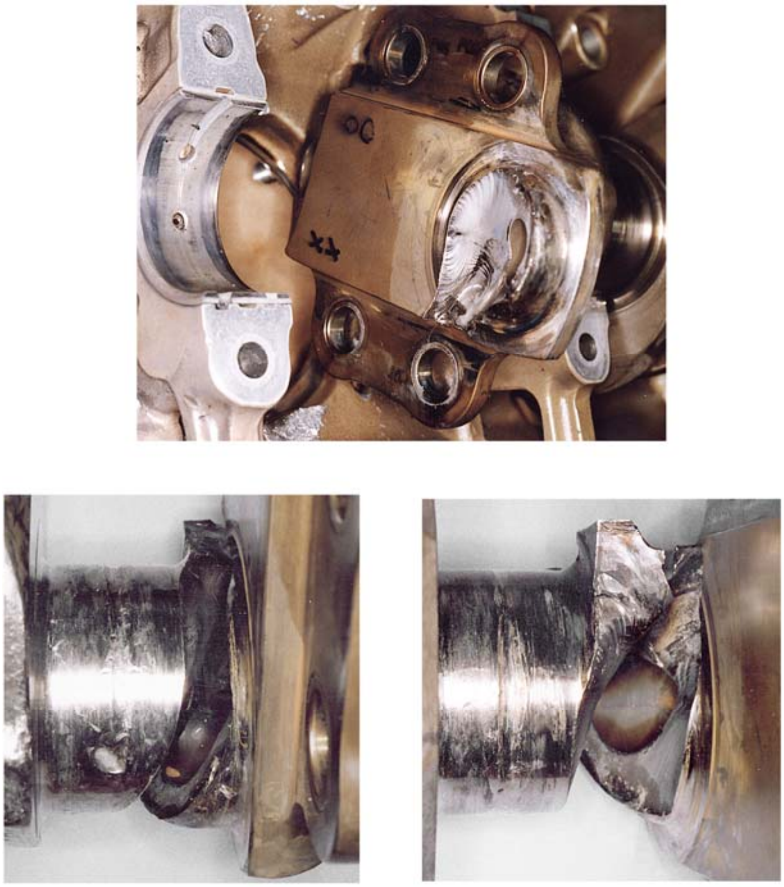
Upon disassembly of the engine, it was clear that the crankshaft had fractured at the No.6 connecting-rod journal, see figure 6.58. The two halves remained supported by the main bearings. The orientation of the plane of fracture allowed rotational forces to be transmitted between the two halves.

Figure 6.58: **The fractured No.6 connecting-rod journal, in situ**



It is evident that with continued engine operation and crankshaft rotation the interlocking parts of the crankshaft halves were being progressively deformed, see figure 6.59. Continued operation with progressive deformation of the fracture surfaces will have an effect on engine timing and as such, engine performance. It is a design feature of the horizontally-opposed engine that ignition and valve timing for all cylinders is indexed to the position of the crankshaft through a gear train driven from the rear of the crankshaft. Correct timing for all cylinders relies on the fixed location of all connecting-rod journals with the timing-gear train.

Figure 6.59: Detailed views of the No.6 connecting-rod journal



Fracture was caused by fatigue crack initiation and growth. Fatigue cracking initiated at the transition between the journal and the crankweb fillet. Distinctive fatigue ‘progression’ marks were present on the fatigue fracture surface, figure 6.60. These marks are created by major changes in the alternating loading spectrum. Typically, for engine crankshafts, they are associated with engine start/stop cycles. It was estimated that fatigue crack growth had occurred over a period of at least 76 engine start/stop cycles.

Figure 6.60: Progression marks associated with fatigue crack growth, No.6 connecting-rod journal

Fatigue cracking initiated at the transition between the No.6 journal surface and the fillet of the crankarm between the No.6/No.5 connecting rod journals at a site below the journal surface, figure 6.61. This region of the fatigue fracture surface had been affected by heating and localised deformation. It is noticeable that a ‘steplike’ feature extended from the site of initiation to the surface, figure 6.62.

The failure of the left engine of VH-JCH is characterised by several processes of wear, crack growth and progressive deformation affecting a number of components over varying periods of operational time before the final engine stoppage.

Figure 6.61: Views of the fatigue fracture, No.6 connecting-rod journal

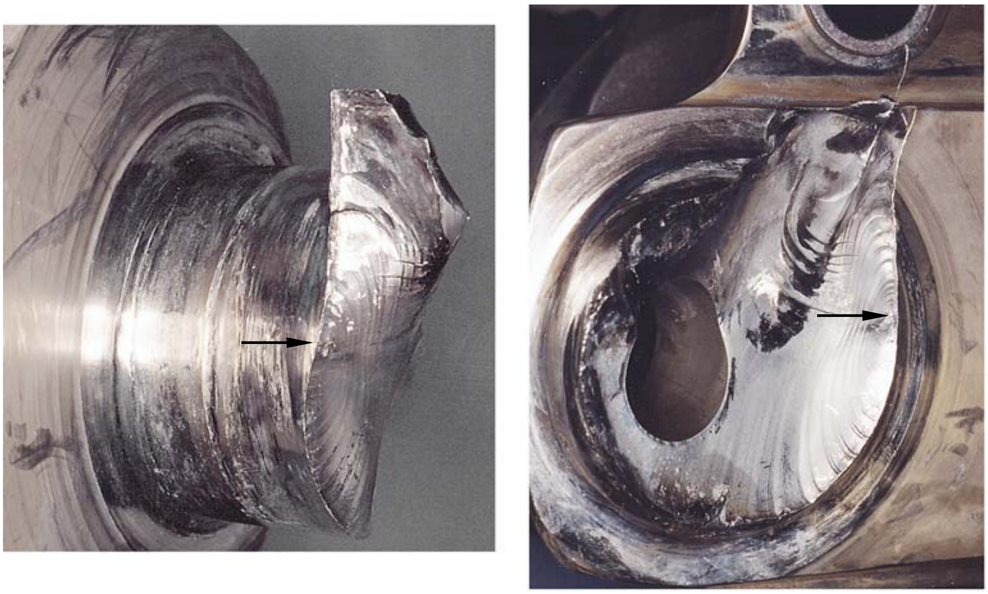
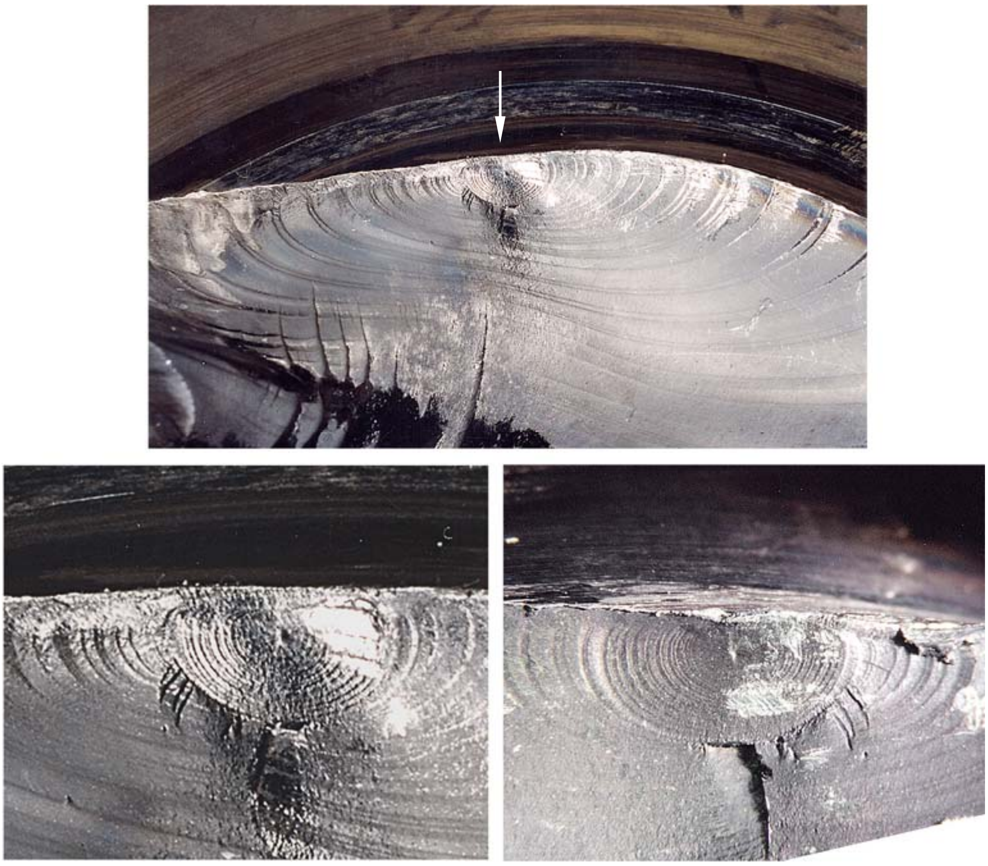


Figure 6.62: Detailed views of the site of fatigue crack initiation



Crankweb side of the fracture. Journal side of the fracture.

6.4.7 Occurrence 2004/2291 VH-VEC

Reported evidence

During the cruise phase of flight, the pilot noticed that the manifold pressure of the right engine dropped from the cruise setting of 32 inches of mercury to 29 inches. Engine power could not be recovered through throttle movement. Subsequently, the oil pressure dropped, suddenly, to zero and the manifold pressure decreased to 20 inches.

A deviation to a nearby airport was initiated and the engine was shutdown according to procedure. In response to the shutdown procedure, the engine stopped suddenly, however, the propeller took between 30 and 60 seconds to feather.

Time since last maintenance action (bulk strip as a result of propeller damage caused during an undercarriage collapse occurrence): 600 hours

Physical evidence

Examination of the engine revealed that no engine oil was lost, 11quarts were recovered. Further examination revealed that the crankshaft had ‘machined’ material from the crankcase at both ends of the shaft (figure 6.63), the oil filters/screens had been clogged by metallic particles, a piston-pin plug from the No.3 piston assembly had fractured (figure 6.64), and the No.3 connecting rod big-end bearing had overheated (figures 6.65-6.67).

Figure 6.63: The regions of crankcase ‘machining’ wear caused by crankshaft expansion

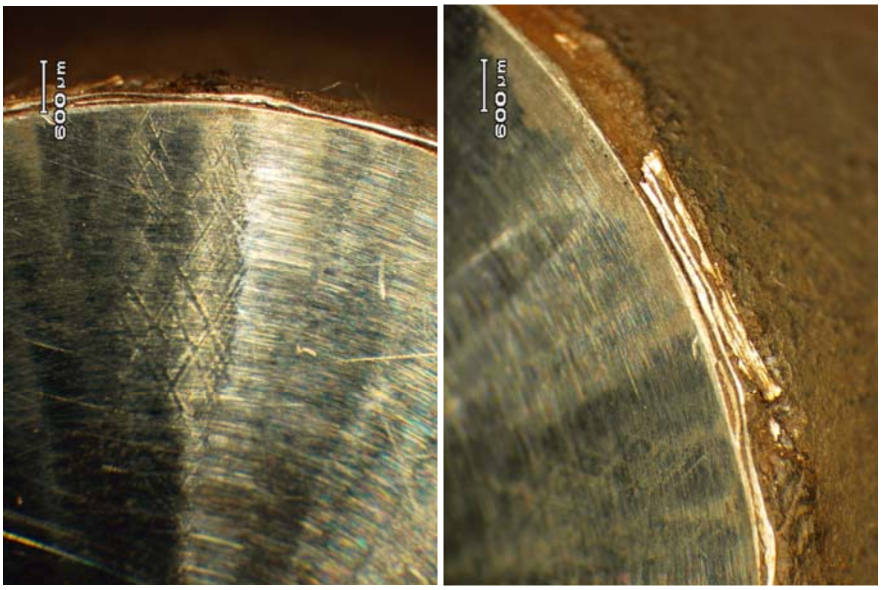
Front of engine

Rear of engine

The engine had been operated under conditions that induced piston-pin shuttle. For cases of piston pin shuttle, the high contact pressures between the piston-pin plug and cylinder wall results in excessive plug wear and possible plug fracture.

Figure 6.64: The extent and nature of damage to piston-pin plugs

No.3 piston-pin plug damage.



Detailed view of piston-pin plug wear (piston pin from another cylinder in the engine).

Figure 6.65: **The nature and extent of damage to the No.3 connecting rod big-end bearing**

Figure 6.66: **Evidence of copper diffusion through the steel backing of the bearing insert and into the No.3 connecting rod housing**

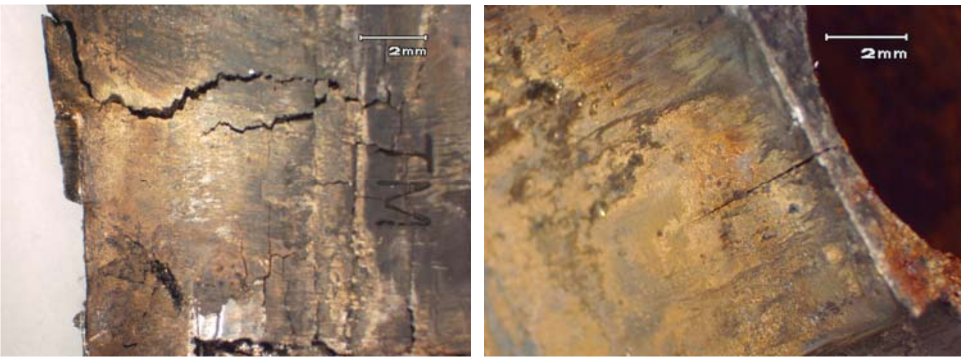


Figure 6.67: **Composite view showing the crankshaft journals**

6.4.8 Occurrence 2005/02231 VH-IGW

Reported Evidence

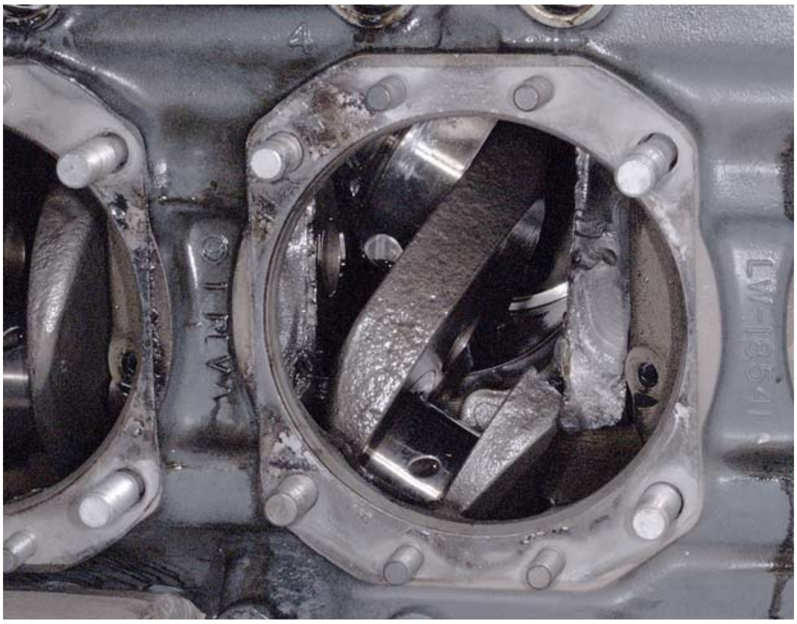
During a flight from Essendon to Armidale, the left engine of a Piper PA31P-350 (VH-IGW) failed during cruise at 17,000 ft. The pilot reported that, prior to the failure, there was a slight variation in the left engine rpm and an increase in left engine vibration. The variation in engine rpm was corrected by adjusting the left propeller speed. The indications on the engine instruments were normal and there were no visible signs of leaking oil. A time period of approximately ten minutes elapsed between the initial observation of engine irregular performance and final failure. The engine shutdown procedure was completed successfully. The aircraft descended to 10,000 ft and diverted to land at Bankstown without further incident.

Time since overhaul: 291 hours

Physical evidence

Initial examination of the Lycoming TIO-540-V2AD engine revealed that the crankshaft had fractured in two places allowing the section containing the No.3 and No.4 connecting-rod journals (the section between the two intermediate main bearings) to become displaced, see figure 6.68.

Figure 6.68: The fractured section of the crankshaft in the position found during initial engine examination



Further examination of the engine revealed that the crankshaft had fractured in two locations: through the crankweb between the No.4 main-bearing journal and the No.4 connecting-rod journal; and through the crankweb between the No.3 main-bearing journal and No.3 connecting-rod journal, see figure 6.69.

Figure 6.69: **The location of both fractures and their orientation with respect to the crankshaft webs**

The fracture of the web between the No.4 main and No.4 connecting rod journals occurred as a result of fatigue crack initiation and growth, figure 6.70. The fatigue fracture progression marks present on the fracture surface indicated that crack growth had occurred over a period of approximately 50 engine start/stop cycles.

Figure 6.70: Crankshaft web fracture, No.4 main/No.4 connecting rod

Maintenance history

Engine s/n L8484-61A, had completed 291.3 hours since overhaul. The crankshaft had been installed in the engine prior to overhaul and had been examined for cracks (magnetic particle inspection) prior to engine reassembly.

The crankshaft was identified by a series of hand etched, stamped, and as-forged numbers. The part number of the crankshaft was LW 17740 (letter stamped into propeller flange), the crankshaft serial number was V5311 (hand etched on the propeller flange). Two, as-forged, numbers (17707 and V60) were present on the edges of two crankshaft webs.

Engine logbook entries on the 20 August 2002 and 21 October 2002 indicated that the crankshaft had been assessed for compliance with Lycoming Service Bulletins, SB 552 and SB 553 and associated Airworthiness Directives. On both occasions, the Service Bulletins where found to be not applicable. A review of Lycoming Service Bulletins, SB 550, SB 552, SB 553, SB 566, SB 569, SB 569A, that address a material issue with Lycoming crankshafts, found that the engine model, TIO-540-

V2AD, engine serial number, L8484-61A, and crankshaft serial number, V5311, were not listed.

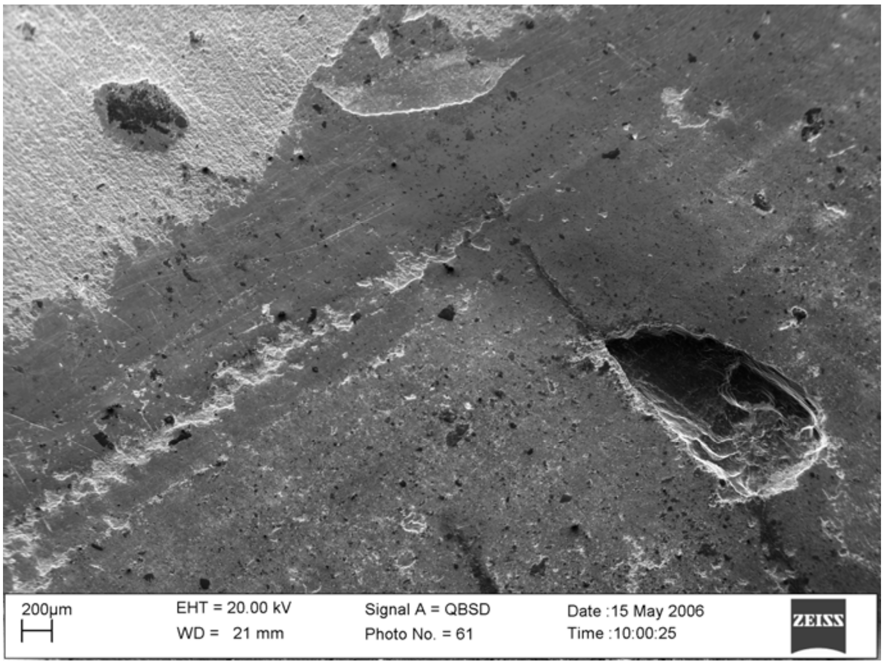
6.5 Crankshaft bearing, reported service difficulties and defects

As a result of some concerns regarding the reliability of crankshaft bearings, a survey of the Australian Major Defect Reporting database was conducted by DP Sprigg (2003, pers. comm., 11 May). On the basis of this survey and the physical examination of bearings, where they were available, it was concluded that there was an increasing trend (over the period 1993 – 2003) for sections of aluminium-tin bearing alloy to separate from the crankshaft bearing inserts of high-power Lycoming engines. Similar examples of bearing alloy separation from crankshaft bearing inserts, manufactured with a copper-lead bearing alloy, were not observed.

Figure 6.71: Example of aluminium-tin bearing alloy separation, 2000/2276 VH-ODE

Time since overhaul 835 hours, bearing part number 74309 – M03, date of manufacture 1-98

Figure 6.72: Example of aluminium-tin bearing alloy separation, 2002/3474 VH-ACZ



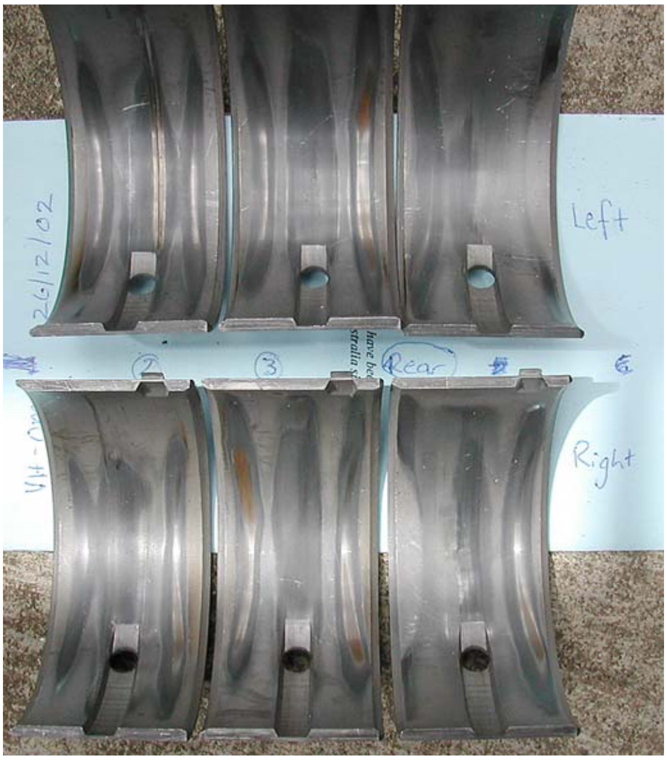
Time since overhaul 157 hours, bearing part number SL 13521-M03, date of manufacture 1-00.

Figure 6.73: Example of aluminium-tin bearing alloy separation, Major Defect Report 02/0277, VH-OMM, PA 31-350, 12 March 2002 (photo, Sprigg, 2003)

Time since overhaul 719 hours, bearing part number 74309 – M03, date of manufacture 1-01.

Figure 6.74: **Back surface of the big-end bearing inserts from VH-OMM (photo, Sprigg, 2003)**

Figure 6.75: **Main bearing surface wear, VH-OMM (photo, Sprigg, 2003)**



The main bearing inserts fitted to OMM were manufactured with a copper-lead bearing alloy intermediate layer.

6.6 References

Lan CE and Roskam J 1988, *Airplane Aerodynamics and Performance,* Roskam Aviation and Engineering Corporation, USA, p 274

Sprigg, DP 2003, *Summary of Lycoming Engine Plain Bearing Failure Events in Australia*, 28 June 2003.

7 EVALUATION OF POWERTRAIN COMPONENT FAILURES

7.1 Introduction

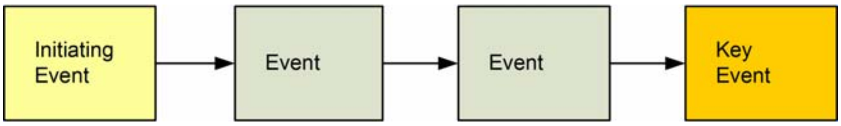
The development of an understanding of the factors that may affect reciprocating-engine reliability requires the evaluation of evidence associated with powertrain component failure events against component failure control plans.

Powertrain component failure was not limited to a particular component and particular mechanism of failure. Of the 20 failures of engines investigated over the period 2000 to 2005, a range of powertrain components was affected and a number of mechanisms initiated failure:

- one engine failure involved cylinder head fatigue fracture;
- three engine failures involved cylinder attachment stud fatigue fracture;
- four engine failures involved piston edge melting;
- two engine failures involved connecting rod little-end fatigue fracture;
- two engine failures involved connecting rod big-end fatigue fracture;
- two engine failures involved crankshaft connecting rod journal fatigue fracture (these two engine failures also involved the failure of the big-end bearing housing and big-end bearing inserts);
- three engine failures involved crankshaft crankweb fatigue fracture, fatigue cracking initiated in the fillet between the main journal and crankweb; and
- two engine failures involved connecting rod big-end bearing insert failure.

In this chapter, use is made of cause-and-effect flow charts are used in the evaluation of failure control plans. The elements of these charts are illustrated in figures 7.1 and 7.2. An event is described as a key event if it creates an outcome that impacts directly on the operation of a system. An event is described as a contributing event if it does not directly affect the operation of a system but, in combination with other events, leads to a key event. Initiating events have their origin in the fundamental processes or mechanisms upon which a system is created.

Figure 7.1: Linear cause and effect linkage schematic



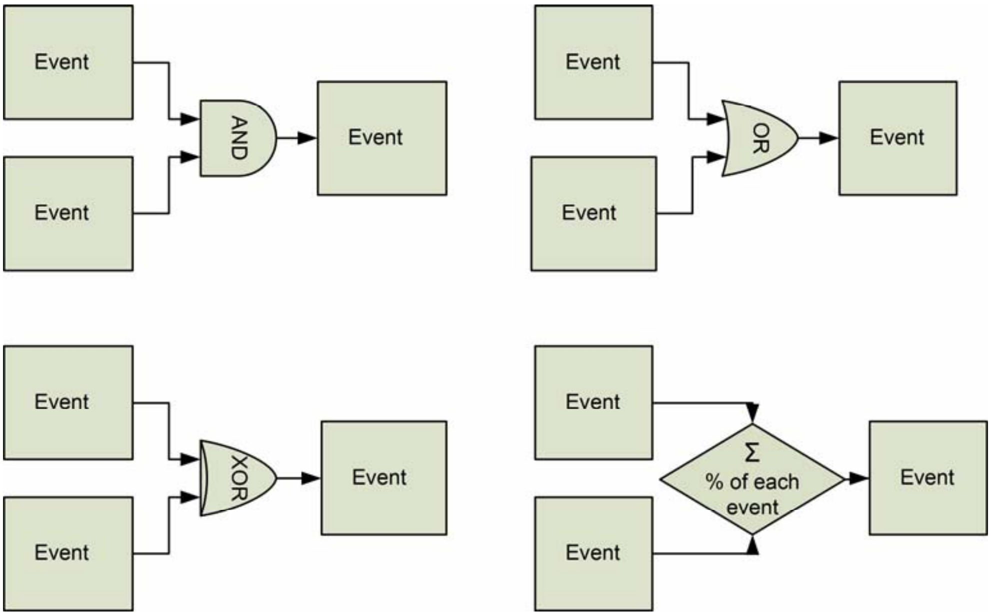
Cause-and-effect sequences do not have to be linear. A number of events may combine to create a new event, figure 7.2. The logical connection between events may be described by binary logic relationships, for example:

> ‘AND’, each contributing event must combine to create the new event;
>
> ‘OR’, one or any combination of contributing events will result in the new event; and
>
> ‘XOR’, exclusive OR, either one event or the other will result in the new event.

However, not all connections between events can be described by binary logic relationships. Some events are the result of the synergistic action of several other events. A new event is the result of the sum of a variable percentage of each contributing event, annotated in cause and effect diagrams as:

> Σ % of each event.

Figure 7.2: Schematic representation of possible logical connections between events



7.2 Cylinder head fatigue fracture

7.2.1 Cylinder assembly design

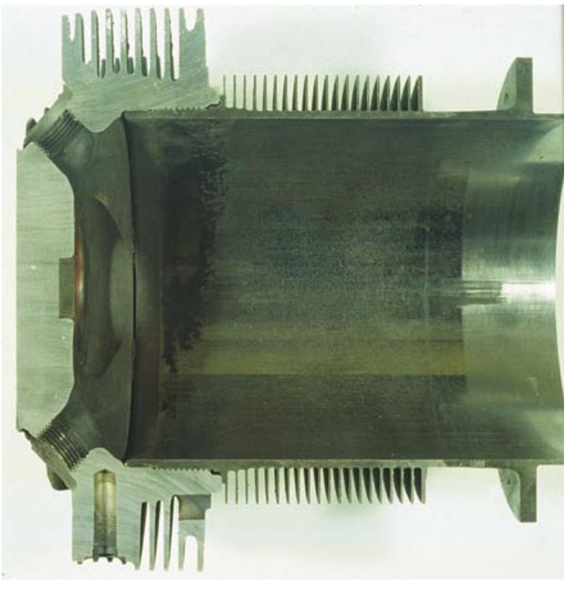
Each engine cylinder assembly and piston in a multi-cylinder reciprocating engine is the reaction vessel where the discontinuous combustion of a gaseous fuel-air mixture occurs. . As with all aircraft structures and components, there is a dominant requirement to provide the function with minimal weight (power-to-weight) while meeting other requirements of reliability (safe operation for a defined period of time) and ease of manufacture and durability (cost of power per unit time).

The cylinder assemblies fitted to air-cooled reciprocating engines normally comprise of an aluminium alloy head joined to a steel barrel by a threaded joint. The cylinder head is a complex form that contains the inlet and exhaust ports and valves. The need to create this form, and maximise strength at engine operating temperatures, requires an alloy that can be cast and is microstructurally stable. The aluminium-copper-nickel alloys used to manufacture cylinder heads, are resistant to overaging and strength reduction at normal engine operating temperatures. The design of the air-cooling system; the cylinder-head fins, the engine cowling, and the baffles between cylinders, is required to maintain the cylinder-head temperature within the design allowable range.

7.2.2 Cylinder stresses

The stresses created in a cylinder assembly during engine operation are derived from two sources; the gas pressures created by combustion, and the thermal strains (expansion and contraction) created by heating and cooling. As a result of the cyclic nature of combustion in a reciprocating engine and the cyclic nature of heating and cooling with each flight, the stresses in the cylinder assembly alternate in magnitude. A region of high stress created by combustion gas pressure is located at the head-to-barrel connection (Kolchin and Demidov, 1984).

Figure 7.3: Cross-section of an aircooled cylinder assembly



Whenever the thermal expansion or contraction (thermal strain) of a body is prevented, thermal stresses develop. It is common to distinguish between thermal stresses caused by external constraint and those that develop without external constraint because of temperature differences within the body. Stress can be created in a uniformly heated or cooled body if it is constrained. For the case of bodies that are not constrained, stresses in the body can be created between regions of varying temperature. For example, cooling the surface of a hot body creates tensile stresses in the surface as the contraction of the cooled material in the surface is restrained by the expanded hot core.

Thermal stresses may be large enough to result in yielding, buckling or fracture. Repeated development of thermal stresses below the elastic limit may result in the initiation and propagation of fatigue cracks.

7.2.3 Fatigue fracture control plan

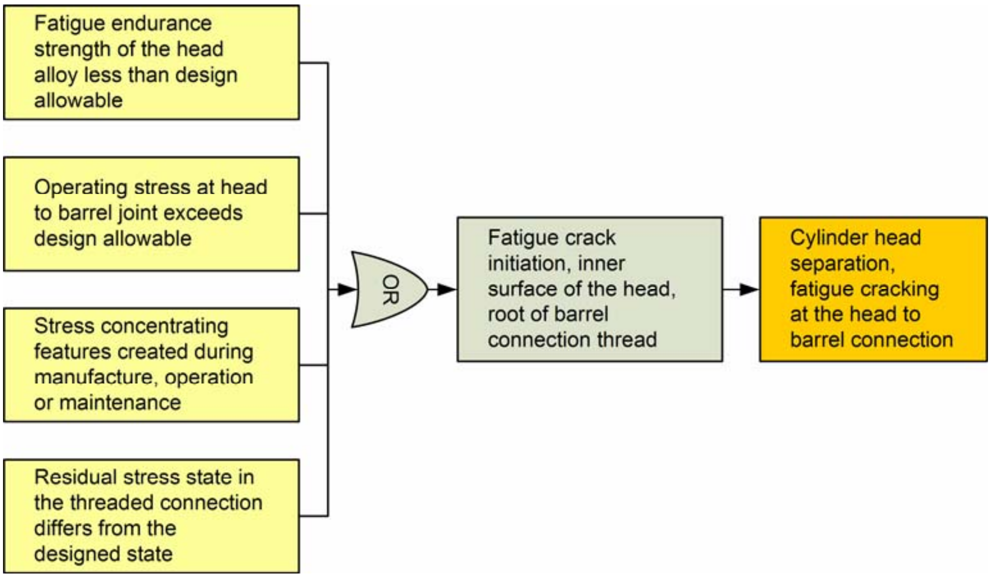
The cylinder head of an air-cooled cylinder assembly is designed to have an operational life not limited by the separation of the head from the barrel due to fatigue cracking at the head-to-barrel threaded connection. The consequences of this type of failure, through the potential to rupture fuel lines, create a threat to aircraft safe operation. The difficulty of detecting fatigue crack growth from the inner surface of the cylinder head in the vicinity of the barrel connection, and the lack of any prior warning through a loss of compression, means that fatigue cracking in this area of the cylinder head must be prevented.

In practice, the prevention of cylinder head separation through fatigue cracking is based on ensuring that the magnitude of the alternating stresses created at the head-to-barrel threaded joint, do not exceed the fatigue endurance strength of the cylinder head.

Fatigue cracking may initiate in the threaded joint between the head and barrel if any one, or combination, of the following conditions occurs:

- the fatigue endurance strength of the cylinder head is lower than the design allowable strength;
- the operating stress at the head to barrel joint exceeds the design allowable stress;
- stress concentrating features are created at the head to barrel connection during manufacture, operation, or maintenance;
- the residual stress state in the head to barrel connection differs from the designed state.

Figure 7.4: Cause-and-effect diagram for fatigue cracking in the head-to-barrel connection



Differential thermal expansion/contraction cycles may result in fatigue cracking in other areas of the cylinder head. However, this form of fatigue cracking may provide an indicator of its presence through a loss of compression prior to final fracture and may be controlled by an 'on-condition'[1] approach.

7.3 Piston crown edge melting

7.3.1 Piston design

The piston in a reciprocating engine provides a movable surface in the combustion chamber and allows the forces developed by combustion in the chamber to be transmitted to the crankshaft through the connecting rod. The piston must be able to withstand the applied forces and provide a gas sealing mechanism that operates under sliding motion.

The requirement to minimise inertia forces developed through the reciprocating action of a piston, has resulted in the use of aluminium alloys to minimise the reciprocating mass. Aluminium alloy pistons may be forged or cast.

The use of an aluminium alloy to form pistons brings with it the need to limit the piston temperature during operation. A threat to the function of a piston is created if localised melting breaches the gas sealing of the piston.

The temperature of the piston is a function of the amount of heat energy created during each combustion cycle and the rate at which heat energy is transferred from the piston. Heat energy from the combustion gases is transferred to the piston crown and is subsequently transferred through the piston rings to the cylinder barrel,

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[1] 'On-condition' means an inspection/functional check that determines a component's performance and may result in the removal of a component before it fails in service.

through the piston pin to the connecting rod, and through oil splash against the underside of the piston crown, to the engine oil. In high-power engines, additional piston cooling may be provided by directing an oil spray to the underside of the piston crown.

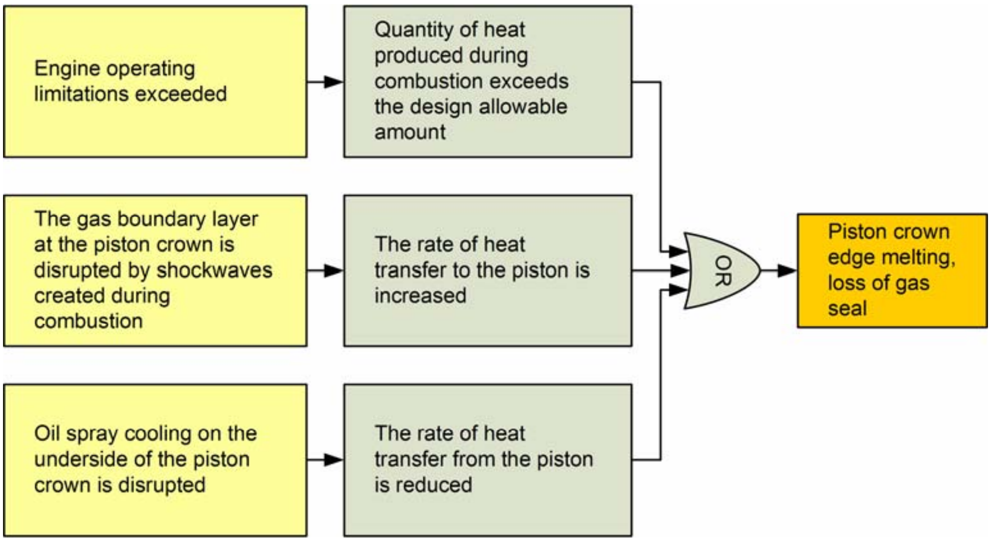
7.3.2 Melting control plan

Piston temperature is a function of a balance between the rate heat energy transfer to the piston crown and the rate of heat energy removal from the piston through the various heat flow paths. The control of piston crown melting requires the control of the rate of heat transfer to the piston crown and the rate of heat transfer from the piston.

An increase in temperature to the incipient melting point of the aluminium alloy at the edge of the piston crown will occur if any one, or combination, of the following conditions occurs:

- the quantity of heat energy produced during combustion exceeds the design allowable amount;
- the rate of heat transfer to parts of the piston crown is increased;
- the rate of heat energy transfer from the piston is reduced.

Figure 7.5: Cause-and-effect diagram for piston crown edge melting



Localised melting in an aluminium alloy cylinder head, sometimes associated with piston crown edge melting, is affected by the same parameters. The only difference is the manner in which heat is removed. Heat is transferred from cylinder heads by the provision of cooling air over the external surface of the head. Investigations of occurrences where localised melting of a piston and cylinder head have occurred, need to consider the different mechanisms of heat transfer from each component to the external environment.

7.4 Cylinder attachment fastener fatigue fracture

7.4.1 Threaded fastener design

Threaded fasteners, in the form of studs anchored in the crankcase and through bolts that join both crankcase halves, form the connections between the cylinder assemblies and the crankcase of horizontally-opposed engines. Threaded fasteners are required to allow the engine to be assembled initially and, subsequently, disassembled and reassembled during overhaul.

Each cylinder attachment fastener is subjected to alternating stresses created by the cyclic gas pressures developed in each cylinder during the combustion cycle. Because of the number of alternating stress cycles created by the combustion cycles, cylinder attachment fasteners are designed to have an operational life not limited by fatigue crack initiation and growth to final fracture.

The nature of load transfer in bolted joints between elastic members, allows the magnitude of the alternating stresses experienced by a preloaded (tightened) threaded fastener, in a joint subjected to alternating loads, to be limited to a magnitude below the endurance strength of the fastener. During assembly, a preload is created in the fastener when a torque is applied to the nut during the process of tightening. The magnitude of fastener preload is critical in limiting the magnitude of alternating stresses in the fastener.

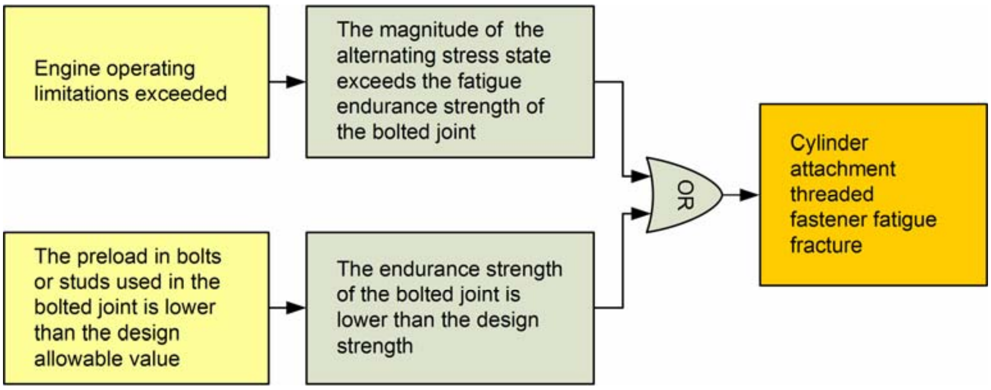
7.4.2 Threaded fastener fracture control plan

Fracture control is based on ensuring that an adequate preload is established in the fastener during assembly, and retained during operation, so that the magnitude of alternating stress in the fastener does not exceed the endurance strength of the fastener.

Cylinder attachment threaded fastener fatigue fracture may occur if any one, or combination, of the following conditions occurs:

- the magnitude of alternating loads imposed on the bolted joint exceeds the design allowable value;
- the preload established in the fastener during assembly is insufficient to achieve the design endurance strength of the bolted joint (fastener preload may be reduced after assembly if deformation occurs within the joint).

Figure 7.6: Cause-and-effect diagram for cylinder attachment threaded fastener fatigue fracture



7.5 Connecting rod bearing housing fatigue fracture

7.5.1 Connecting rod design

The connecting rod provides the link between each piston and the crankshaft. The conversion of reciprocating piston motion to rotational power creates alternating stresses in the connecting rod. The rod and bearings are placed under compression by the combustion gas pressure loads and are placed under tension by the inertia loads created by the change of piston direction at the top of its travel.

Because of the requirement to transmit force between two components in relative motion, bearings are provided at both ends of the connecting rod - the 'little-end' bearing provides the connection to the piston pin and the 'big-end' bearing provides the connection to the crankshaft journal. The differences in surface sliding speed between the low-speed oscillating motion of the little-end bearing and the high speed rotational motion of the big-end bearing, combined with the need to be able to assemble this part of the powertrain mechanism, shapes the nature of the bearing surface and the bearing housings.

The little-end bearing housings of connecting rods used in horizontally-opposed engines are of one piece. The bearing surface is provided by a press-fit leaded bronze bush. The big-end bearing housing is split, and provided with bolts, to allow assembly onto the crankshaft journal. Two precision inserts comprising of various bearing alloys coated onto a steel backing provide the bearing surface. These inserts are retained in the housing by an interference fit created by a dimensional difference between the housing and inserts, and the tightening of the big-end housing bolts.

Because of the number of alternating stress cycles created during engine operation, connecting rods are designed not to have an operational life limited by fatigue crack initiation and growth to final fracture.

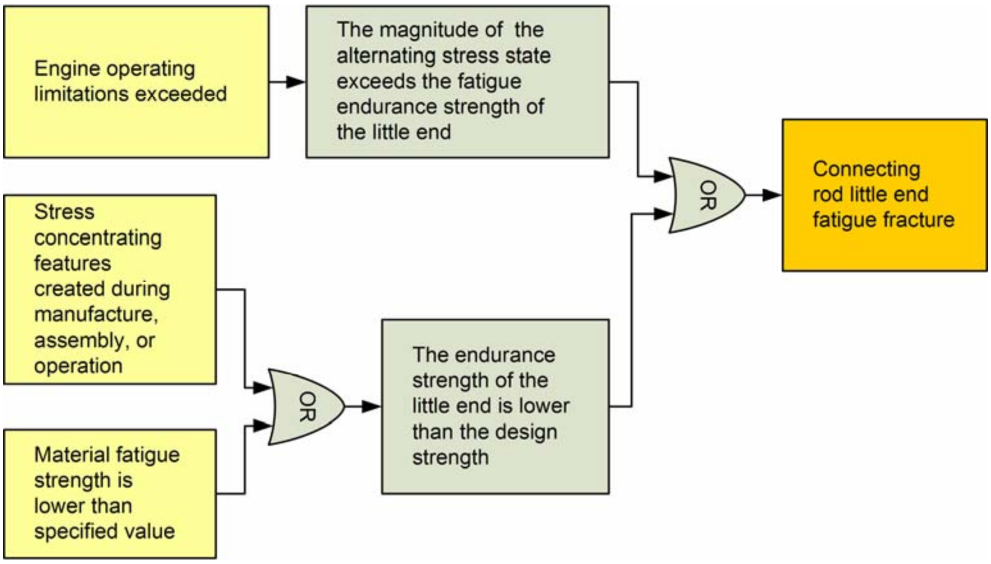
7.5.2 Connecting rod little-end fatigue fracture control

Fatigue fracture control is based on ensuring the magnitude of alternating stresses created during engine operation does not exceed the endurance strength of the connecting rod little-end.

Connecting rod little-end fatigue fracture may occur if any one, or combination, of the following conditions occurs:

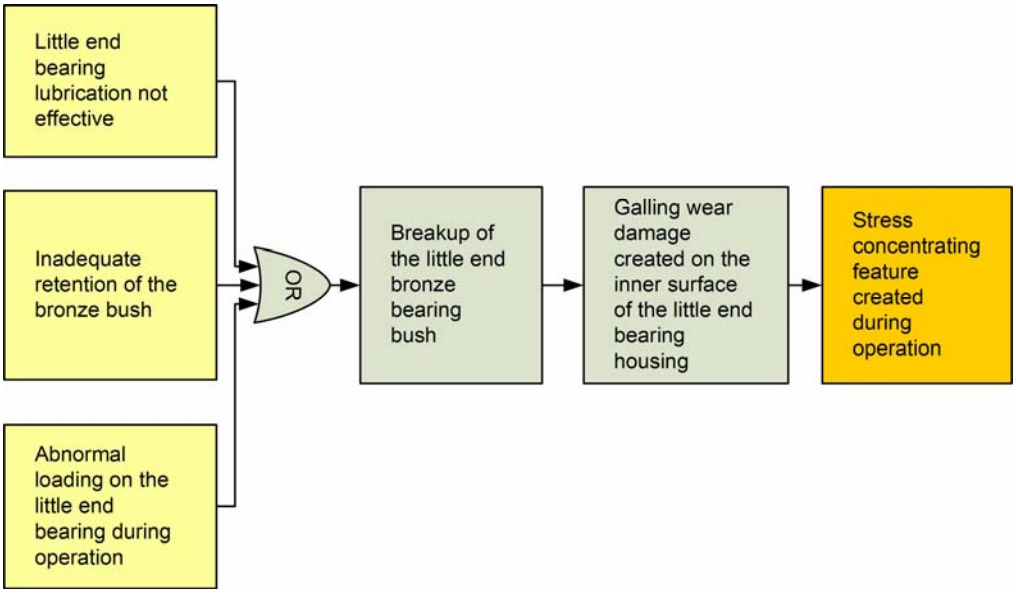
- the engine operating limitations are exceeded (the tension stress developed in the connecting rod is at a maximum when the engine is operated at maximum speed under conditions of low engine load);
- the material fatigue endurance strength is lower than the specified value;
- stress concentrating features are created in the housing during manufacture, operation or maintenance.

Figure 7.7: Cause-and-effect diagram for connecting rod little-end fatigue fracture



Each of the potential initiating events may be examined in more detail. For example, it is known that galling (adhesive wear) on the inner surface of the little-end housing is a potent initiator of fatigue cracking. However, galling cannot occur if the little-end bearing remains intact. Observations of galling between the little-end housing and piston pin, requires a sequence of events to occur that result in the breakup of the little-end bearing. These events may relate to the lubrication of the bearing, the magnitude of the bearing retention force, or an abnormal loading condtion.

Figure 7.8: **Cause-and-effect diagram for the creation of a stress concentrating feature in the little-end housing during operation**



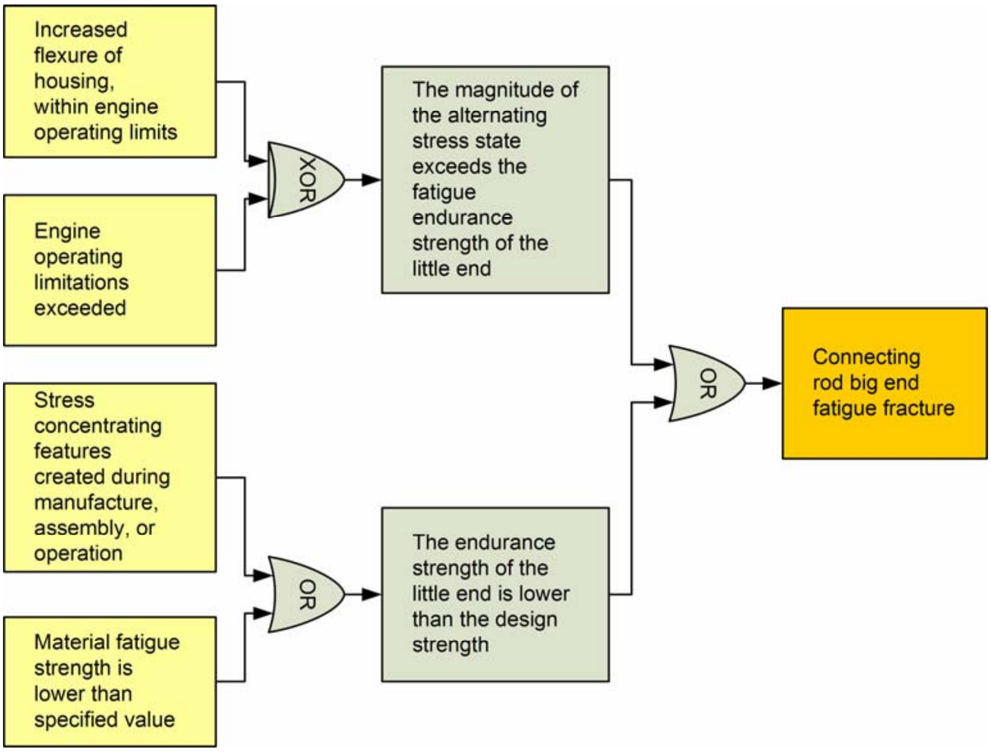
7.5.3 Connecting rod big-end fatigue fracture control

Fatigue fracture control is based on ensuring that the magnitude of alternating stresses created during engine operation does not exceed the endurance strength of the connecting rod big-end. Because the big-end housing is a bolted assembly, and because it is larger than the little-end housing, fracture control is more complex. In addition to stresses developed through gas pressure loads and inertia, stresses arising from housing flexure need to be considered. A fracture control plan also has to be developed for the bolts used to assemble the housing. The control of bolt fatigue fracture is based on the establishment of a preload in the bolt, of sufficient magnitude, to prevent the alternating stresses in the bolt exceeding the endurance strength of the bolt.

Connecting rod big-end fatigue fracture may occur if: any one, or combination, of the following conditions occurs:

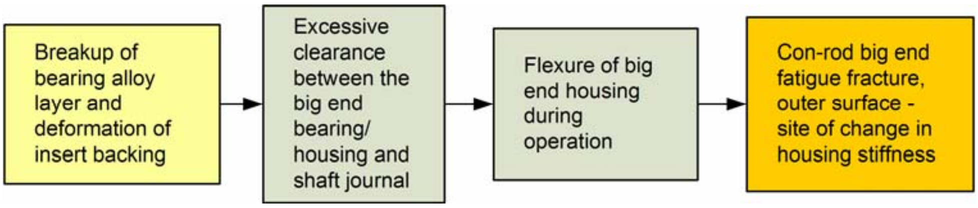
- the engine operating limitations are exceeded (the tension stress developed in the connecting rod is at a maximum when the engine is operated at maximum speed under conditions of low engine load, the compression stress developed in the connecting rod is at a maximum when the engine is operated under conditions that create maximum combustion gas pressures);
- the material fatigue endurance strength is lower than the specified value;
- the flexure of the housing is increased while operating within specified engine limits;
- stress concentrating features are created in the housing during manufacture, operation or maintenance.

Figure 7.9: **Cause-and-effect diagram for connecting rod big-end fatigue fracture**



Each initiating event may be examined in more detail, for example, a fatigue fracture initiating on the housing outer surface, at a point of change in stiffness, may be associated with a chain of events that starts with the breakup of the big-end bearing inserts.

Figure 7.10: **Cause-and-effect diagram for fatigue fracture at a point of change in big-end housing stiffness**



7.6 Crankshaft fatigue fracture

7.6.1 Crankshaft design

The crankshaft in a multicylinder reciprocating engine combines the force created by combustion of the fuel-air mixture in each cylinder to provide rotational power at the end of the shaft.

The crank is the key element in the mechanism for translating reciprocating motion to rotary motion. Cranks are formed by bending a shaft through several right angle bends so that a small section of the shaft is displaced parallel to the main axis of the shaft.

The form of a crankshaft is shaped by; the length of the crank arm, the arrangement of multiple cylinders around the crankshaft, the need to provide bearing journals of sufficient area to maintain bearing loads within the design limit of the bearing, and to limit the magnitude of crankshaft alternating stresses developed during engine operation.

During engine operation each crank is acted upon by the gas pressure developed in the combustion chamber; the inertia forces of the reciprocating masses, and centrifugal forces developed by rotation. These forces on the crankshaft are created by the engine through the crankshaft main bearings to the crankcase and engine mounts. During each combustion-exhaust-induction-compression cycle (two crankshaft revolutions for a four stroke engine) the forces acting on the crank vary continuously in magnitude and direction.

The varying forces acting on a crankshaft create alternating stresses in the shaft through the alternating flexure of the shaft in both lateral and torsional directions. The magnitude of the alternating stresses created by the alternating lateral and torsional flexure of the shaft, depends on the manner in which multiple cylinders are attached to the crankshaft and the detail of design of journals and crankwebs.

There are only two ways to arrange multiple cylinders around a crankshaft; in a row or rows along the length of the crankshaft, or radially around a crankshaft like the spokes of a wheel. The two layouts of interest to aircraft reciprocating engines are the horizontally-opposed layout (two equal rows of cylinders all within the same horizontal plane) and the radial layout (one or more banks of up to nine cylinders arranged around the crankshaft).

Because the cylinder layouts of radial and horizontally-opposed engines are very different, the form of the crankshafts are very different and the phenomena that have impacted on crankshaft reliability are different.

The short length of a radial-engine crankshaft, and its inherent lateral stiffness, limits the magnitude of stresses developed through lateral flexure. The effect of the impulses from combustion pressures in multiple cylinders, acting on one crank for each revolution of the shaft, creates the need to control the magnitude of stresses developed through torsional flexure and the potential for resonant conditions.

The length of a horizontally-opposed engine crankshaft, the limited stiffness of the engine crankcase, and the placement of main bearings between every two connecting rod journals, creates the need to control the magnitude of stresses developed through lateral flexure, as well as the stresses developed through torsional flexure.

Inherent points of stress concentration are created at the transitions between the crankshaft bearing journal and the crankwebs. The magnitude of alternating stresses at these sites, created by crankshaft flexure, is controlled by; the sizing of journals and crankwebs, the overlap between adjacent journals, the rigidity of the supporting structure (crankcase), the size of the fillet radius between the journals and crankwebs, and the creation of residual compressive stresses in the material at the fillets.

The dimensions of the bearing journals are also based on a consideration of the maximum allowable bearing loading.

Because the journals are subjected to abrasive wear, through the action of fine abrasive particles suspended in the lubricating oil, journal surfaces in aircraft engines are hardened. Nitriding is the preferred method of hardening. In addition to creating a wear resistant surface, nitriding also creates a compressive residual stress in the surface zone of the journal and journal fillets. This residual compressive stress acts to increase the resistance to fatigue crack initiation in the region of the journal.

7.6.2 Crankshaft fatigue fracture control

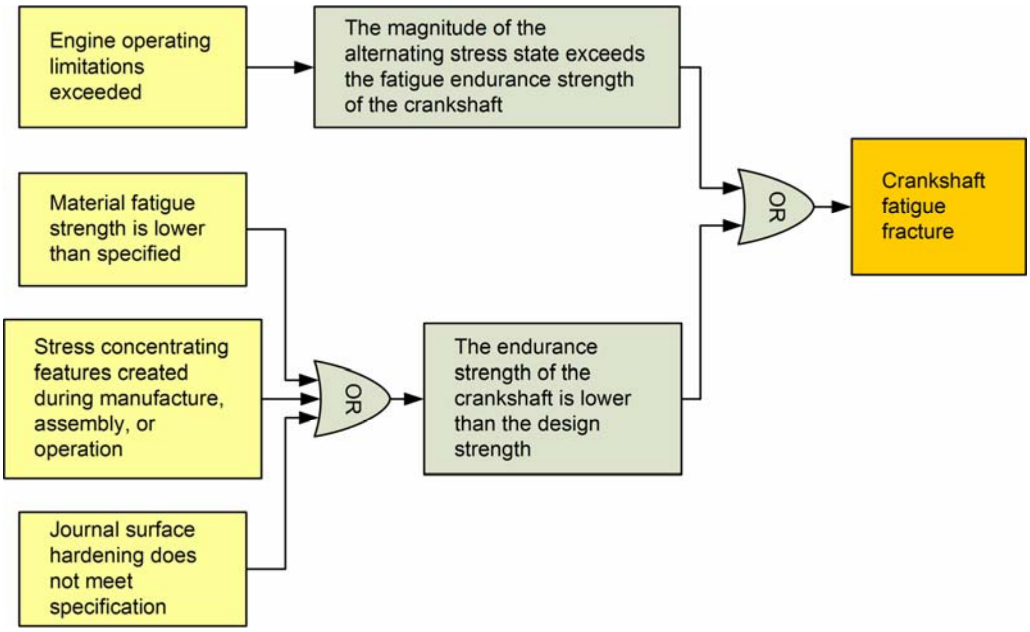
Because of the very high number of alternating loading cycles created by engine operation (thousands per minute – engine revolutions), crankshaft design, regardless of the end application of the engine, is centred on restricting the magnitude of alternating stresses created by the alternating external loads so that the fatigue endurance strength of the crankshaft is not exceeded. Crankshafts are designed to have a life not limited by the initiation and growth of fatigue cracks.

The endurance strength of a crankshaft is a function of; the geometry of the shaft (dimensions of journals, webs, and journal fillets), the presence of surface hardening, the presence of residual compressive surface stresses, and the crankshaft material properties. Reductions in the endurance strength of a crankshaft to levels below the design limit may erode safety margins and result in fatigue fracture during engine operation. Similarly, increases in the magnitude of alternating stresses developed during engine operation that exceed the design limit may erode safety margins and result in fatigue fracture during operation.

Crankshaft fatigue fracture may occur if any one, or combination, of the following conditions occurs:

- engine operating limitations, such as, engine maximum speed or combustion gas pressures (bmep), are exceeded;
- stress concentrating features are created at critical locations during manufacture, operation or maintenance;
- the journal surface hardening treatment does not meet the design specification;
- the fatigue strength of the steel alloy is lower than the design allowable value.

Figure 7.11: Cause-and-effect diagram for crankshaft fatigue fracture



7.7 Powertrain plain bearing failure

7.7.1 Plain bearing design

Plain bearings are used to allow the transmission of force between the piston, connecting rod, crankshaft, and crankcase. Plain bearings operate through the creation of a hydrodynamic oil film when two components are moving relative to each other. A slight eccentricity in the rotation between the two components results in a converging wedge geometry being formed between the two bearing surfaces. The action of rotation with convergent wedge geometry is to increase the oil pressure, from the supply pressure, to a pressure that prevents bearing surface contact under the loads imposed on the bearing during engine operation.

Because hydrodynamic lubrication is dependent on rotation between two components, there will be short periods when the rotational speed is insufficient to establish or maintain hydrodynamic lubrication. This lubrication regime is known as boundary lubrication and, normally, is encountered during engine starting and stopping when the operational loads are low. Bearing surfaces are designed to accommodate these periods of bearing surface sliding contact, without seizure, through the principle that low friction sliding contact occurs between dissimilar metals. For example, lead-tin alloys, aluminium-tin alloys, and lead-copper alloys are used as bearing couples with steel.

The bearing load is a function of the bearing area and the magnitude of the operational load. For the case of powertrain bearings, two types of relative motion shape the size and nature of the bearings. The motion between the piston pin and connecting rod little-end bearing is characterised by low-speed oscillating movement. Because oscillating bearings operate at low average surface speeds, the problem of wear is less than that in rotating bearings as the heat generated by friction is relatively small, so bearing material selection is made on the basis of high endurance strength in preference to low friction surfaces, conformability and embedability. As the name suggests, the connecting rod little-end bearing is smaller than the big-end bearing, and a leaded bronze alloy is used as the bearing material.

The high-speed rotational movement between the connecting rod big-end and crankshaft, and between the crankshaft and main bearings in the crankcase, require a consideration of wear, heat, endurance strength, and bearing load.

A limit on the use of a simple coating of lead or tin alloy on a bearing housing, is the low-bearing load capacity of the alloy under repeated loading conditions (low fatigue strength). Bearings have developed from in-situ formed lead-tin or tin-lead alloy coatings, to precision bearing inserts with various alloy layers, in response to the need to; provide accurate geometric conditions necessary for hydrodynamic lubrication, cope with boundary lubrication, and allow efficient replacement after wear.

Connecting rod big-end bearings and crankshaft main bearings are manufactured as a laminate of different metal alloys; depending on the number of layers used they are termed bimetal or trimetal bearings. Each layer in the bearing insert has a particular function.

A low-carbon steel layer provides support to the bearing alloy layers. The strength of the steel allows the bearings to be seated in their housings with a high degree of conformance and be retained by an interference-fit force sufficient to retain the inserts under all normal operating conditions. Precision bearing inserts are retained in their housings by an interference fit created during assembly. Simply, the circumference of the outer surface of the precision bearing inserts exceeds the circumference of the housing bore. The difference in dimension is commonly referred to as ‘bearing crush’. The lugs formed on the end of each insert are provided to locate the inserts accurately in the housing prior to final tightening of the housing bolts. The surface finish of the housing and precision bearing insert backs are required to be of high quality to ensure that the bearing is not distorted, the interference fit is established, and heat transfer through metal-to-metal contact can occur.

The factors that determine which bearing alloy is used, are related to the need to be able to withstand the repeated bearing loads created by the alternating inertia and combustion gas pressure loads and the surface properties of the bearing. For the case of light-weight high-power engines, the fatigue-endurance strength of the bearing alloy needs to be maximised.

Lead-tin or tin-lead alloys provide the best bearing surface under conditions of boundary lubrication and the best ability to accommodate fine abrasive material (embedability) entrained in the lubricating oil. However, they have the lowest fatigue endurance strength.

The optimum bearing performance is achieved through a thin layer of lead-tin alloy bonded to a thicker layer of a copper-lead, or aluminium-tin, bearing alloy layer, which is in turn, bonded to a steel backing layer. Bearing inserts of this type are known as trimetal bearings. The intermediate bearing material increases the fatigue endurance strength of the bearing and provides protection from seizure if the overlay is removed, by wear, within the specified overhaul interval of the engine.

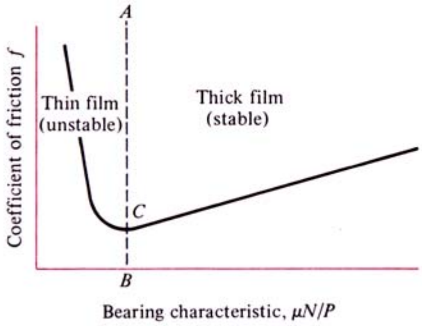
7.7.2 Plain bearing failure control plan

Plain bearings can be considered to have failed when; seizure occurs between the bearing surfaces, the bearing surface breaks up to an extent that destroys the hydrodynamic lubrication operating regime, or when other associated components are damaged by wear, increased flexure, or heat. Plain bearing failure control plans are based on the maintenance of hydrodynamic lubrication under all operating conditions, except the low load conditions at engine start and stop, and the retention of bearing inserts in their housings.

The critical features for successful bearing operation are the dimensions and geometry of the shaft and bearing, the surface roughness of the shaft and bearing, the rotational speed of the shaft in the bearing, and oil viscosity.

Hydrodynamic oil films possess some capacity for self correction when changes occur in oil viscosity, bearing load or shaft speed. The extent of oil film stability is commonly shown by the relationship between the coefficient of friction of the bearing and the bearing characteristic parameter, μN/P (μ –viscosity, N – rotational speed, P – load per unit of projected bearing area), see figure 7.12.

Figure 7.12: Variation of the coefficient of friction with bearing characteristic parameter (Shigley and Mischke, 1989, p.485)



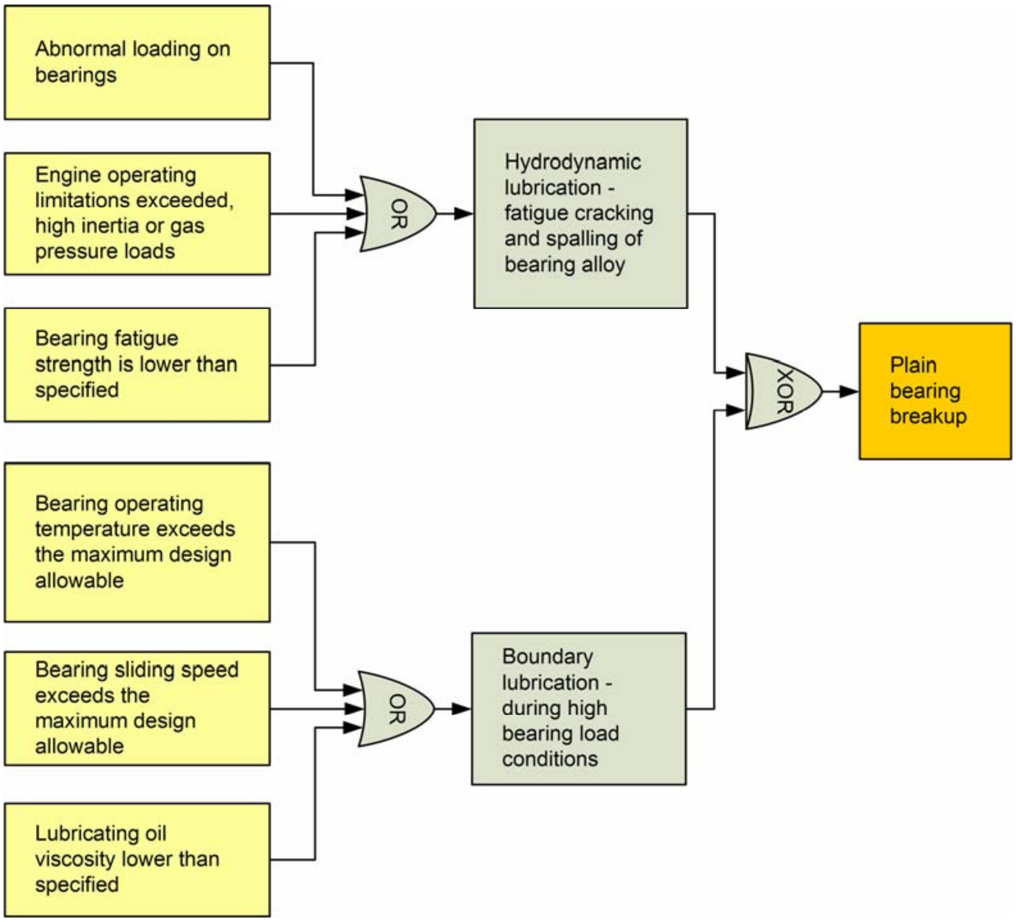
If the bearing operating parameters are to the right of the line BA and there is a change in viscosity, speed or loading pressure that decreases the bearing characteristic parameter, then the reduction in friction results in a reduction in heat in the lubricant and an increase in viscosity. If the bearing parameters lie to the left of the line BA, then a decrease in viscosity would increase friction, a temperature rise would occur and the viscosity would be reduced further, resulting in unstable lubrication and the increasing possibility of metal to metal contact.

The magnitude of clearance between the bearing and shaft has an important effect on plain bearing performance (Shigley and Mischke, 1989, p.508). If the radial clearance is too tight, the temperature within the bearing will be too high and the oil film thickness will be too low. Large clearances also result in low oil film thickness.

Bearing failure may occur through fatigue cracking in the bearing alloy under full oil film conditions if the repeated bearing pressure loads are higher than the design allowable value or the bearing endurance strength is lower than the design allowable value.

Bearing failure, through excessive wear or excessive friction, may occur if boundary lubrication conditions occur during periods of high bearing load. Boundary lubrication is favoured by high bearing operating temperatures, sliding speeds that exceed the design allowable value, and oil viscosities lower than the design allowable value.

Figure 7.13: Cause-and-effect diagram for plain bearing breakup

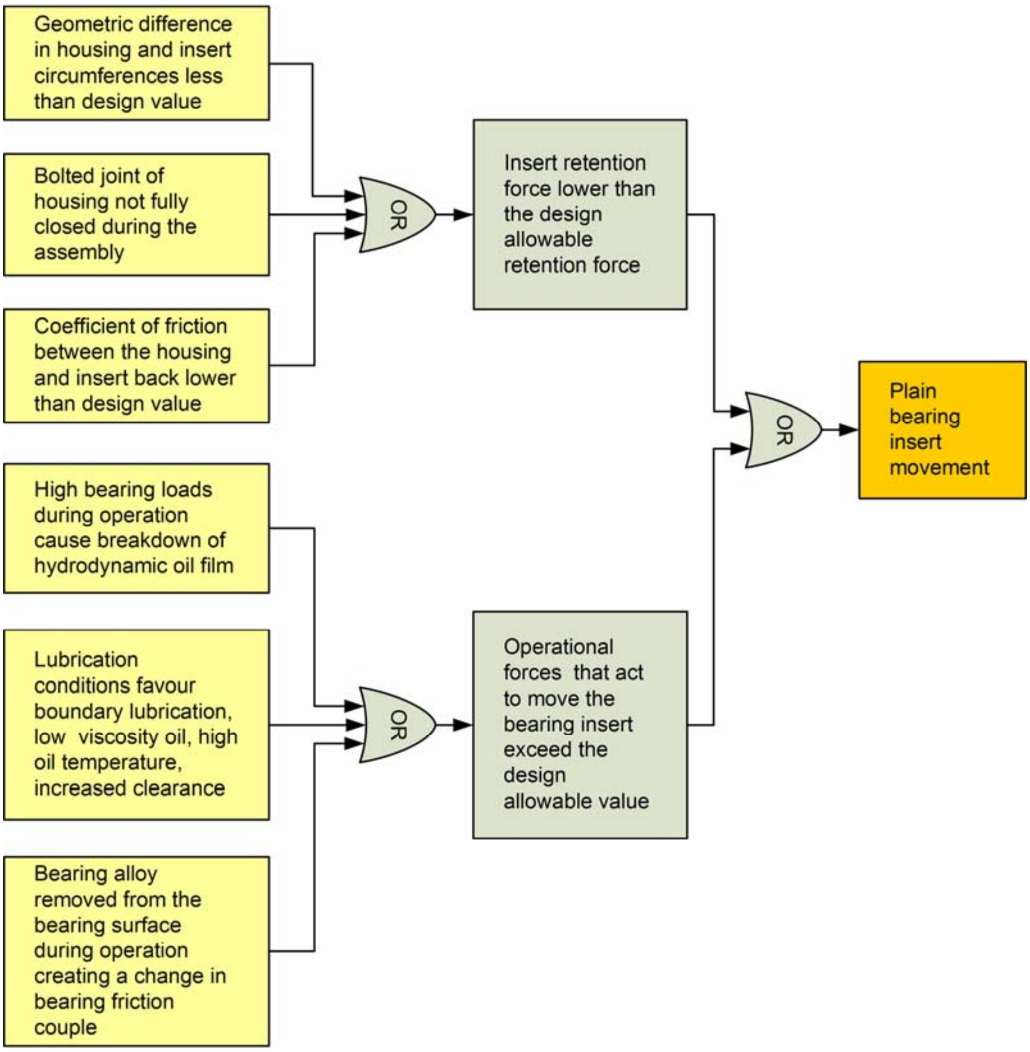


Plain bearings can also be considered to have failed if the bearing inserts are displaced from their housings and damage is created in other components, for example, housing surfaces or journal fillets. The control of bearing insert movement is based on creating a retention force of sufficient magnitude to resist the operational forces that act to move inserts during engine operation.

Bearing insert movement may occur if the insert retention force is lower than the design allowable force. The retention force is developed by an interference fit and, as such, is affected by the geometric differences between the housing and insert, the closure of the bolted assembly, and the coefficient of friction between the insert back and housing surface.

Bearing insert movement may also occur if the operational forces on the bearing insert exceed the design allowable force. Boundary lubrication under high engine loading conditions, shaft flexure beyond design allowable limits, and high friction coefficients between the bearing and journal surface, following wear of the bearing surface, may result in insert movement.

Figure 7.14: Cause-and-effect diagram for plain bearing insert movement



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8 ANALYSIS OF POWERTRAIN STRUCTURAL FAILURES

8.1 Introduction

The initiating events leading to powertrain structural failures investigated in this study, are dominated by combustion chamber component melting, the initiation and growth of fatigue cracking in components that are designed to have a life not limited by fatigue, and plain bearing breakup or movement. The factors that contribute to these initiating events are those factors that affect heat transfer to and from components, affect the fatigue endurance strength of a component and the magnitude of alternating stresses during engine operation, and affect bearing surface behaviour and bearing insert retention in their housing. Engine design seeks to control these factors, so that the sequence of events leading to powertrain component failure does not occur during engine operation.

For the engines studied, operational experience has established that powertrain components can perform reliably within the specified operational limits, overhaul periods, and maintenance actions. There is no one solution to the goal of producing a specified output power/torque for a minimal weight. While some design features displayed by different models and different manufacturers are similar, other features are different. For example: a particular power output may be achieved by various combinations of gas pressure (bmep) and engine speed; component fatigue endurance strength may be achieved by a combination of the sizing of the component and the dimensions of design details such as fillets.

Use is made of safety factors to achieve a reliable design in situations where properties are not known with certainty and behaviours are not clearly defined. It is important to be aware that safety factors are not constant for all components and all conditions. Some engine designs will display sensitivity to variations in particular initiating factors. Variations from predicted properties and behaviours may occur during component manufacture, engine assembly, engine operation, and engine maintenance.

In order to understand why powertrain components and high-power reciprocating engines are not meeting the expectation of reliable operation, it is necessary to examine, in detail, the factors that affect component melting, fatigue crack initiation, and bearing behaviour. There are relationships between these factors that range from simple to complex. For example, the factors involved with the combustion of the fuel-air mixture may affect the rate of heat transfer to combustion chamber components and affect the nature of stresses developed in a number of powertrain components (connecting rods, crankshafts, bearings, fasteners). It is also apparent that in any one engine, multiple event sequences may occur

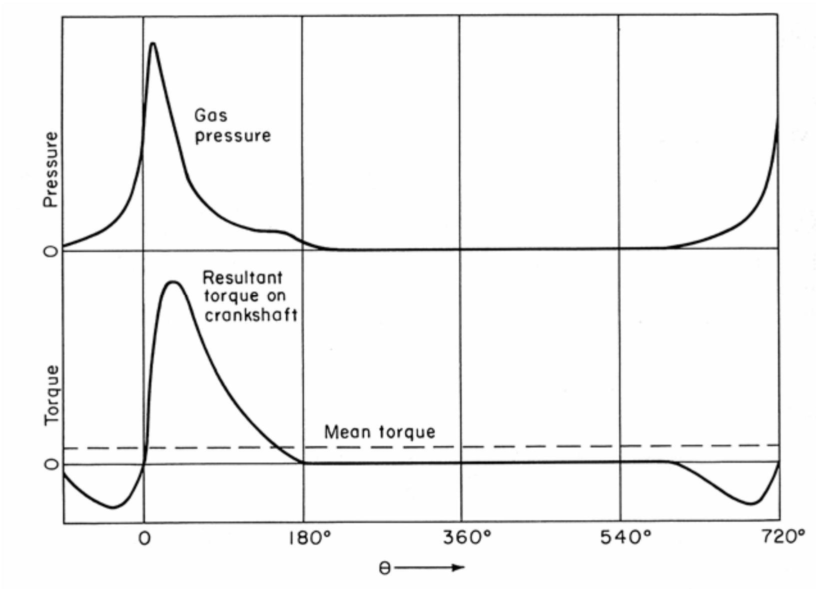
8.2 Factors associated with combustion

8.2.1 Normal combustion

The operation of a conventional spark-ignition engine is based on the combustion of a gaseous mixture of hydrocarbon fuel and air. The process of combustion is characterised by the propagation of a flame front (a narrow zone of intense chemical reactions) radiating from the site of spark ignition. When flame propagation continues throughout the entire fuel-air charge, without abrupt change in speed or shape, combustion is termed normal.

As far as engine performance is concerned, the important aspect of flame propagation is on the development of gas pressure in each combustion chamber. A secondary issue is the control of the effects of heat generated by discontinuous combustion.

Figure 8.1: Typical curve of gas pressure versus crank angle (θ) for a 4-cycle engine, with resultant torque on crankshaft, (Taylor, 1999, vol.2 p.270)



Combustion process design is based on control of flame propagation within the engine design allowable limits of maximum pressure and rate of pressure rise.

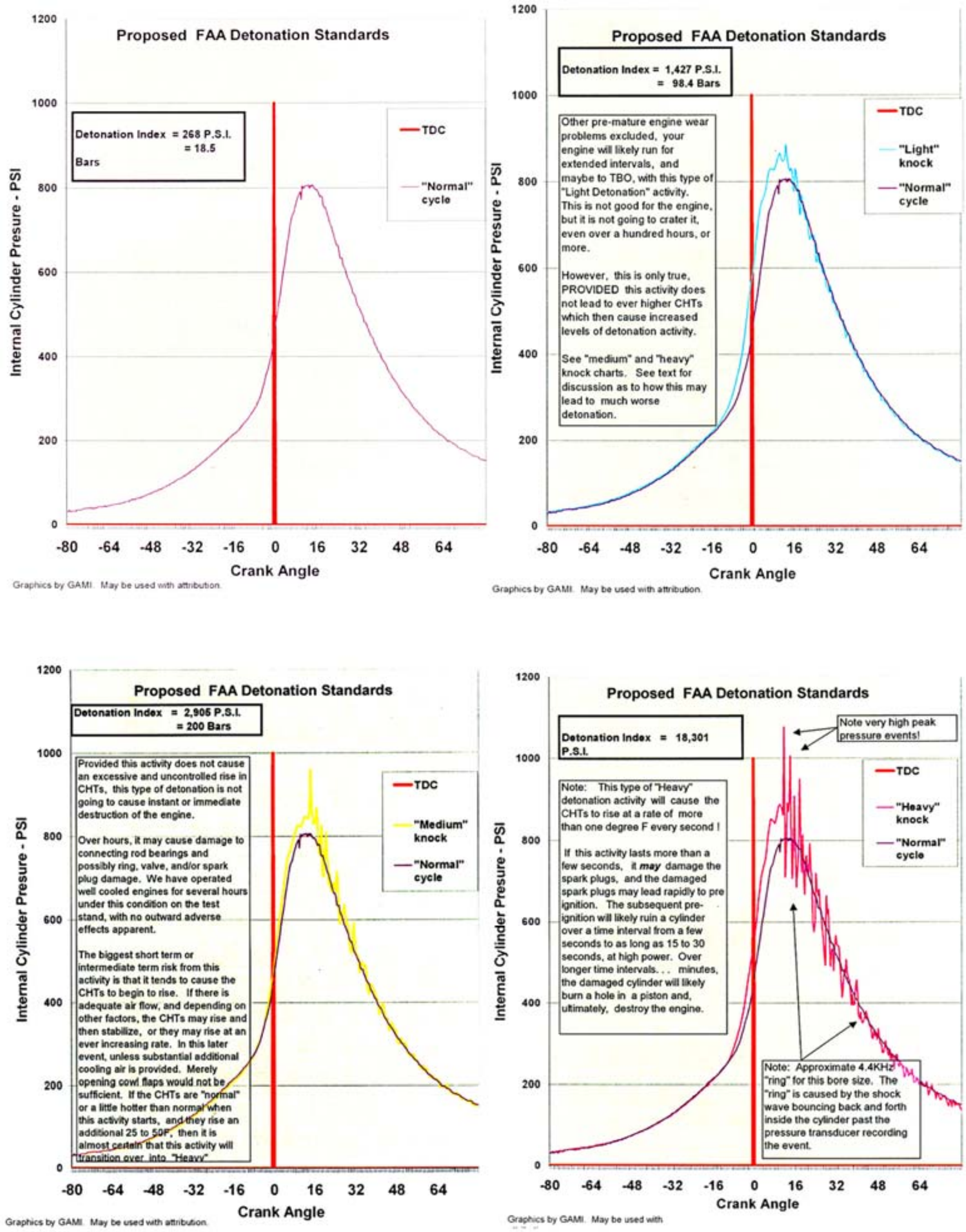
For an established aircraft engine design, the operator-controlled variables of engine power setting, temperature control, and fuel-air mixture selection, have a significant effect on the combustion process through their affect on flame velocity, maximum gas pressure, and fuel-air charge temperature.

8.2.2 Abnormal combustion – detonation

Combustion may not always progress to completion by the propagation of a flame front through the fuel-air mixture. There are occasions when the conditions in the combustion chamber result in the combustion of the fuel-air mixture in front of the flame front. This phenomenon is described as auto-ignition. The sudden increase in the rate of combustion created by auto-ignition. The accompanying propagation of shockwaves through the gas in the combustion chamber is known by the term detonation (Taylor 1999, vol.2 pp.34-85).

Detonation may affect the reliability of powertrain components through increased maximum pressure, increased pressure rise rate, and increased heat transfer to pistons and cylinder heads. The effect of detonation on powertrain reliability is a function of the intensity of detonation. The intensity of detonation, in turn, is related to the volume of end-gas that is involved in the auto-ignition event – the larger the volume of end-gas subjected to auto-ignition, the more intense the detonation. Examples of combustion chamber pressure development for varying degrees of detonation are shown in figure 8.2.

Figure 8.2: **Examples of detonation on pressure development in a reciprocating-engine combustion chamber (GAMI)**



Detonation Index = 268 P.S.I. = 18.5 Bars

Graphics by GAMI. May be used with attribution.

Detonation Index = 1,427 P.S.I. = 98.4 Bars

Other pre-mature engine wear problems excluded, your engine will likely run for extended intervals, and maybe to TBO, with this type of "Light Detonation" activity. This is not good for the engine, but it is not going to crater it, even over a hundred hours, or more.

However, this is only true, PROVIDED this activity does not lead to ever higher CHTs which then cause increased levels of detonation activity.

See "medium" and "heavy" knock charts. See text for discussion as to how this may lead to much worse detonation.

Graphics by GAMI. May be used with attribution.

Detonation Index = 2,905 P.S.I. = 200 Bars

Provided this activity does not cause an excessive and uncontrolled rise in CHTs, this type of detonation is not going to cause instant or immediate destruction of the engine.

Over hours, it may cause damage to connecting rod bearings and possibly ring, valve, and/or spark plug damage. We have operated well cooled engines for several hours under this condition on the test stand, with no outward adverse effects apparent.

The biggest short term or intermediate term risk from this activity is that it tends to cause the CHTs to begin to rise. If there is adequate air flow, and depending on other factors, the CHTs may rise and then stabilize, or they may rise at an ever increasing rate. In this later event, unless substantial additional cooling air is provided. Merely opening cowl flaps would not be sufficient. If the CHTs are "normal" or a little hotter than normal when this activity starts, and they rise an additional 25 to 50F, then it is almost certain that this activity will transition over into "Heavy"

Graphics by GAMI. May be used with attribution.

Detonation Index = 18,301 P.S.I.

Note very high peak pressure events!

Note: This type of "Heavy" detonation activity will cause the CHTs to rise at a rate of more than one degree F every second !

If this activity lasts more than a few seconds, it *may* damage the spark plugs, and the damaged spark plugs may lead rapidly to pre ignition. The subsequent pre-ignition will likely ruin a cylinder over a time interval from a few seconds to as long as 15 to 30 seconds, at high power. Over longer time intervals. . . minutes, the damaged cylinder will likely burn a hole in a piston and, ultimately, destroy the engine.

Note: Approximate 4.4KHz "ring" for this bore size. The "ring" is caused by the shock wave bouncing back and forth inside the cylinder past the pressure transducer recording the event.

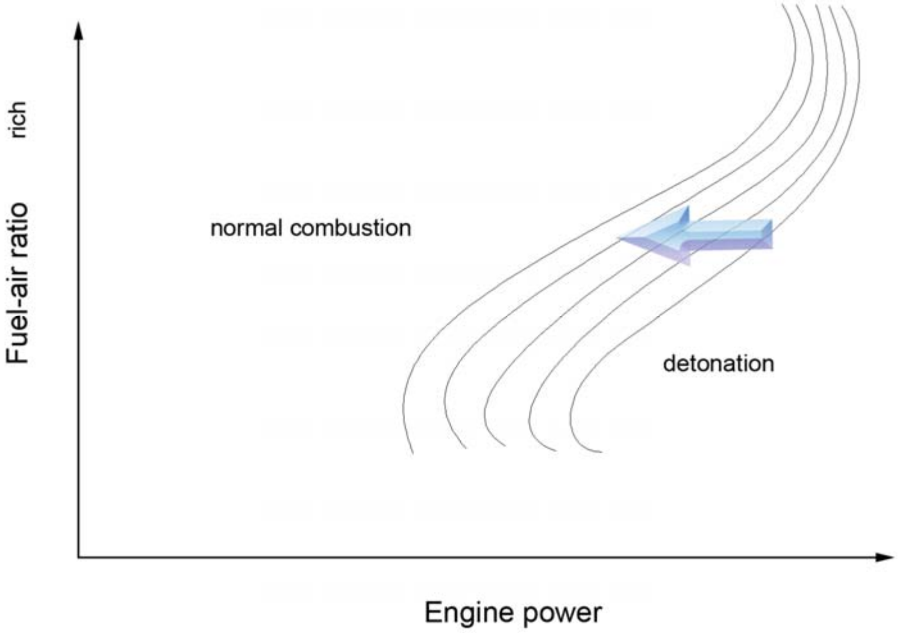
Graphics by GAMI. May be used with

The aim of engine design is to establish the combination of mechanical design, fuel resistance to auto-ignition (octane rating), and operational control that allows engine power to be developed without detonation.

For an established engine design, and a fuel of known detonation resistance, the likelihood of end-gas detonation is dependent on those factors that increase the temperature of the end gas (Taylor 1999, vol.2 p.61) – factors such as; inlet air temperature, extent of inlet air pressure boosting (turbo-charging), combustion chamber surface temperature, high power setting, high rate of pressure rise (ignition advance or surface ignition in addition to spark ignition), and fuel-air mixture. Detonation control is based on establishing operational limits for each of these factors.

Fuel-air mixture control is an important variable in the control of detonation in aircraft reciprocating engines, rich mixtures allow higher engine power to be developed without detonation, while at lower engine power, leaner mixtures allow less fuel to be used. A typical relationship between engine power and fuel-air mixture is shown in figure 8.3. The effect of fuel-air mixture variation is related to the effect of the fuel-air ratio on the velocity of flame propagation and, particularly at very rich mixtures, the cooling effect of fuel vapourisation. Flame velocity is a maximum at a mixture that is slightly rich of the stoichiometric[1] mixture and decreases as the fuel-air ratio is increased (enriched) or decreased (leaned) (Turns, 1996, pp.224-225).

Figure 8.3: Schematic representation of detonation boundaries, as a function of fuel-air ratio and engine power setting, for variation in factors that increase the tendency for detonation (AFM 51-9, 1954)



Any change that increases the tendency for end-gas detonation to occur will shift the detonation boundary in the direction of the arrow, lowering the detonation limited power for constant fuel-air ratios.

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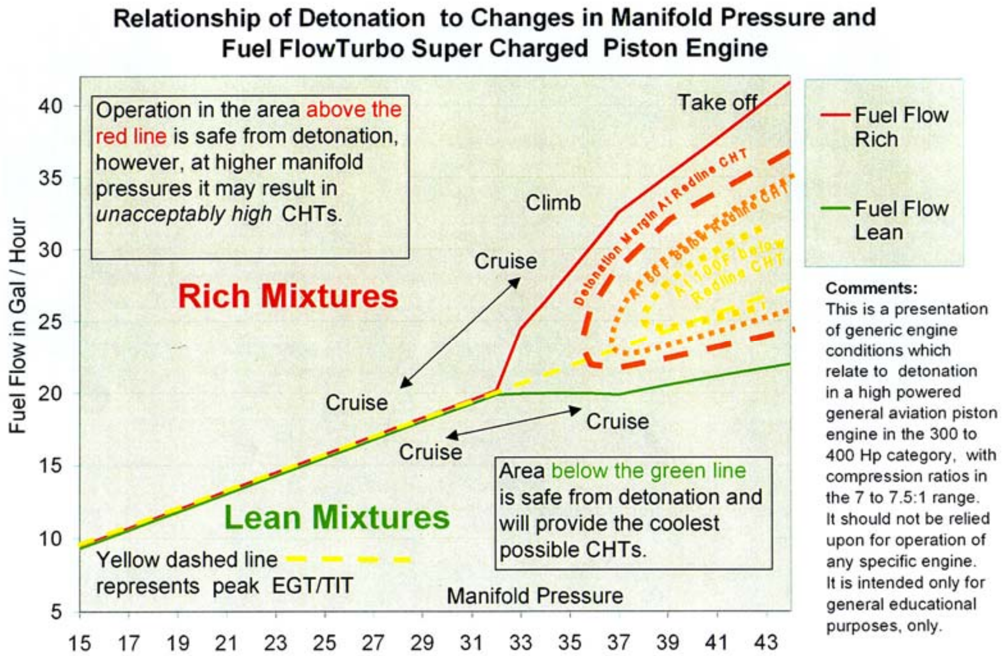
[1] The stoichiometric mixture is the mixture of fuel and air that results in the complete combustion of the mass of fuel with the mass of oxygen in the air

The relationship between engine power setting (manifold pressure), fuel-air mixture (fuel flow) and detonation, has been determined experimentally for a high-power horizontally-opposed air-cooled aircraft reciprocating engine (GAMI), figure 8.4.

Figure 8.4: Effect of mixture and power setting with effect of variation in cylinder head temperature (GAMI)



Comments:
This is a presentation of generic engine conditions which relate to detonation in a high powered general aviation piston engine in the 300 to 400 Hp category, with compression ratios in the 7 to 7.5:1 range. It should not be relied upon for operation of any specific engine. It is intended only for general educational purposes, only.

Graphic by George W. Braly at GAMI. May be used with attribution.

Pre-ignition and multiple ignition events

The term pre-ignition refers to the ignition of the fuel-air mixture before normal spark ignition. In this case, ignition of the charge is caused by contact with a hot surface, for example, hot spark plug electrode or other heated, high melting point materials, projecting into the combustion chamber. The effects of pre-ignition are similar to an increase in spark advance – the rate of pressure rise is increased and, with the consequent increase in end-gas compression heating, there is an increased tendency for detonation to occur.

The term pre-ignition is also used to refer to a runaway detonation process where detonation leads to a cycle of combustion chamber heating, the creation of non-spark ignition sites, more intense detonation, and finally combustion chamber component melting.

Ignition of the fuel-air mixture from hot surfaces may also occur after the spark ignition event. In this case, additional flame fronts are created and the mixture is combusted more rapidly, resulting in a rapid rate of pressure rise.

Combustion chamber deposits

In a clean engine, it is usual for detonation to be the limiting factor for maximum manifold pressure or compression ratio. However, pre-ignition has been found to be the limiting factor (Taylor 1999, vol.2, p.153) in high-compression engines that have accumulated deposits from the combustion of leaded fuels. The heated deposits create non-spark ignition sites, either prior to spark ignition or after spark ignition.

The presence of deposits on combustion surfaces may also increase the tendency for detonation. This increase in susceptibility has been attributed to an increase in effective compression ratio (lowering of combustion chamber volume) and an increase in combustion chamber surface temperature (Taylor 1999, vol.2, p.84).

8.2.3 The effect of combustion on engine roughness

In addition to controlling the maximum combustion chamber pressure (measured as the brake mean effective pressure), engine roughness is a phenomenon that affects engine design. Roughness has been observed in spark-ignition engines when the rate of pressure rise developed through normal combustion exceeds a particular level. Investigation has shown that roughness is caused by severe vibration of certain engine parts, usually including crankshaft bending vibration (Taylor, 1999, vol.2, p.32). Roughness can be controlled by controlling the rate of pressure rise during combustion or by stiffening the engine structure.

The mechanical control of roughness relies on creating a stiff engine structure. In particular, in order to eliminate crankshaft bending vibration, the crankshaft needs to be stiff and the supporting crankcase structure needs to be stiff (Taylor, 1999, vol.2, p.297). Short compact engines, with generous crankshaft dimensions, are inherently stiffer `than longer engines, for example, the V8 engine layout is stiffer than the inline eight-cylinder layout.

When an engine structure cannot be stiffened, roughness can only be controlled by reducing the rate of pressure rise. For cases where the combustion chamber design is fixed, control of the flame speed may be used to control the rate of pressure rise.

8.2.4 Combustion chamber condition - engines studied

Examination of the combustion chambers from the engines examined in this study, where available, revealed that deposits of a lead oxybromide compound, $Pb_3O_2Br_2$ (Heath et al., 2005), were present on piston crowns and cylinder heads, figures 8.5 - 8.24. This compound is not volatile, melting point 709°C, 1308°F (Newby and Dumont, 1953), and persists on the combustion chamber surfaces during continued engine operation. The presence of glassy (melted and resolidified) deposit edges, see for example figure 8.16, provides evidence that lead oxybromide deposits have been heated, locally, to temperatures exceeding its melting point during engine operation. It is likely that these deposit 'hot spots' would provide sites of fuel-air mixture ignition.

It is also evident that there is a cycle of deposit buildup followed by deposit loss through the mechanical effects of heating and cooling, and, possibly, detonation.

Figure 8.5: Cylinder head surface condition, 2000/90, VH-MZK (left engine)

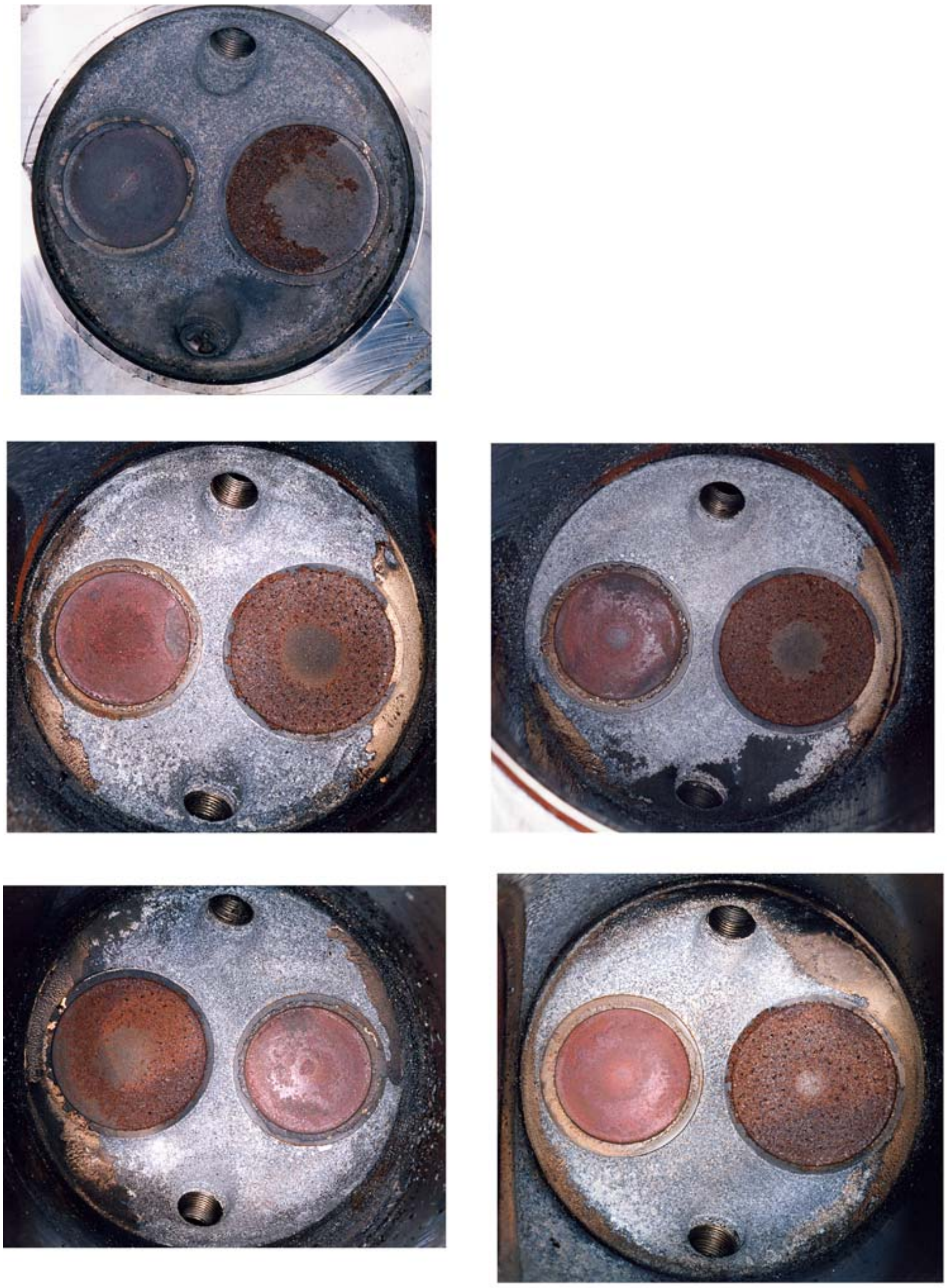
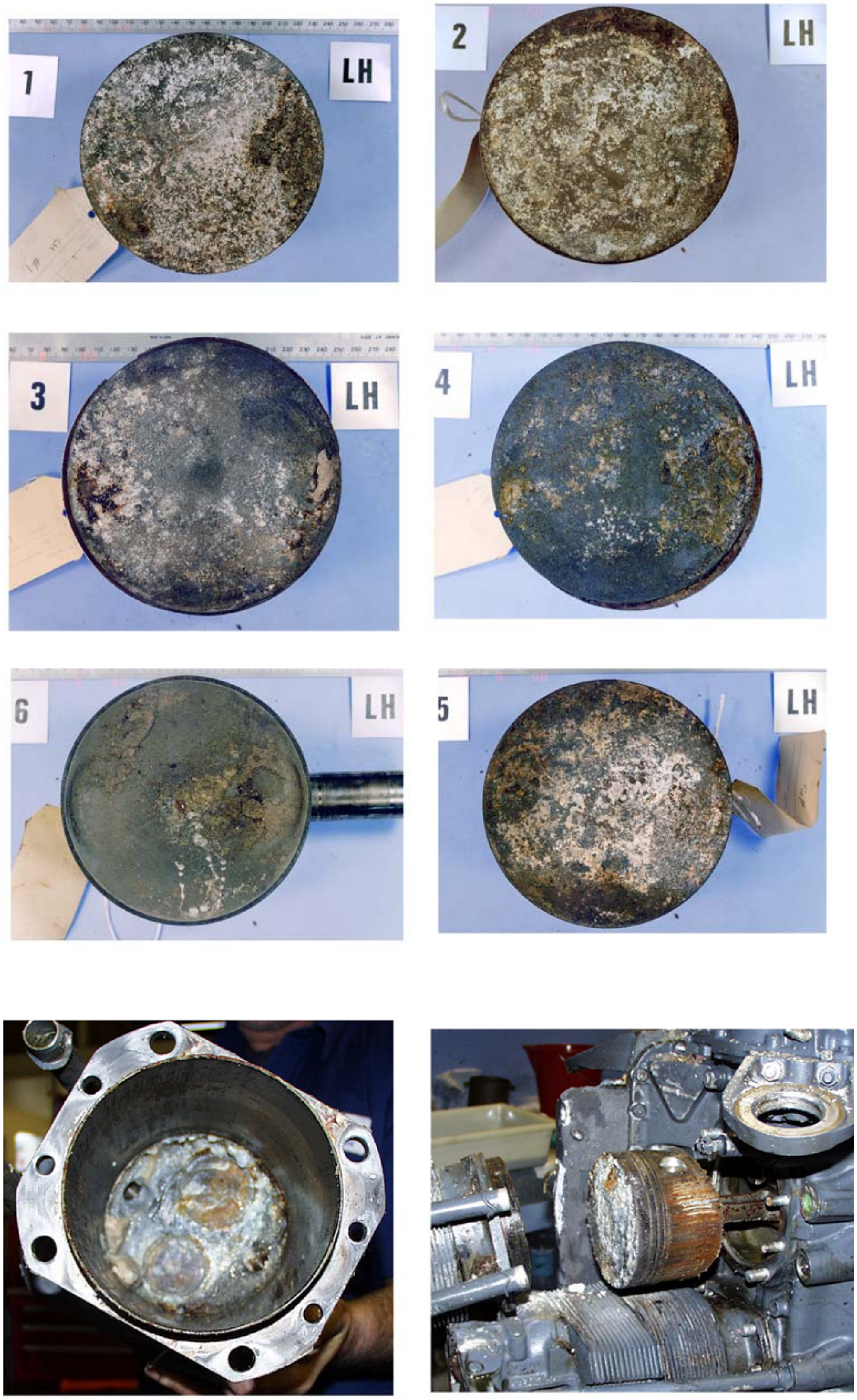


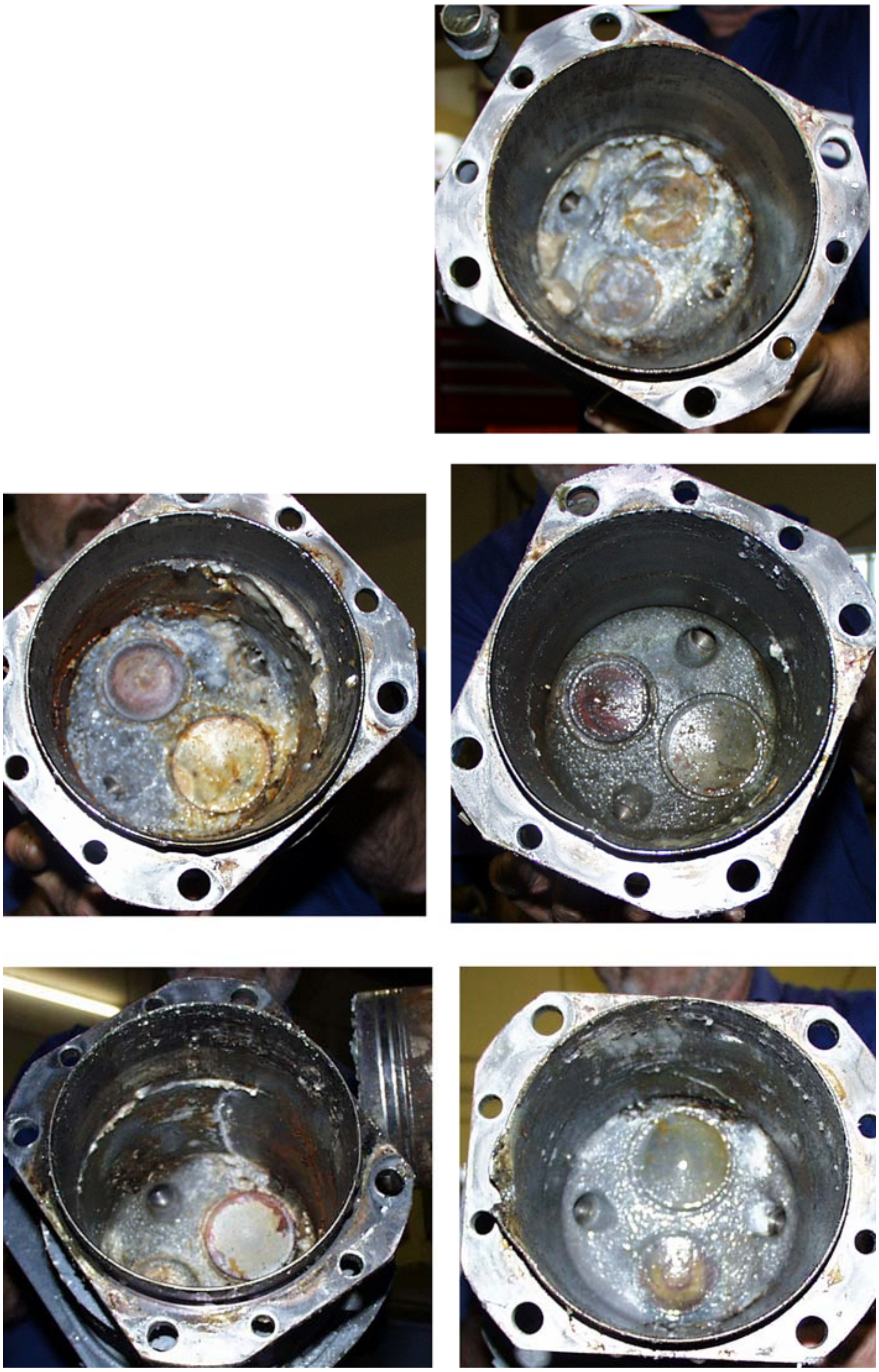
Figure 8.6: Piston surface condition, 2000/90, VH-MZK (left engine)

Figure 8.7: **Piston surface condition, 2000/2157, VH-MZK (left engine)**



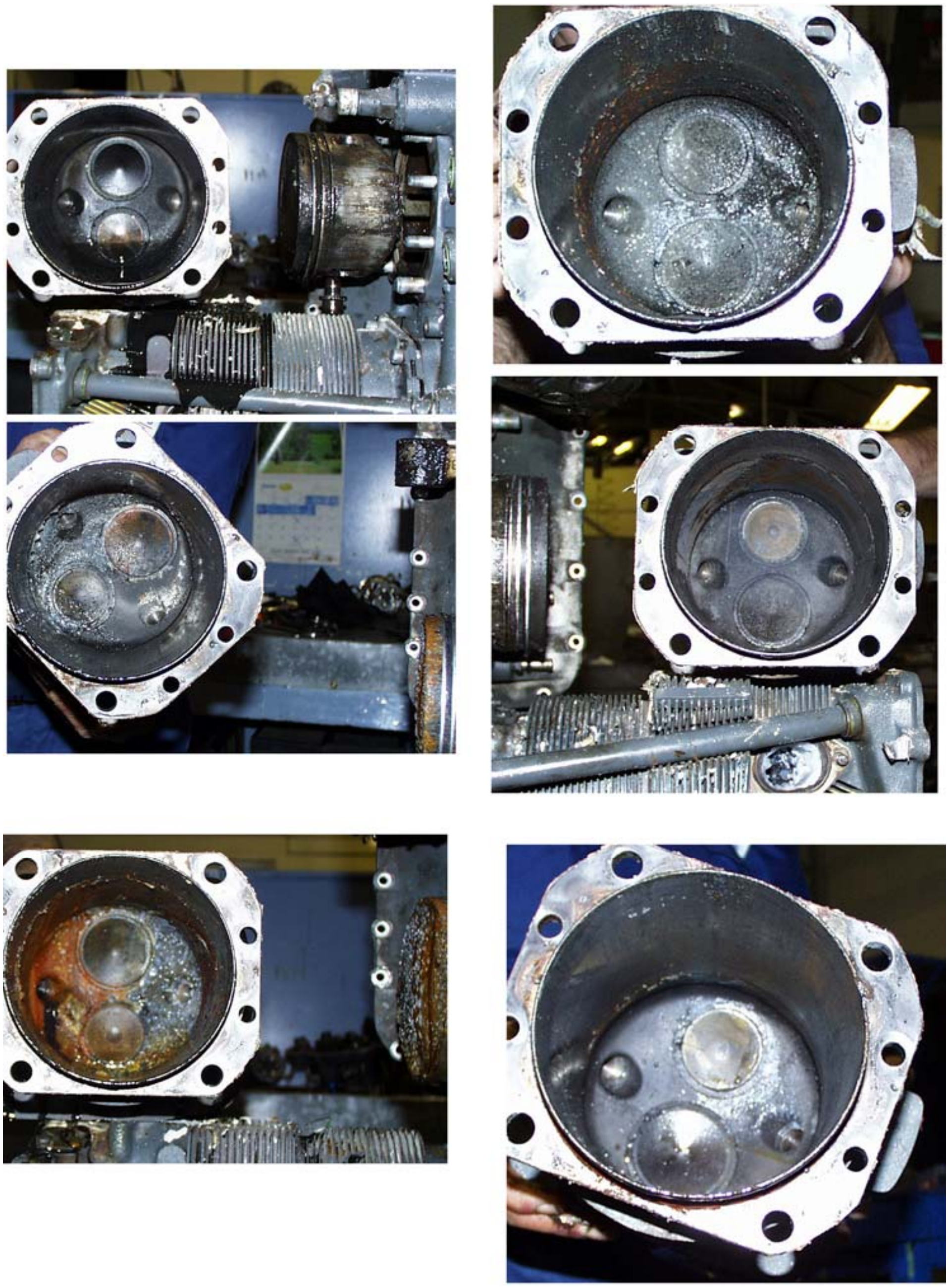
This engine was recovered after immersion in seawater for several days.

Figure 8.8: Cylinder head surface condition, 2000/2157, VH-MZK (left engine)



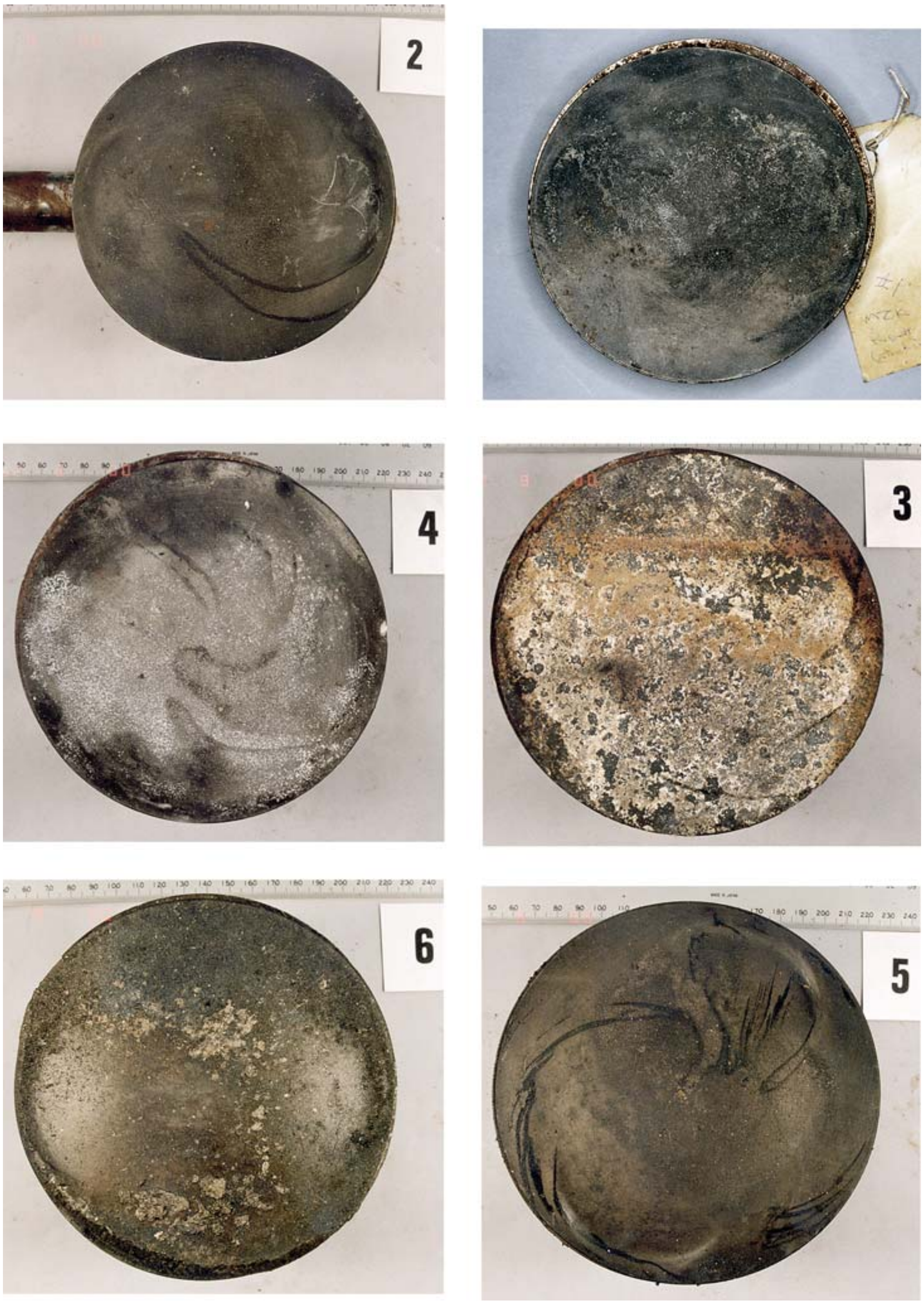
The condition of the combustion chamber surfaces at engine disassembly, showing the effects of immersion in seawater.

Figure 8.9: Cylinder head surface condition, 2000/2157, VH-MZK (right engine)



The condition of the combustion chamber surfaces at engine disassembly, showing the effects of immersion in seawater.

Figure 8.10: Piston surface condition, 2000/2157, VH-MZK (right engine)



While the piston crown surfaces from this engine were affected by immersion in seawater, it is evident from the residual deposits on the pistons that the engine was operating under very different combustion conditions to the left engine (MZK) prior to engine failure, see figures 8.6 and 8.7, and other Lycoming TIO-540 engines, see for example figures 8.12 – 8.14.

Figure 8.11: Cylinder head surface condition, 2001/5866, VH-JCH (right engine)

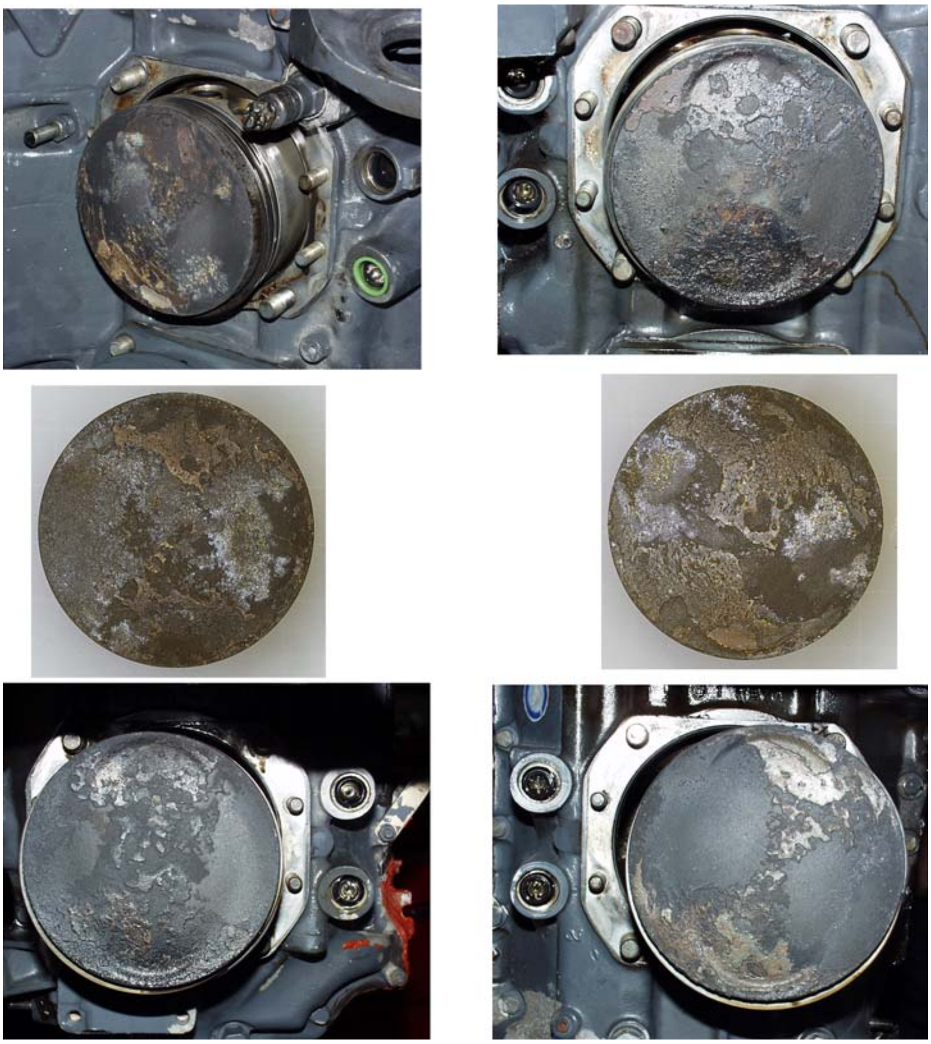
Figure 8.12: Piston surface condition, 2001/5866, VH-JCH (right engine)

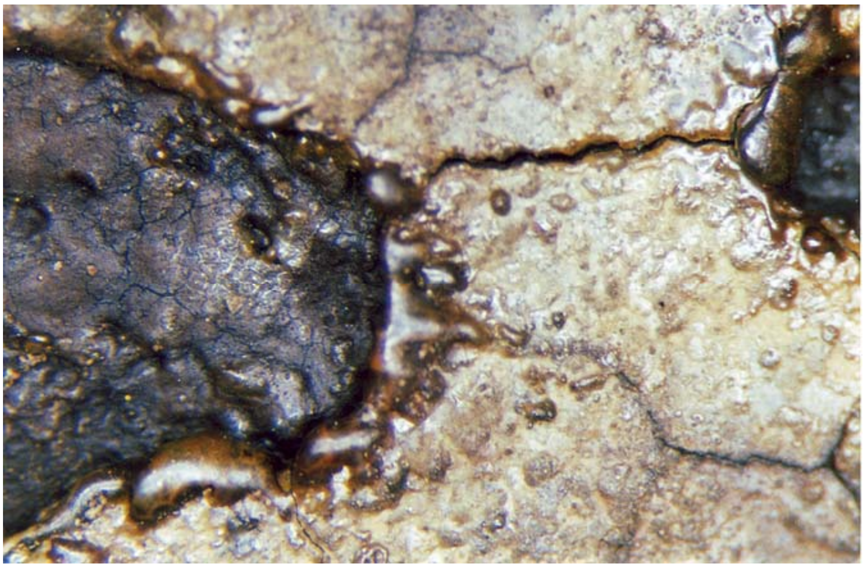
Figure 8.13: Piston surface condition, 2000/2276, VH-ODE (left engine)

Figure 8.14: **Piston surface condition, 2000/3675, VH-NPA (right engine)**

Figure 8.15: Piston surface condition, 2002/3474, VH-ACZ (left engine)

Figure 8.16: Piston surface condition, 2001/2544, VH-TTX (left engine)





Detail of piston crown deposit showing the features created by deposit edge melting and resolidification

Figure 8.17: **Cylinder head surface condition, 2001/4799, VH-BEM (left engine)**

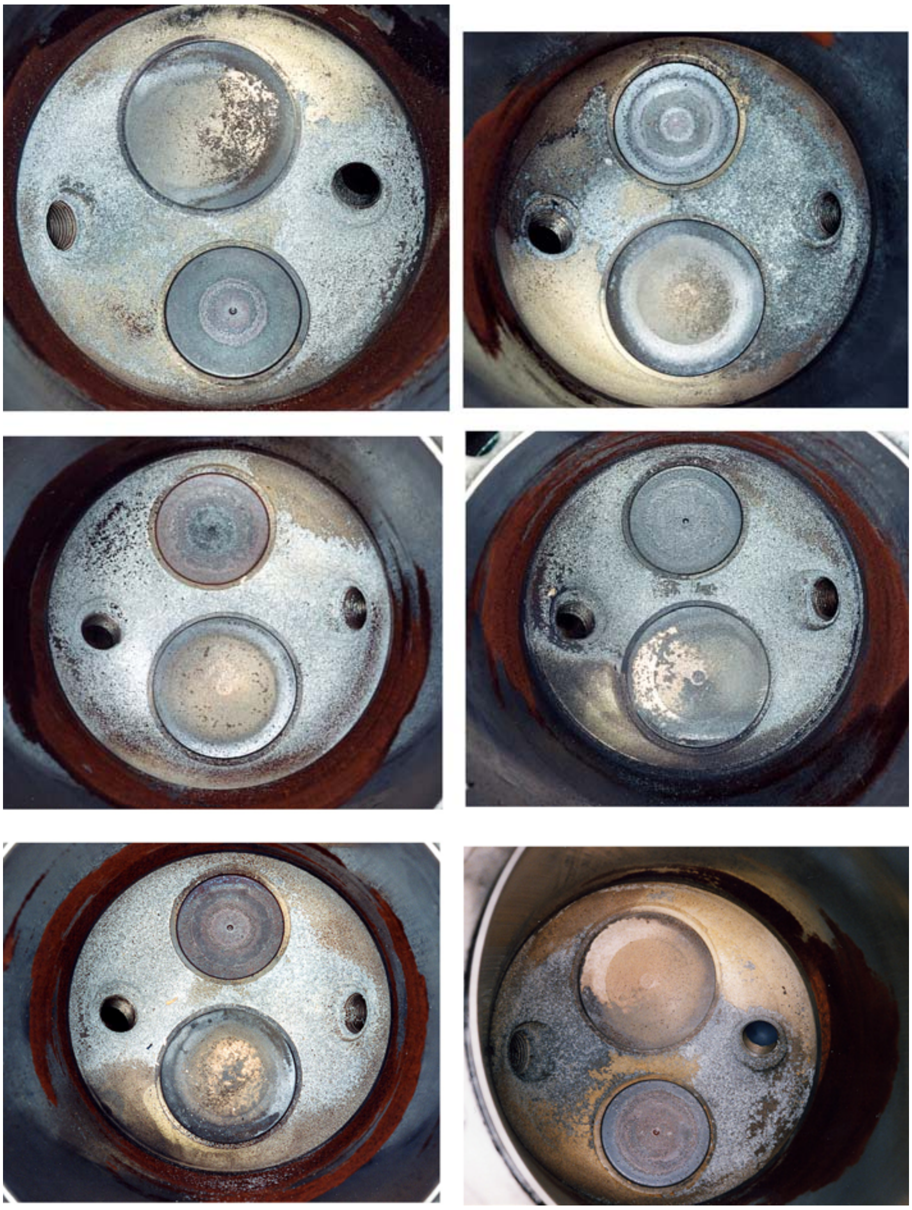


Figure 8.18: Piston surface condition, 2001/4799, VH-BEM (left engine)

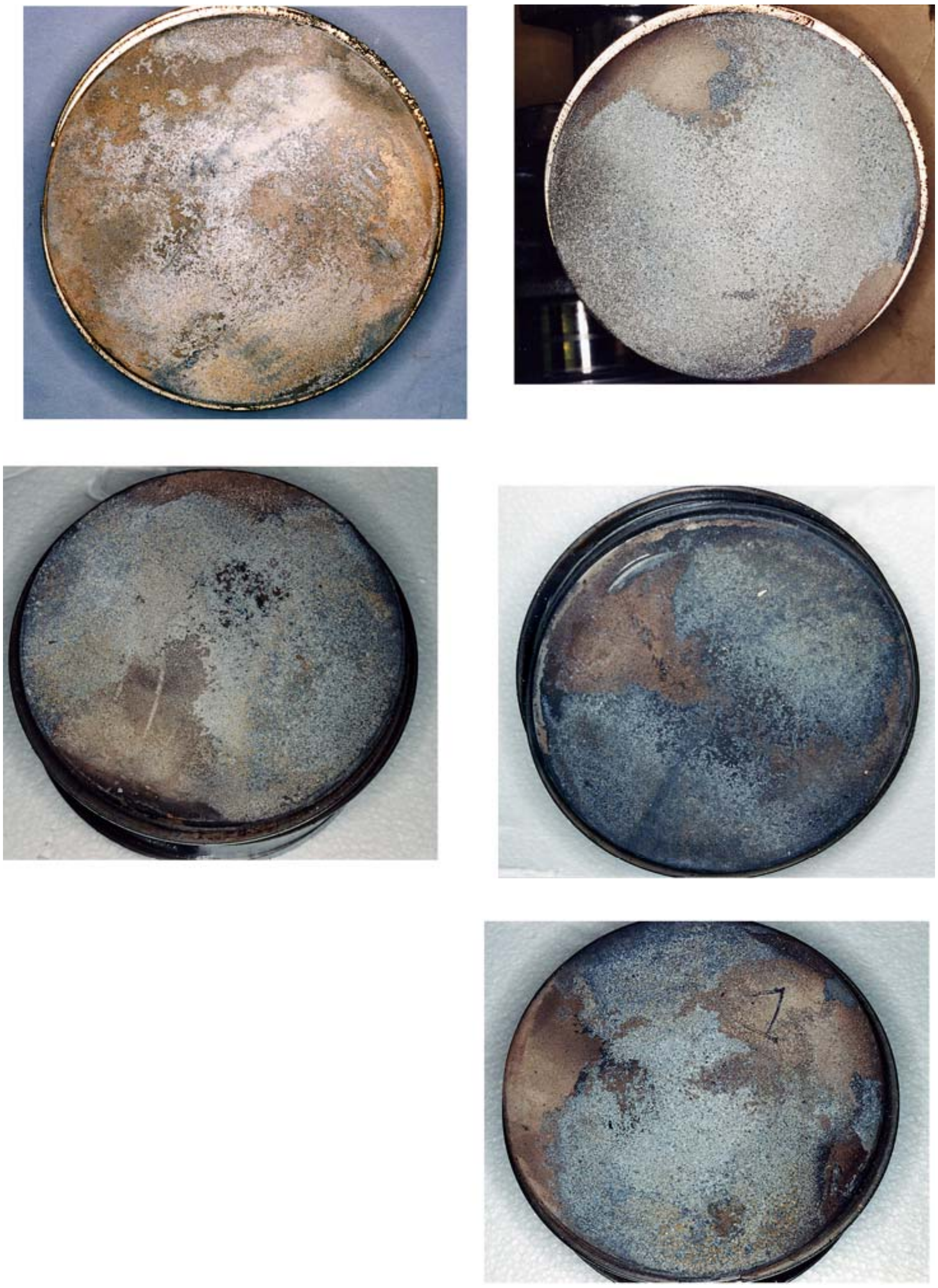


Figure 8.19: Cylinder head surface condition, 2003/2701, VH-OCF (left engine)

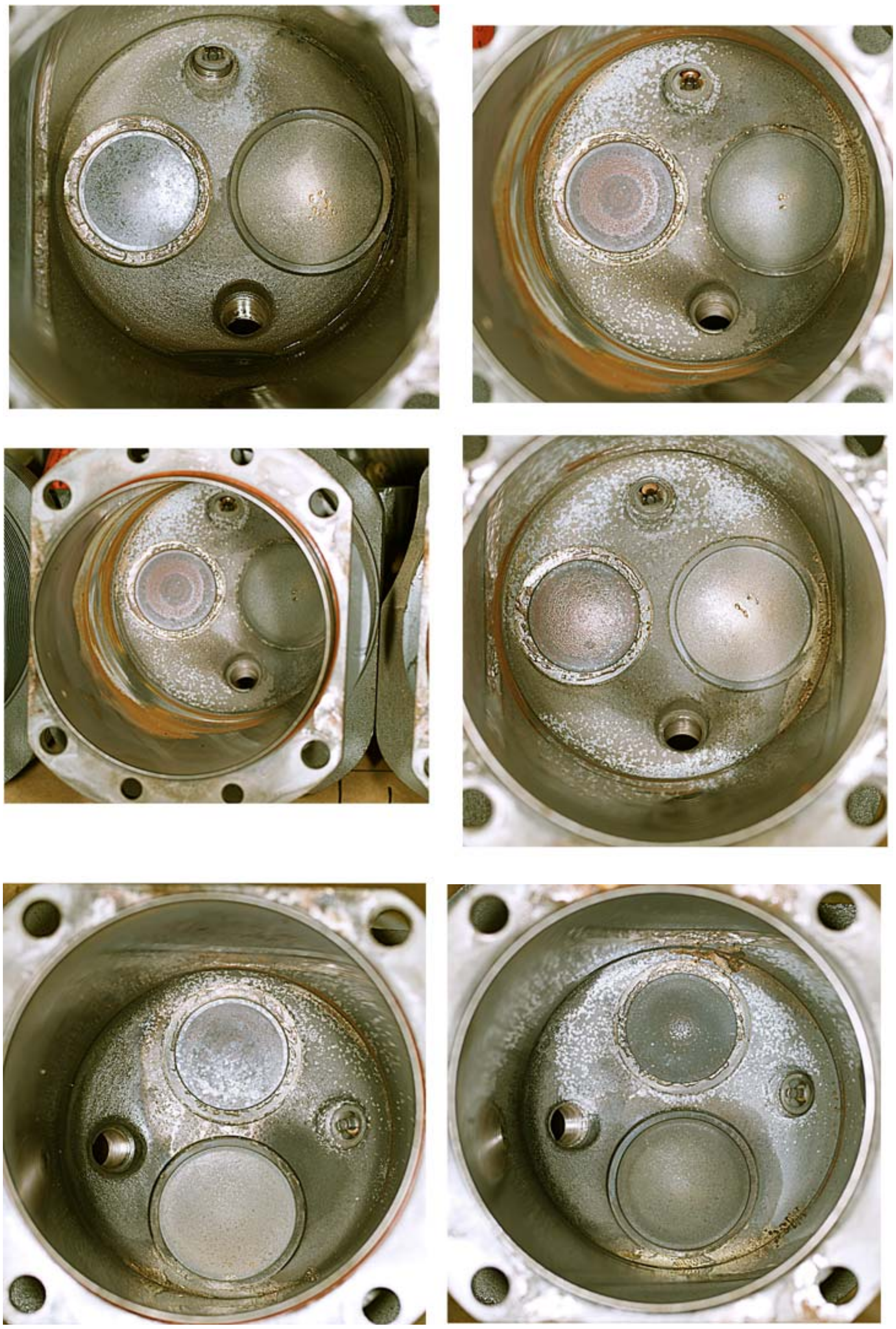


Figure 8.20: Piston surface condition, 2003/2701, VH-OCF (left engine)

Figure 8.21: Piston surface condition, 2001/1405, VH-LTW (left engine)

Figure 8.22: Cylinder head surface condition, 2001/2885, VH-MJA (left engine)

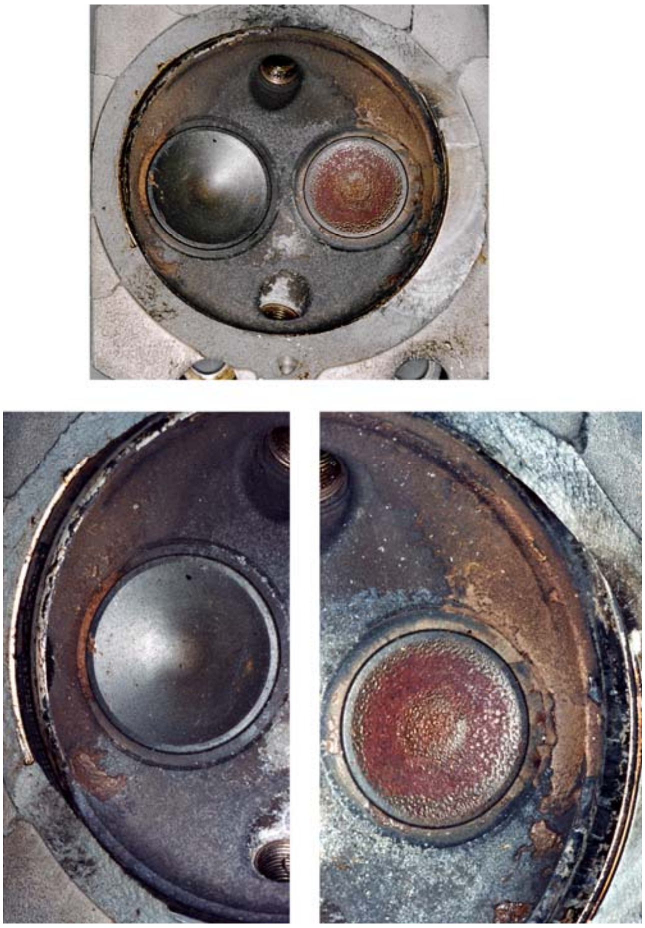


Figure 8.23: Piston surface condition, 2000/1327, VH-BNN

Figure 8.24: Piston surface condition, 2004/2291, VH-VEC (right engine)

Lead oxybromide deposits may also form in low power engines. However, it is apparent in the example shown in figure 8.25 that localised heating to the deposit melting point has not occurred under the engine operating conditions.

Figure 8.25: O-360 low power engine (180 HP) deposits

8.2.5 Engine control settings

Because of the operational need to maximise engine power and reduce fuel consumption during takeoff, climb and cruise phases of flight, the margin between operational settings and the detonation limited power boundary is minimised. In practice, the control of detonation depends on knowledge of the detonation-limited power boundary, for a particular engine and fuel, as a function of engine power and fuel-air mixture, and the control of the operational factors that shift the boundary.

In this present study of high-power horizontally-opposed aircraft engine powertrain failures, it became apparent that there was considerable variation in fuel-air mixture control during the climb and cruise phases of flight.

Fuel-air mixture control

Takeoff

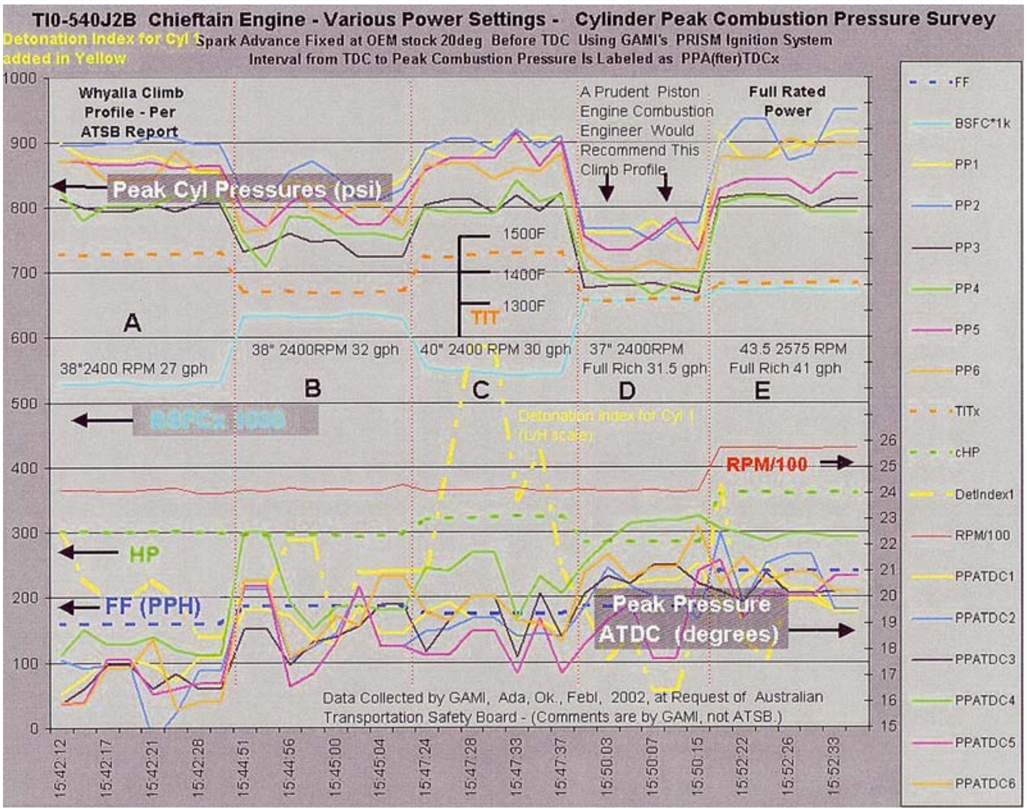
During takeoff, the engine systems are designed to create a ‘full’ rich mixture appropriate for the rated power of the engine with no scope for operational variation.

Climb

A survey of Lycoming TIO-540-J2B engine operation revealed that mixture setting during climb ranged from ‘full’ rich to various degrees of leaning, for example, 36 inches MAP/2400 rpm, full rich; 40 inch MAP/2400 rpm, 33 US gal/h; 38 inches MAP/2400 rpm, 30 US gal/h; 36 inches MAP/2400 rpm, 27 US gal/h; 35 inches MAP/2400 rpm, 25 US gal/h.

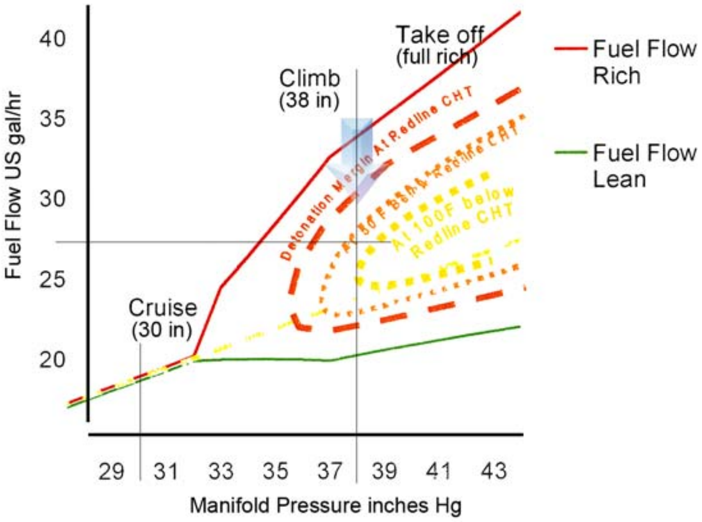
Engine test data (GAMI) shows that cylinder gas pressures increase to the same level as those at take-off power when the mixture is leaned at climb power settings In addition, the rate of pressure rise is increased and the peak pressure is developed with the crank closer to top centre, see figure 8.26.

Figure 8.26: Effect of engine control settings on peak pressure and the timing of peak pressure development (GAMI)



Leaning at climb power reduces the margin between the power setting and the onset of detonation, figure 8.27.

Figure 8.27: Detail from experimentally determined detonation limited power as a function of power and mixture (GAMI)



At typical climb power settings (38 inches manifold pressure), leaning from a full rich mixture will increase the likelihood of encountering end gas detonation.

The extent of detonation; light, medium or heavy, depends on the presence of other factors that determine the position of the detonation-limited power boundary, for example, cylinder head temperatures approaching or exceeding limits, ignition advance, and increase in the rate of pressure rise.

Cruise

The survey of Lycoming TIO-540-J2B operators also showed that there was considerable variation in mixture settings at cruise power. Typically, cruise mixture settings are made with reference to the peak exhaust gas temperature (EGT). The cruise settings ranged from: 32 inches MAP/2300 rpm, peak EGT; 30 inches MAP/2200 rpm, between peak EGT and 50°F rich of peak; 32 inches MAP/2200 rpm, 125°F rich of peak. The engine test data presented in figure 8.4 shows that, at cruise power settings, fuel-air mixture adjustment is not detonation limited.

The mixture setting used in climb and cruise does have an effect on combustion chamber component temperature, see figure 8.28.

Figure 8.28: Comparison of piston operating temperature, as evidenced by the extent of varnish formation, for two climb/cruise mixture settings.

Occurrence 2000/90; Time since overhaul, 1673 hours, mixture setting - climb 27 US gal/h, cruise between peak EGT and 50°F rich of peak.

Time since overhaul, approximately 1000 hours, mixture setting – climb, full rich, cruise 100°F rich of peak EGT.

8.2.6 The effect of detonation – shockwave propagation

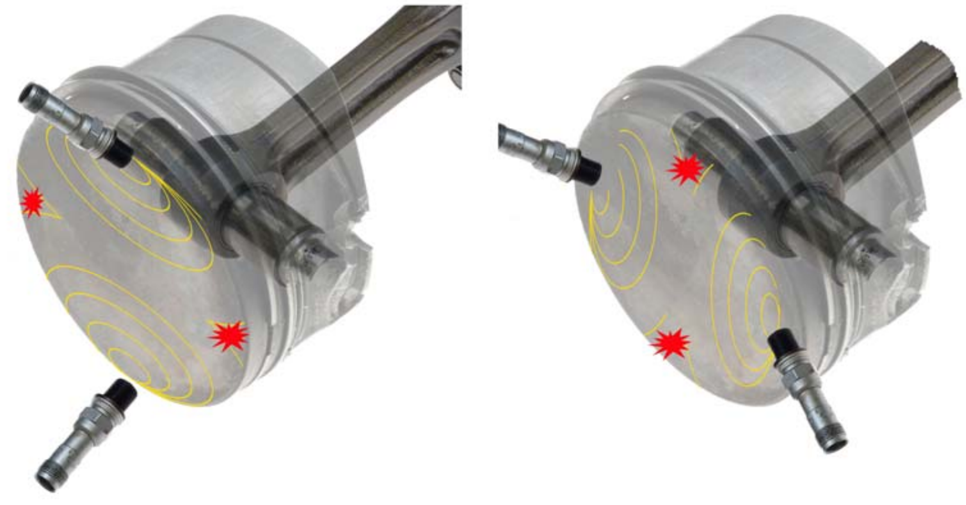
The effect of detonation is a function of its intensity; light, medium or heavy. The affect on powertrain component reliability can be related to high local combustion gas pressures, high rates of pressure rise, the mechanical effects of shockwave propagation across the piston crown, and the effects of shockwave propagation on the heat transfer to combustion chamber components.

Mechanical effects

With normal combustion, the pressure rise in a combustion chamber acts uniformly on the piston. However, when detonation occurs, localised regions of high pressure are created. As these regions of high pressure move, shockwaves are created.

It is a feature of horizontally-opposed reciprocating engines that two spark plugs are used to initiate flame fronts during each combustion cycle. Each flame front radiates from its site of ignition leaving the regions of end gas, at a circumferential location, approximately 90° from the spark plugs, see figure 8.29. The effect of non-uniform piston pressure distribution on the piston and connecting-rod assembly, is a function of engine layout. For the case of a horizontally-opposed engine layout, end-gas detonation will occur in the regions over the piston pin ends, with shockwave propagation in a direction parallel with the piston pin, see figure 8.29. The piston and connecting rod assembly will be affected by the rocking of the piston pin in the little-end bearing and the out-of-plane rocking of the big-end bearing. For the case of a radial engine layout, the regions of end-gas detonation at sites 90° to the piston pin ends, with shockwave propagation in a direction perpendicular to the piston-pin, see figure 8.29. End-gas detonation in a radial engine will cause the piston to rotate in the plane of the little-end bearing, rocking about the piston pin will not occur.

Figure 8.29: Schematic showing the locations of end-gas detonation (coloured red) for different engine layouts



Horizontally-opposed layout. Radial layout.

Combustion chamber component temperature

The rate of heat transfer from the combustion gas to the combustion chamber (cylinder head and piston) is controlled, under normal combustion conditions, by heat transfer across a gas boundary layer adjacent to the combustion chamber surface. However, as the intensity of detonation and associated shockwave propagation increases, the increasing turbulence in the combustion gases disrupts the gas boundary layer. Once the gas boundary layer is disrupted, heat is transferred rapidly to the combustion chamber components, leading to a rapid, large increase in component temperature, and component failure when the incipient melting point is reached.

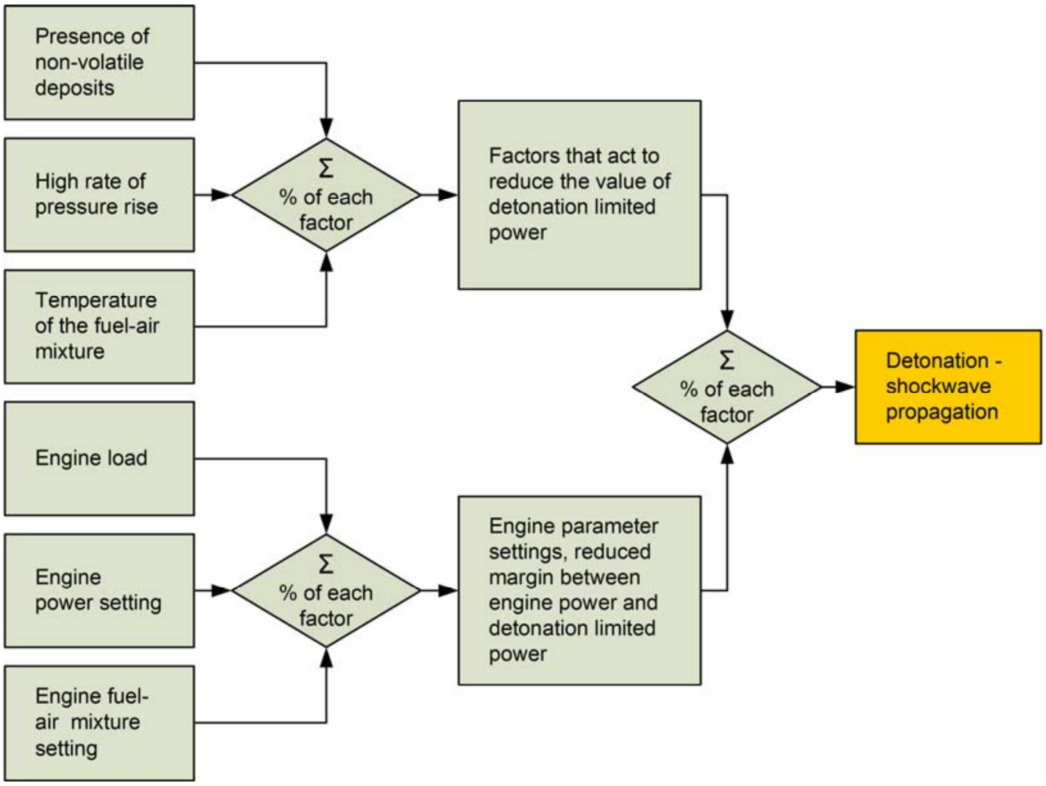
8.2.7 Summary

A change in the combustion process – from flame propagation throughout the fuel-air mixture to the auto-ignition of some part of the mixture – has the potential to affect the reliability of powertrain components. The effect of detonation is related to the intensity of detonation, which in turn, is dependent on the volume of end-gas that undergoes auto-ignition. Light to medium detonation may result in some mechanical damage. The actual nature of mechanical damage is dependent on the robustness of powertrain components and assemblies to abnormal loading. Heavy detonation results in the melting of aluminium alloy combustion chamber components.

Detonation-free operation, for a fuel of known detonation resistance, is based on limiting the operator-controlled engine parameters of manifold pressure (power), speed, mixture, and engine load. Additionally, detonation-free operation is based on designed limits for; combustion chamber surface temperatures (spark plugs, piston crown and cylinder head inner surface, the presence of deposits), inlet air temperature, and rate of pressure rise (spark ignition advance, ignition from sites other than spark plugs). Variations in any of these factors, beyond designed limits, will increase the likelihood of detonation during engine operation. In addition, the cumulative effect of variations in a number of factors may also act to increase the likelihood of detonation. The general form of relationships between factors which may contribute to the onset of detonation is shown in figure 8.30.

For the engine failure occurrences investigated in this study, it is clear that leaning at climb power settings increases the likelihood of detonation. It is also evident that the fuel-air mixture settings – lean climb and lean cruise, resulted in the deposition of a non-volatile lead compound on combustion chamber surfaces. The presence of non-volatile deposits also increases the likelihood of detonation.

Figure 8. 30: **Schematic showing the general form of relationships between factors that contribute to the onset of detonation**



8.3 Factors associated with bearing surface breakup

There are three processes that may lead to bearing surface breakup; fatigue cracking of the bearing surface under hydrodynamic lubrication conditions, a change from hydrodynamic to boundary lubrication during periods of high engine power, and abrasive wear caused by particles entrained in the oil. The evidence examined in this study indicates that the first two processes are important factors in the breakup of connecting-rod bearings.

8.3.2 Connecting rod little-end bronze bush breakup

The sequence of events leading to the fracture of a connecting rod little-end housing, on two occasions, involved the breakup of the little-end bearing, see, for example, figure 8.31. It is evident from an examination of the remnants of the bushes and the condition of other little-end bushes, that the process of bearing breakup did not involve bearing seizure but occurred as a result of the development of cracking at bush edges and axial displacement of the bush, figures 8.31, 8.32 and 8.33.

Figure 8.31: Remnants of the little end bush, No.6 connecting rod little fracture, VH-OCF (left engine)

Figure 8.32: No.1 connecting rod little end bush, VH-OCF (left engine)

Figure 8.33: No.1 connecting rod little-end bearing, VH-OCF (right engine)

The physical evidence of little-end bearing breakup, indicates that the alternating loads imposed on each bearing, through the piston pin, was not uniform. It is apparent that bearing breakup was associated with the rocking of the piston pin.

A significant factor in the development of piston-pin rocking, in horizontally-opposed engines, is the propagation of shockwaves, in the combustion gases, across the surface of a piston.

8.3.3 Connecting rod big-end bearing boundary lubrication

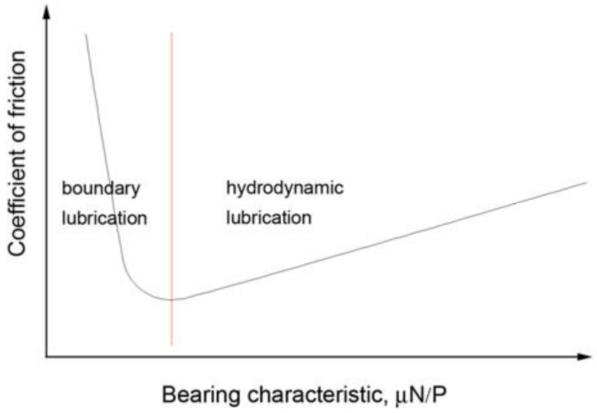
Bearing design is based on selecting values of oil viscosity, sliding speed between the bearing surfaces, and load per unit of projected bearing area (a function of load and bearing dimensions) to maintain hydrodynamic oil film lubrication during all engine operating conditions other than starting and stopping.

For an established bearing design in an aircraft engine, control of the oil film temperature in the bearing is the critical factor in maintaining hydrodynamic lubrication. The temperature of the oil film is a function of the temperature of the oil introduced into the bearing and the heat created through the continual shearing of the oil film.

There is a particular value of the bearing characteristic that defines the boundary between hydrodynamic oil film lubrication and boundary lubrication, figure 8.34. In the hydrodynamic regime self-correction of the effects of oil-film heating occurs.

Any increase in oil-film temperature is accompanied by a lowering of oil-film viscosity and a decrease in oil-film frictional heating, resulting in a return to the normal oil-film temperature (Shigley and Mischke, 1989, p.485). However, if the increase in oil-film temperature is too high the oil film will breakdown and allow metal to metal contact to occur. Metal-to-metal sliding contact (boundary lubrication) will result in the increased frictional heating of the bearing.

Figure 8.34: The relationship between the bearing characteristic parameters and lubrication regime (Shigley and Mischke, 1989, p.485)



Loads associated with oil-film breakdown

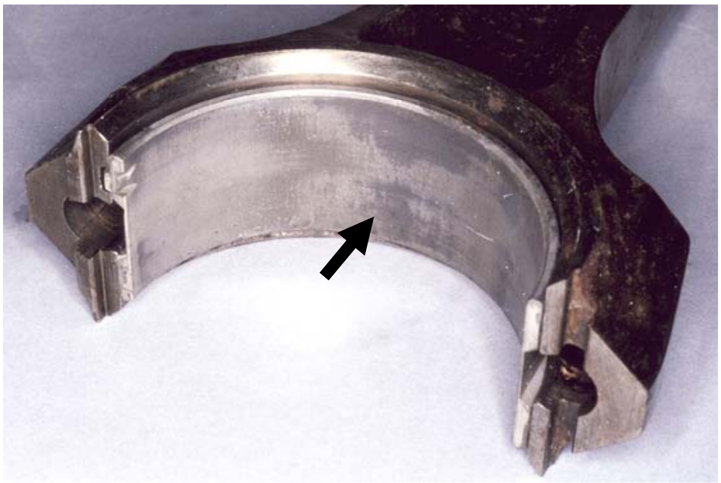
There are two loading conditions that may lead to hydrodynamic oil-film breakdown; loads from the gas pressures developed in combustion chambers, and loads developed by the rotation and reciprocating action of powertrain components. The type of loading, gas pressure or inertia, will affect different regions of the bearing. For the case of connecting rod big-end bearings, boundary lubrication caused by high gas pressure loading will affect the region of the big-end bearing adjacent to the connecting rod, while boundary lubrication caused by high-inertia loading will affect the region of the big-end bearing adjacent to the connecting-rod cap.

Figure 8.35: An example of localised bearing surface wear associated with oil-film breakdown under gas pressure loading

TCM GTSIO-520 engine, trimetal bearing inserts with a copper-lead intermediate layer.

Figure 8.36: Typical region of bearing surface wear (gas loads)

VH-TTX (left engine) No.5



VH-MZK (left engine) No.4

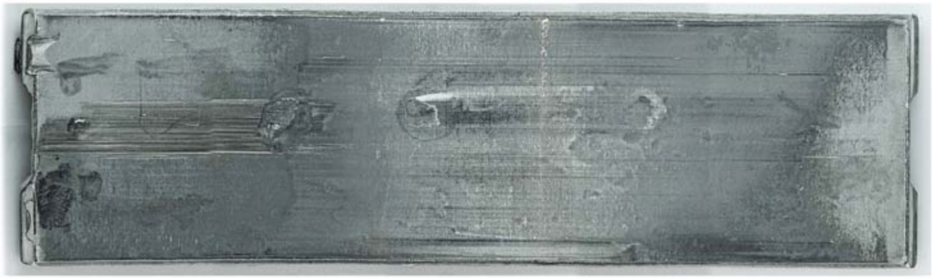
Lycoming TIO-540-J2B, trimetal bearing inserts with an aluminium-tin intermediate layer.

8.3.4 Connecting rod big-end bearing breakup

Connecting rod big end bearing structure

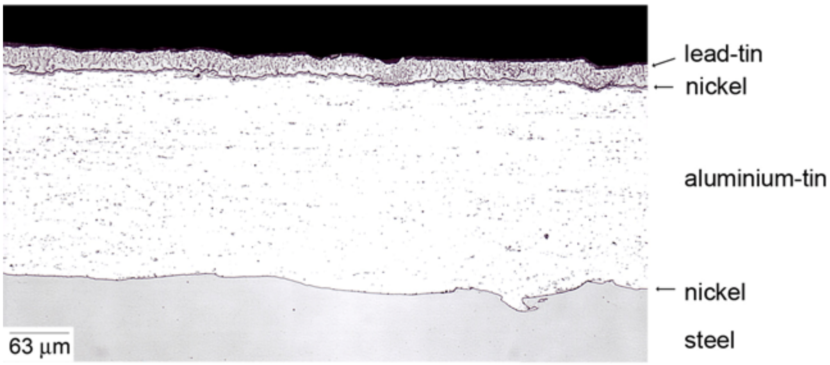
The key feature of the alloys used in the intermediate layer of trimetal bearings is the inclusion of a soft metal phase that will provide a low friction couple with the journal under conditions of boundary lubrication if the normal lead-tin alloy surface layer is removed by a process of wear, figure 8.37. Two alloy systems are used as the intermediate bearing alloy in trimetal bearings; copper-lead, and aluminium-tin. Normally, the lead or tin phase is distributed throughout a matrix of the stronger copper or aluminium phase, figure 8.38. The nature of this distribution determines the fatigue endurance strength of the alloy used as the intermediate bearing layer, and, in turn, affects the endurance strength of the bearing.

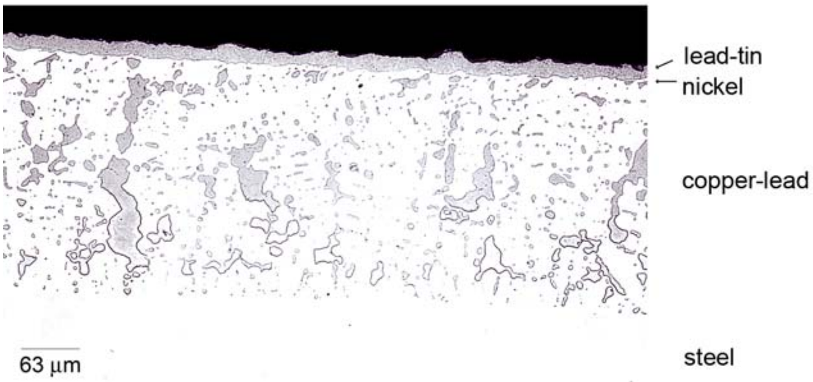
Figure 8.37: Examples of trimetal bearing surface alloy wear (Aluminium tin) trimetal (rod side)



Examples of bearing surface wear from bearings that had been in service for a short time (top), and an engine that had been in service for approximately 1,300 hours (bottom).

Figure 8.38: Photomicrographs showing the layers present in two types of trimetal bearings





Note: the roughness of the bearing surface evident in the micrographs was created during the mounting of bearing sections in a mineral filled plastic mounting compound.

Aluminium-tin alloy endurance strength change during operation

The distribution of the soft-metal phase is critical in determining the structural response of the bearing to repeated loading. It is expected that the distribution and morphology of the soft-metal phase will not change during operation and that the structural response of the bearing will not change during continued operation (Romeyn, 2006).

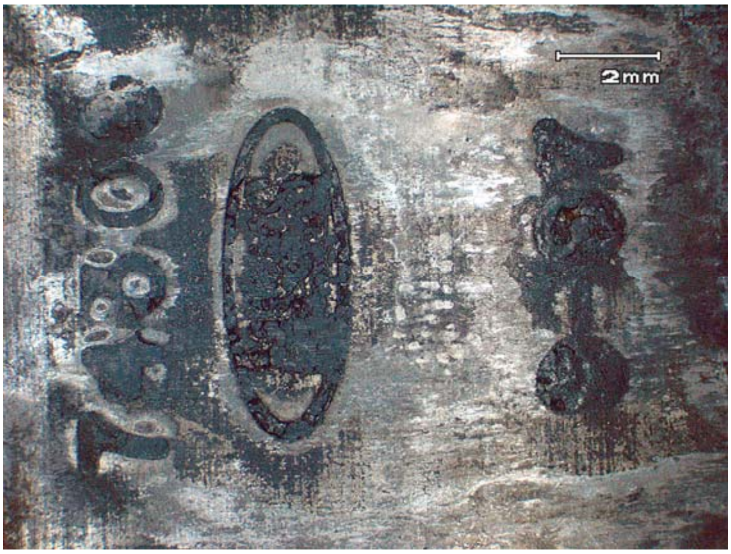
The distribution and morphology of phases in alloy systems can change as a result of diffusion of one or more elements. Diffusion occurs when one metallic element is soluble in another. It is important to note that for the aluminium-tin alloy system, tin is not soluble in aluminium below 228°C. However, it is slightly soluble in aluminium above 228°C (ASM, 1992, vol.3, p.2.52). In contrast, lead only becomes very sparingly soluble in copper at temperature of 326°C (ASM, 1992, vol.3, p.2.175).

Bearing Temperature

The temperature of a plain bearing is a function of the rate of heating by friction (oil film shearing and metal-to-metal sliding) and the rate of heat removal from the bearing by oil flow and conduction to the bearing housing.

Conduction to the bearing housing is affected by resistance to heat transfer from the bearing insert to the bearing housing. In the course of this study, it has become evident that contact between the insert back and housing, has been affected by the inclusion of a variety of lubricants between the insert back and housing. The temperatures attained during operation have been sufficient to carbonise the lubricant, see figure 8.39.

Figure 8.39: An example of a bearing insert back showing the carbonised residue of oil included between the insert back and bearing housing

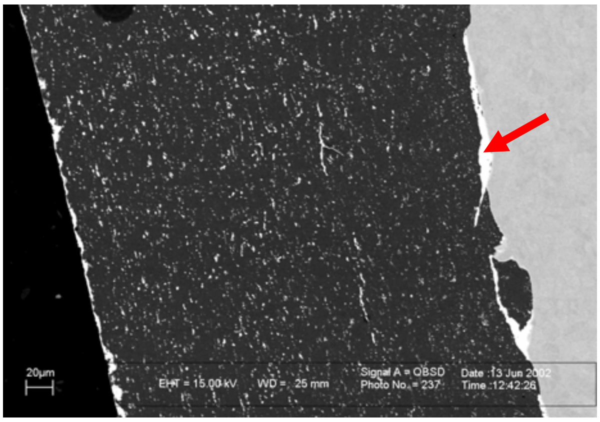


VH-TTX No. 5

Aluminium-tin alloy microstructure

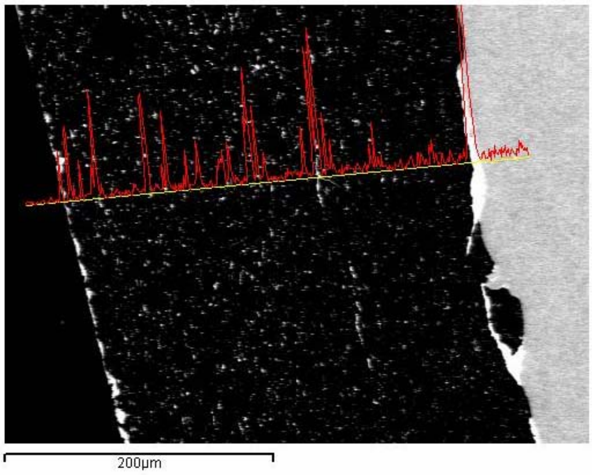
Metallographic examination of bearing inserts, from engines that have been the subject of this study, has revealed that the distribution and morphology of the tin phase, in bearings manufactured with an aluminium-tin intermediate layer, may change during engine operation. A characteristic of the modified distribution of tin is the formation of coarse particles of tin at the interface between the aluminium-tin layer and the nickel plating on the steel backing, see figures 8.40 and 8.41.

Figure 8.40: Metallographic section through an aluminium-tin intermediate layer, occurrence 2000/2276, VH-ODE



This section is taken through a region of surface layer wear, backscattered electron image. A coarse particle of tin at the interface between the intermediate layer and insert backing is arrowed.

Figure 8.41: Tin x-ray line scan, micrograph 8.41



The formation of coarse particles of tin, at the interface between the aluminium-tin layer and the steel backing, will reduce the endurance strength of the bearing. The endurance strength will no longer be determined by the endurance strength of the aluminium phase but will be determined by the endurance strength of the tin phase. It is apparent, through the observation that tin diffusion in the aluminium-tin intermediate layer has occurred during engine operation, that bearing temperatures may reach 228°C (the melting point for the tin phase) during some periods of engine operation. Under these conditions, the endurance strength of the bearing will be determined by the distribution of coarse particles of molten tin at the boundary between the aluminium-tin alloy layer and the steel backing. It would be expected that bearing breakup would involve the loss of sections of the aluminium-tin alloy layer, with separation at the interface with the steel backing. Examples of this type of bearing surface breakup are shown in figures 8.42 and 8.43.

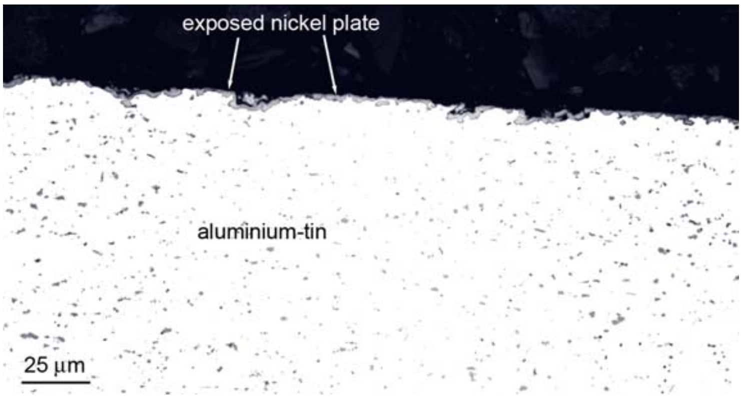
Figure 8.42: **Bearing surface breakup, trimetal bearing with aluminium-tin intermediate layer, occurrence 2000/2276, VH-ODE**

Figure 8.43: **Bearing surface breakup, trimetal bearing with aluminium-tin intermediate layer, major defect report 99/1447, Piper PA 31-350, Lycoming LTIO-540-J2BD**

Effect of the nickel plating between the lead-tin surface layer and the aluminium-tin intermediate layer

It is common practice to incorporate a thin layer of nickel between the surface layer and intermediate layer of trimetal bearings. In the course of this safety study, it has become apparent that nickel plating applied to the aluminium-tin intermediate layer remains attached to the aluminium alloy even after the removal of the surface lead-tin alloy by wear, see figures 8.44, 8.45.

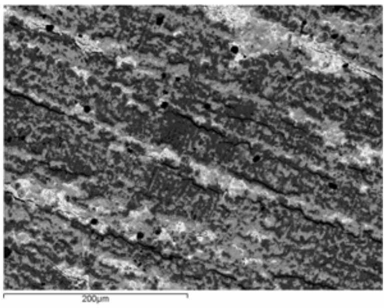
Figure 8.44: Metallographic section showing the exposed, adherent, nickel plate in a region where the lead-tin alloy has been worn away



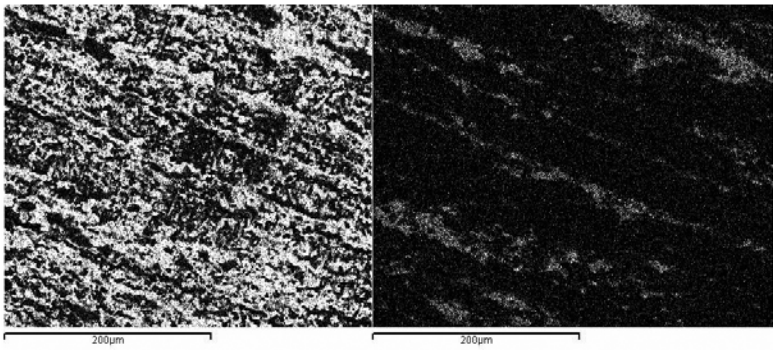
X-ray maps, figure 8.45, clearly show that in regions where the lead-tin surface layer has been worn through the nickel layer overlying, the aluminium-tin intermediate layer is exposed and remains adherent.

The effect of an adherent film of nickel is to isolate the intermediate bearing alloy layer. In cases where the surface bearing alloy layer has been removed by wear, the intermediate bearing alloy cannot act to provide a suitable bearing surface during periods of boundary lubrication. The sliding couple, in this case, is nickel against steel with a consequential increase in frictional heating and a greater frictional force acting to move the bearing insert in its housing.

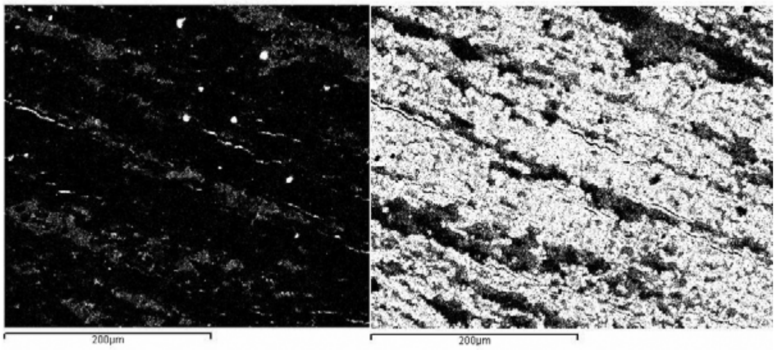
Figure 8.45: **Trimetal bearing, worn lead-tin surface layer, aluminium-tin intermediate layer, X-ray distribution maps for tin, lead, aluminium and nickel**



Backscattered electron image showing surface topography and compositional contrast. The light regions indicate the presence of high atomic number elements, e.g. lead. The dark regions indicate the presence of low atomic number elements, e.g. aluminium.



Tin x-ray map Lead x-ray map



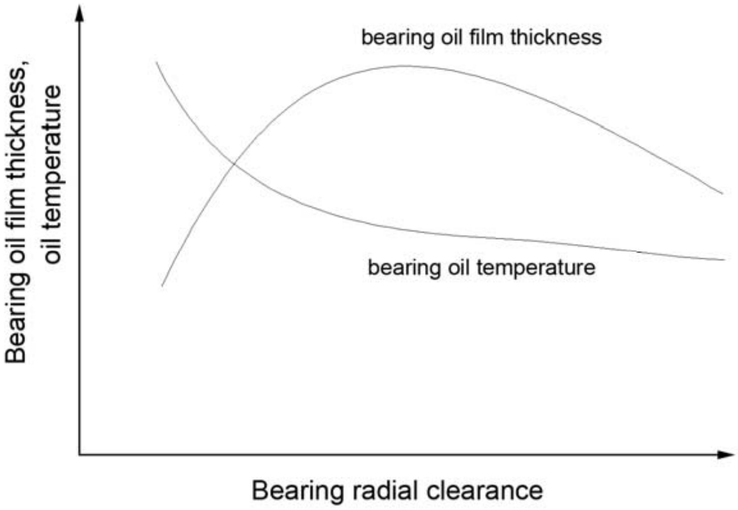
Aluminium x-ray map Nickel x-ray map

The light regions in the X-ray maps indicate the presence of the element, while the black regions indicate the absence of the element

Bearing clearance

Bearing clearance is an important variable that affects the nature of bearing lubrication through its affect on oil-film thickness and oil-film temperature, figure 8.46. If the radial clearance is too small, the increase in oil film temperature and decrease in oil film thickness will lead to boundary lubrication.

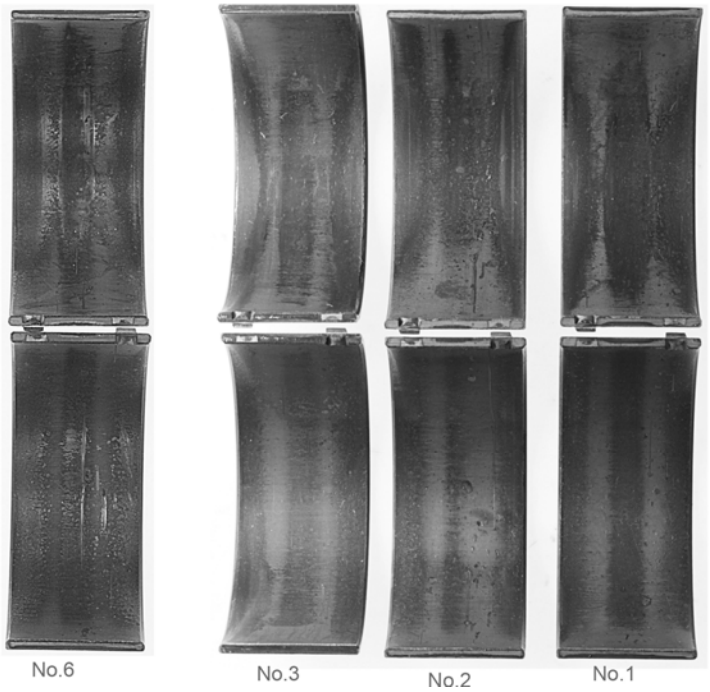
Figure 8.46: The effect of bearing clearance on oil-film thickness (Shigley and Mischke, 1989, p.508)



Crankshaft journals may wear during engine operation. The effects of journal wear may be corrected during engine overhaul by polishing the journals to an ‘undersize’ diameter, and installing ‘oversize’ bearing inserts. For Lycoming engines, journals may be reduced in diameter by 0.003in during overhaul. The oversize bearing inserts include a marking ‘M03’, (journal, minus 0.003in) with the bearing part number marking.

Two powertrain failure events investigated in this study were associated with crankshafts that had been polished to an undersize condition during overhaul; occurrence 2000/2276, VH-ODE and occurrence 2002/3474, VH-ACZ. The physical evidence available for occurrence 2002/3474, VH-ACZ, indicated that bearing damage, through boundary lubrication, differed from other occurrences investigated, figures 8.47 and 8.48. It is apparent that boundary lubrication affected the surface of both the rod and cap inserts, and was localised to several circumferential tracks. A detailed metrological inspection of the journals revealed that polishing to an undersize state had left the journals in an out-of-round condition, figure 8.49.

Figure 8.47: **An overview of the nature of connecting-rod bearing surface damage and journal markings, occurrence 2002/3474, VH-ACZ**



The inserts on the rod side of the big end bearings are shown at the top of the figure and the cap side inserts are shown at the bottom of the figure

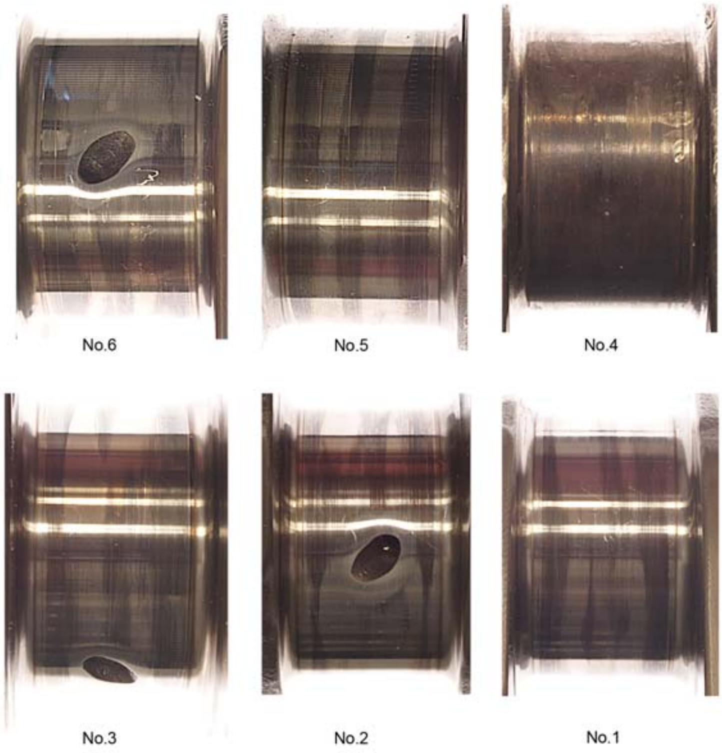
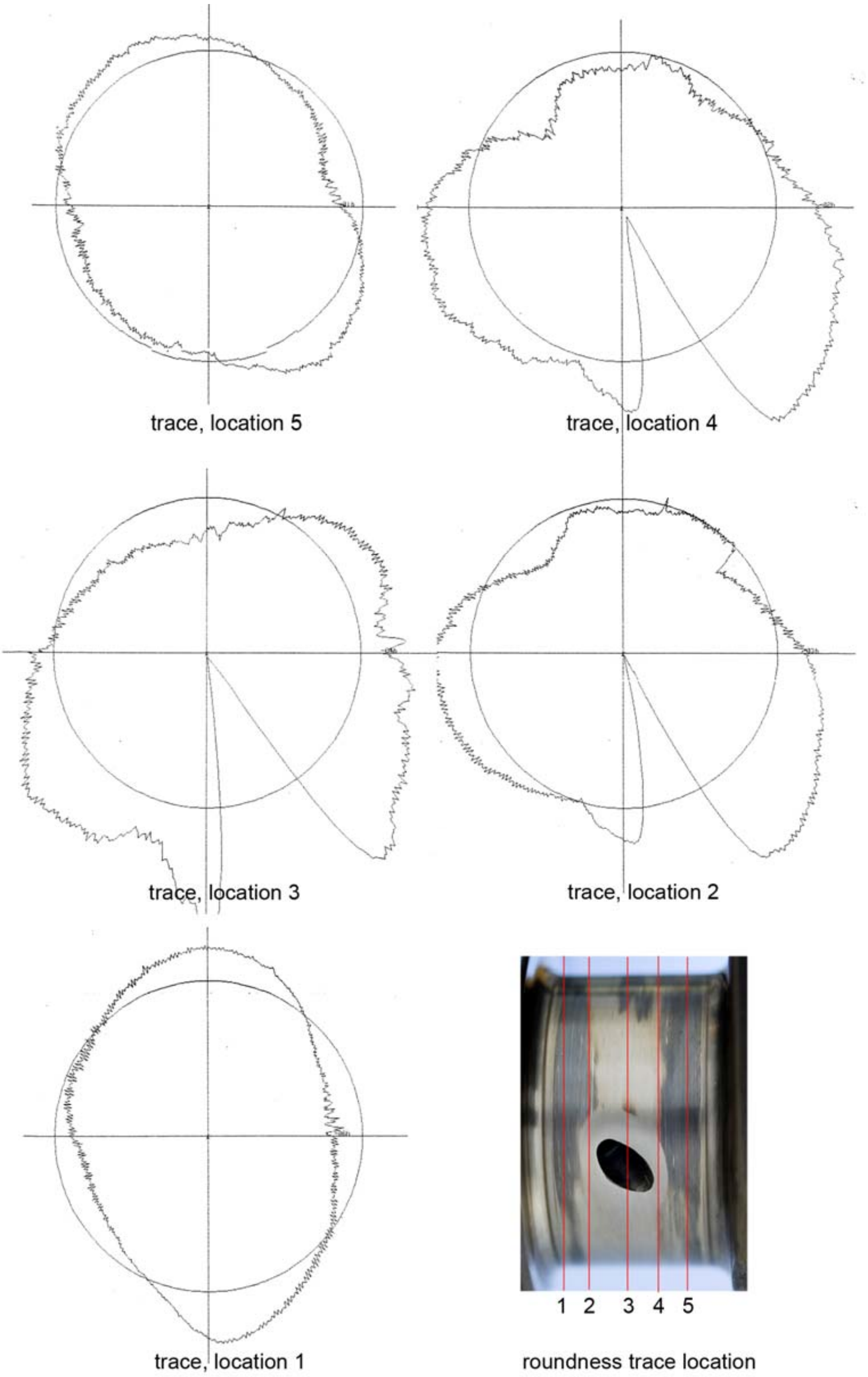


Figure 8.48: Detailed view of the nature of the No.5 connecting-rod bearing inserts, VH-ACZ

Connecting-rod cap insert.

Connecting-rod insert.

Figure 8.49: **Crankshaft journal roundness traces, VH-ACZ No.5 connecting-rod journal**



trace, location 5

trace, location 4

trace, location 3

trace, location 2

trace, location 1

roundness trace location

Notes: the reference circle is a least squares circle, the plot magnification is 5,000 times, trace 3 is over the oil hole, traces 2 and 4 are adjacent o the oil hole.

The available connecting-rod bearing inserts from the occurrence involving VH-ODE, also show a wear pattern that indicates a lack of uniformity in the roundness of crankshaft connecting-rod journals, figure 8.50.

Figure 8.50: An example of the connecting rod bearing surface wear from occurrence 2000/2276, VH-ODE

Bearing insert marked M03

Steel backing breakup

It is a characteristic feature of the breakup of trimetal connecting rod big-end bearings, manufactured with an aluminium-tin intermediate layer, that the steel backing is reduced in thickness while being lubricated with oil. It appears that the deformation of the steel backing involves progressive extrusion through the clearance between the sides of the connecting rod big-end housing and the crankshaft journal, figures 8.51 and 8.52.

Figure 8.51: Example of steel backing deformation and breakup, occurrence 2000/2276, VH-ODE

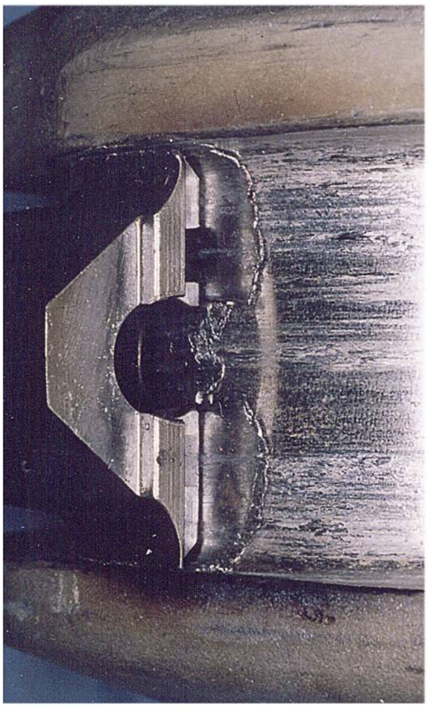
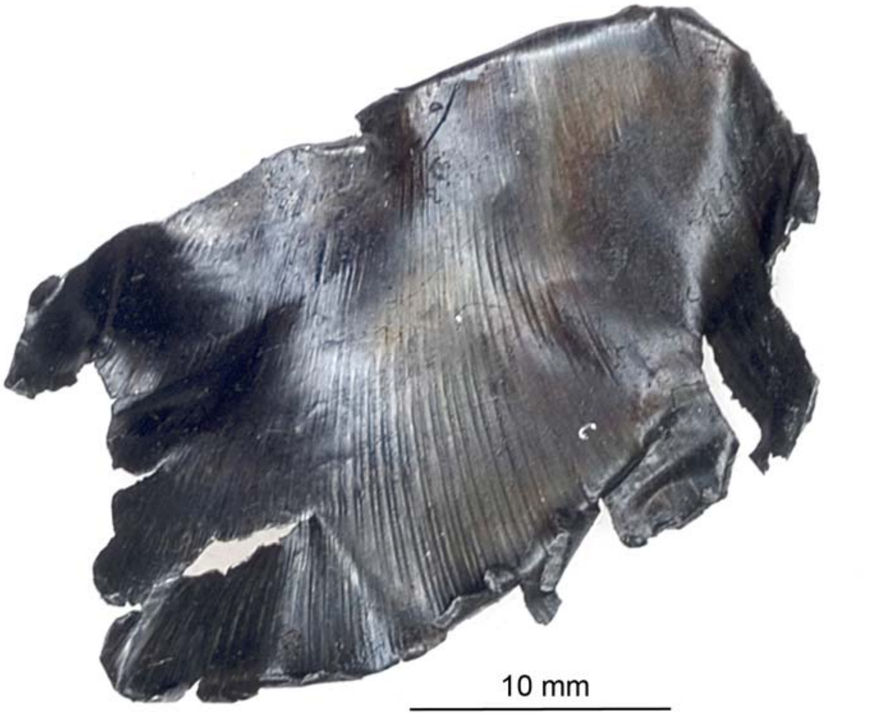


Figure 8.52: **Detailed view showing the typical features created during the process of steel-backing deformation, trimetal bearing with aluminium-tin intermediate layer**



8.3.5 The effects of boundary lubrication on trimetal bearing inserts manufactured with a copper-lead intermediate layer

The response of trimetal bearings manufactured with a copper-lead intermediate layer differs from trimetal bearings manufactured with an aluminium-tin intermediate layer.

Under conditions of bearing surface wear, removal of the surface lead-tin layer exposes the underlying copper-lead layer. Unlike the behaviour of the aluminium-tin trimetal bearings, the nickel plating between the surface and intermediate layers does not remain firmly attached to the intermediate layer. The exposure of the intermediate layer allows it to fulfil its designed purpose as a backup bearing surface during periods of boundary lubrication.

The distribution and morphology of the dispersed lead phase in the copper-lead alloy, is thermally stable. However, it is evident that under conditions of high bearing load and sustained boundary lubrication, the bearing temperature may increase to a level where copper diffuses through the steel backing, and may diffuse into the connecting rod big-end housing and the crankshaft journal, see figure 8.53.

For occurrence 2004/2291, VH-VEC, the heating of the No.3 journal resulted in the expansion of the crankshaft, ‘machining’ of the crankcase by the ends of the crankshaft, followed by a loss of engine oil pressure as the oil filter screen was blocked by ‘machining’ debris.

Figure 8.53: The effect of high-load boundary lubrication, copper-lead trimetal bearing, No.3 connecting-rod journal, occurrence 2004/2291 VH-VEC

The No.3 bearing inserts; the temperature created by continued boundary lubrication during engine operation, was sufficient to allow copper from the intermediate layer to diffuse through the steel backing.

The No.3 connecting-rod journal was also affected by copper diffusion from the intermediate layer of the connecting-rod bearing inserts.

8.4 Factors associated with the retention of bearing inserts in their housings

Connecting rod big-end and crankshaft main-bearing inserts, are retained in their housings by an interference fit created during assembly. Simply, the circumference of the outer surface of the precision bearing inserts exceeds the circumference of the housing bore. The difference in dimension, commonly referred to as ‘bearing crush’, creates a radial force between the insert and housing when the housing is assembled and bolts tightened. The action of this force, in combination with the coefficient of friction between the insert back and housing surface, provides a resistance to forces that act to move the bearing, circumferentially or axially, in the bearing housing.

The surface finish of the housing and the bearing-insert backs are required to be of high quality to ensure that the bearing is not distorted, the interference fit is established, and heat transfer through metal to metal contact can occur.

8.4.2 Connecting rod big-end bearing insert retention

In the course of this safety study, evidence of connecting rod big-end movement was observed in the connecting rod assemblies in a number of engines. This evidence comprised of wear damage created by, small scale, relative movement between the insert back and housing surface, see for example, figures 8.54 to 8.56, and deformation of the insert-locating tang, see figure 8.57.

Figure 8.54: Example of big-end insert back wear, occurrence 2001/2544, VH-TTX

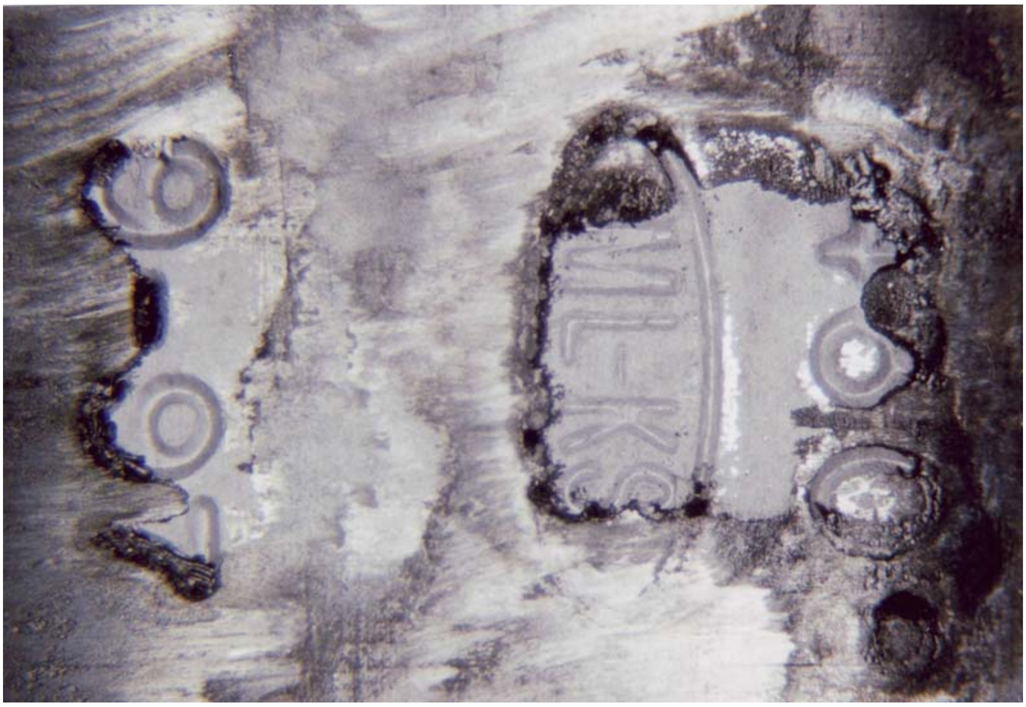


Figure 8.55: Example of big-end insert back wear, occurrence 2001/5866, VH-JCH

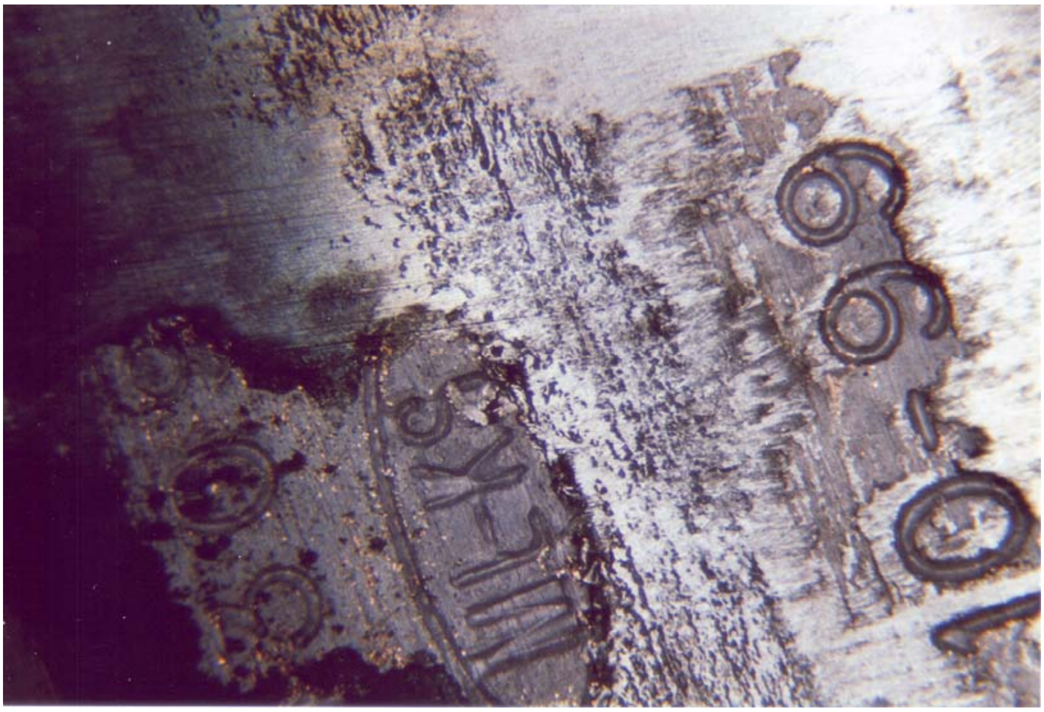
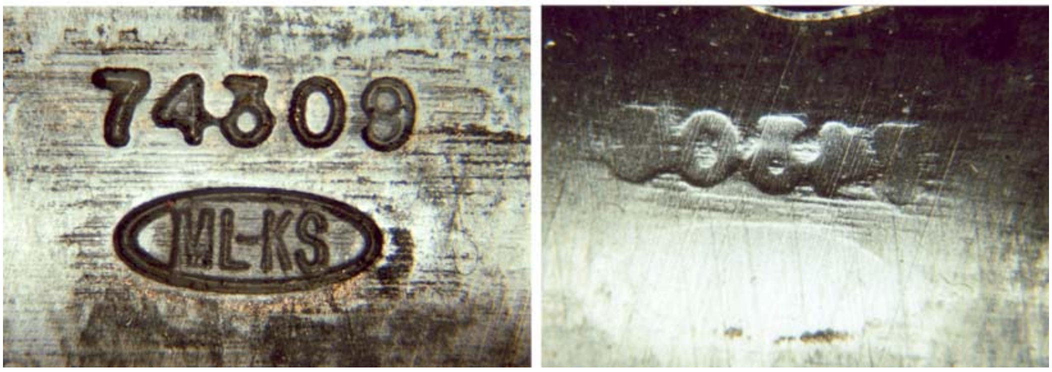
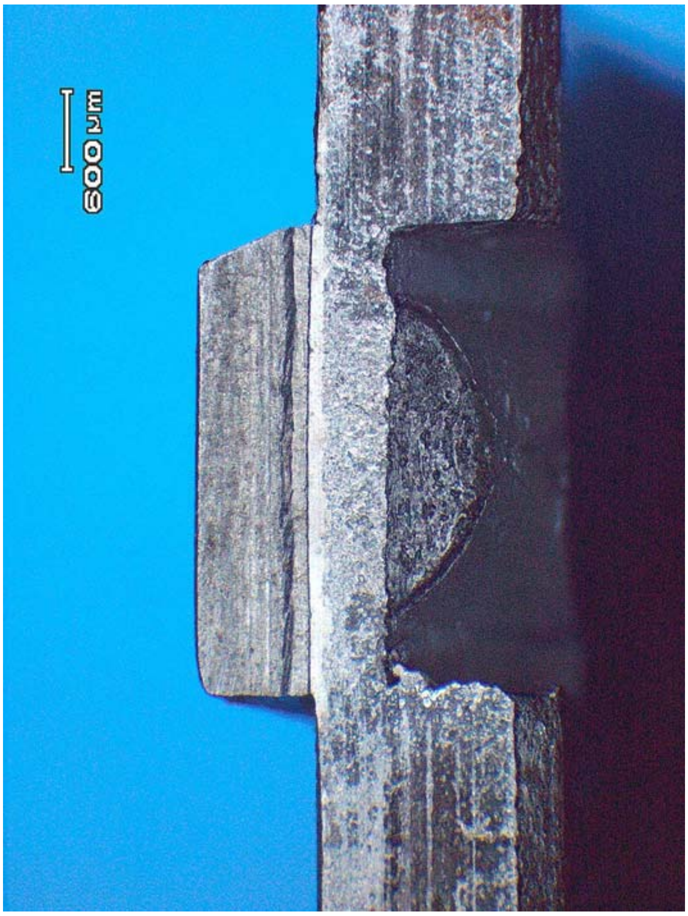


Figure 8.56: No.4 big-end housing surface and insert wear, occurrence 2000/2157, VH-MZK (left)



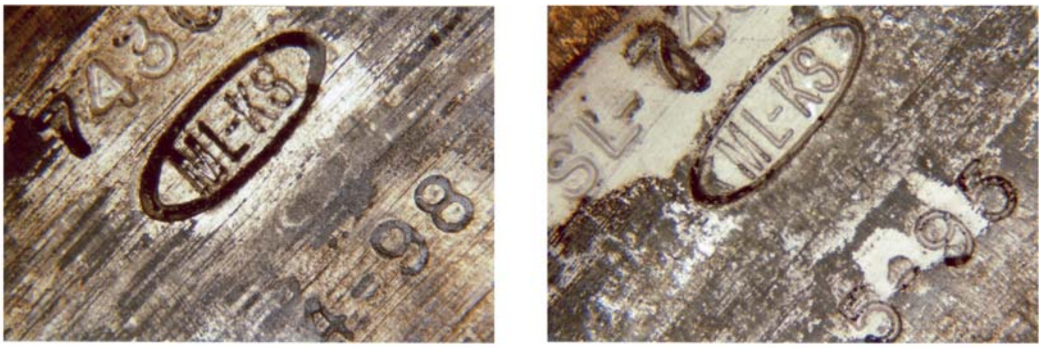
The insert back is shown on the left and the corresponding housing surface is shown on the right.

Figure 8.57 Example of insert-locating tang deformation



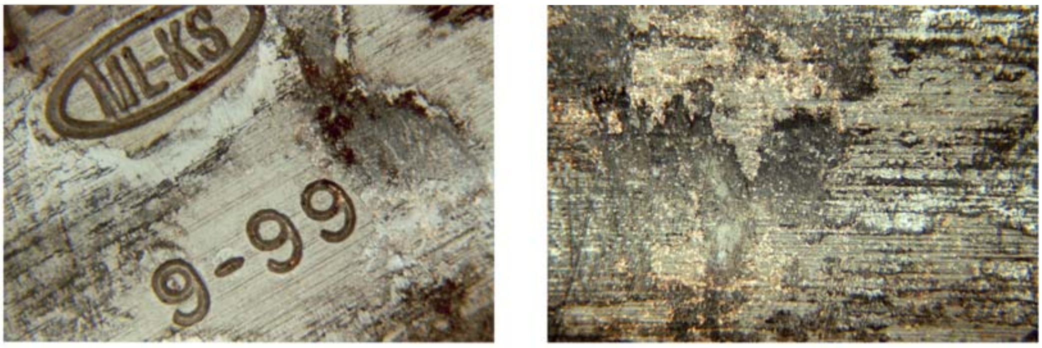
It was also evident during the course of this safety study, that connecting rod big-end bearings had been assembled with lubricant placed between the back of the bearing insert and the housing surface, figure 8.58. The lubricants varied from oil to anti-galling compounds. In many cases, the oil had been carbonised as a result of the temperatures attained at the insert back. The inclusion of lubricant between the back of a bearing insert and the bearing housing surface will reduce the coefficient of friction between the two surfaces and, as a result, reduce the bearing insert retention force.

Figure 8.58: Examples of lubricant residue present on the backs of connecting-rod bearing inserts



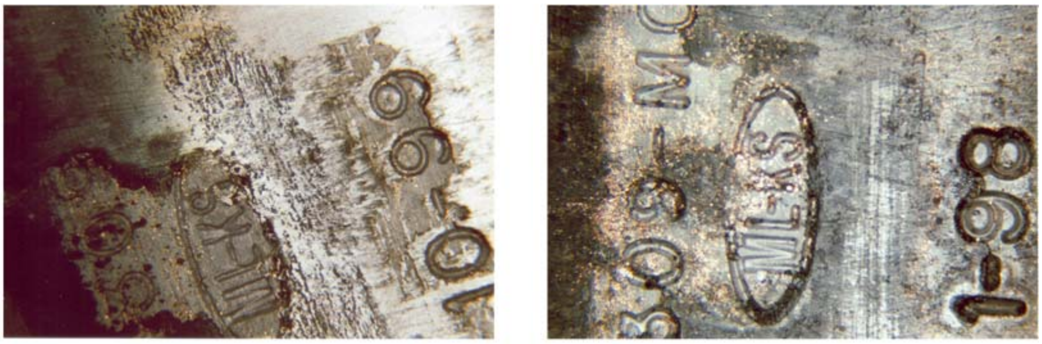
MZK right 2000/2157

MZK left 2000/90



MZK left 2000/2157

MZK left 2000/2157



JCH right 2001/5866

ODE left 2000/2276

The presence of anti-galling compound can be discerned through the residue of fine copper flakes, see VH-MZK left 2000/2157, VH-ODE left 2000/2276, and VH-JCH right 2001/5866.

8.4.3 Crankshaft main-bearing retention

During engine assembly, the bolts used to join the crankcase halves also compress the main bearing inserts and create a radial force between the inserts and housing. The friction force that acts to retain the inserts in the housing is created through the action of the radial force and the coefficient of friction between the contacting insert and housing surface.

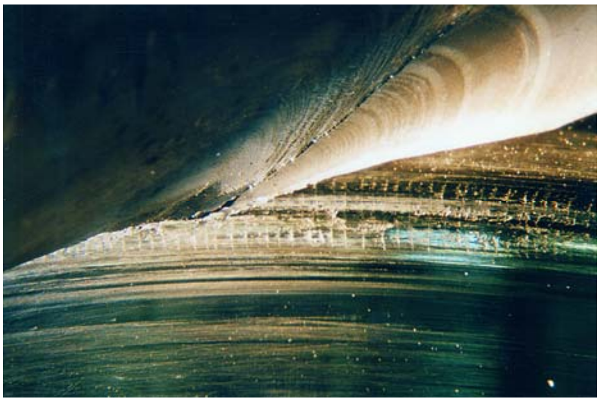
Main bearings, in a horizontally-opposed six-cylinder engine, are subjected to forces arising from the need to resist crankshaft bending moments created by the inertia of rotating masses and combustion events in multiple cylinders.

Operational experience has shown that the rearmost intermediate main bearing in a six cylinder horizontally-opposed engine (No.4, Lycoming numbering convention, No.2 Continental numbering convention) is the most sensitive to increases in the magnitude of crankshaft bending moment. This sensitivity is related to the placement of intermediate main bearings between two connecting-rod journals, the distance of the bearing from the propeller, and the successive firing of cylinders on either side of the bearing.

The movement of main-bearing inserts in their housings is a function of the magnitude of the insert retention force and the magnitude of the forces acting to move the inserts. Movement may lead to the rotation of the inserts in the housing and/or axial displacement of the inserts in the housing, culminating in contact with the fillet radius of the crankshaft. Contact between the edge of a main bearing insert and the fillet radius of a nitrided crankshaft changes the fillet radius through wear and creates a series of cracks in the nitrided surface through localised thermal expansion, figures 8.59 and 8.60.

Figure 8.59: An example of crankshaft fatigue fracture initiated by main bearing insert contact, occurrence 2001/2544, TTX

Figure 8.60: An example of the type of damage created in the main bearing journal radius through contact with the bearing insert, occurrence 2001/2544, VH-TTX



Note: the scoring damage is circumferential and the thermal expansion cracks in the nitrided surface are aligned in a radial direction.

The inclusion of any material between the parting faces of the main bearing housings will have the effect of reducing the difference in the circumference of the housing and the outer circumference of the bearing inserts, and will reduce the magnitude of the insert retention force. Examination of the main bearing housings from the engine involved in occurrence 2005/02231, VH-IGW, revealed that a jointing compound had been placed on the parting faces of each main bearing housing, see figures 8.61 and 8.62.

Figure 8.61: No.4 main bearing displacement, occurrence 2005/02231, VH-VEC

The extent of bearing displacement is shown on the left, and the extent of damage to the housing created by the bearing tang is shown on the right.

Figure 8.62: Detailed view of the material placed between the parting faces of each main bearing housing, occurrence 2005/02231, VH-IGW

8.4.4 Summary

Plain bearings in high-powered aircraft reciprocating engines are an example of a complex subsystem operating within a complex thrust system. Complexity brings with it a variety of failure modes and a sensitivity of the failure process to initial conditions.

The failure of bearings in aircraft horizontally-opposed engines can be related to factors that affect hydrodynamic oil film stability, factors that lead to an increase in the temperature of bearing materials, factors that control the magnitude of the bearing insert retention force, and factors that control the magnitude of forces which act to displace the bearing insert. These factors are shaped by the functioning of other engine subsystems and the actions of operators and maintainers.

The key factor in the loss of oil film stability was found to be the development of high combustion gas pressures during high power operation.

The key factors that were found to increase the temperature of bearings were high engine power operation combined with boundary lubrication, the presence of an adherent nickel layer between the lead-tin and aluminium-tin bearing layers exposed after bearing surface wear, and the loss of metal-to-metal contact between the bearing insert and housing through the inclusion of a lubricant.

The effect of increased bearing temperature on those bearing inserts manufactured with an aluminium-tin intermediate layer was the change in the distribution of tin through diffusion. The formation of coarse tin particles at the interface with the insert backing results in a reduction of strength of the intermediate layer and the breakaway of sections of the bearing.

The key factors in bearing insert movement were found to relate to the magnitude of the friction force created by the interference fit and the magnitude of forces acting to move the insert circumferentially and axially.

The magnitude of the forces acting to move an insert in its housing are affected by increases in sliding surface friction (boundary lubrication and, in particular, the sliding of a steel journal against an adherent nickel bearing surface) and the nature of loading created by combustion. Combustion may have an effect through an increased load on the bearing surface, increased bending moments on the main bearings of crankshafts, and increased big-end bearing edge loads associated with non-uniform gas loads on the piston and the propagation of shock waves in the combustion gases during combustion with light to medium detonation.

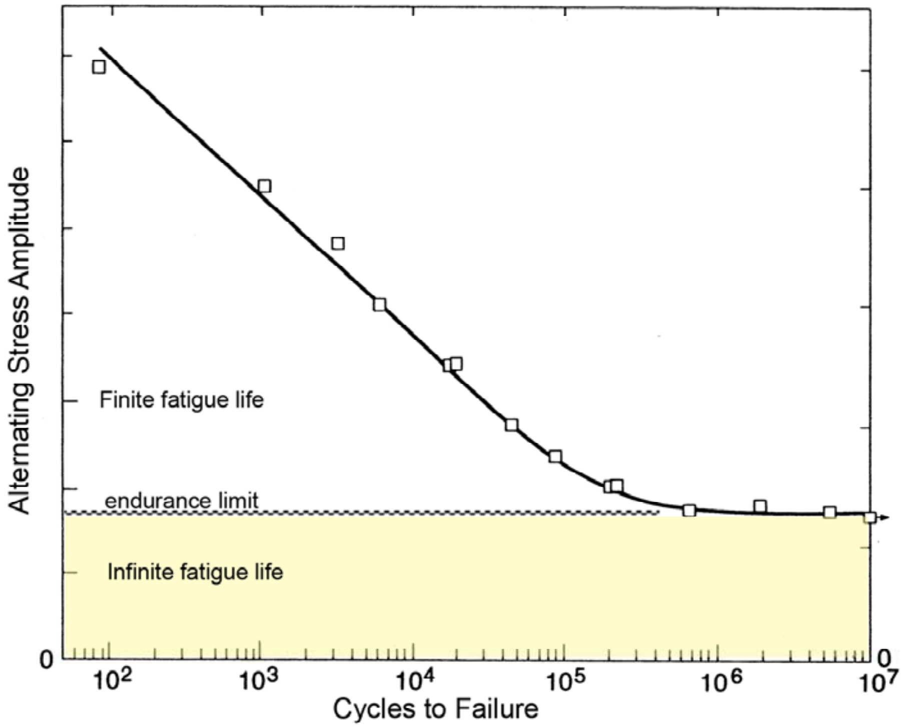
8.5 Factors associated with fatigue cracking in powertrain components

The powertrain components are designed to have a life not limited by fatigue crack initiation and propagation to final fracture, within the bounds of specified operational limits.

Powertrain components are subjected to alternating loading cycles through the effect of discontinuous combustion in multiple cylinders and the reciprocating motion of the crankshaft/connecting rod/piston assembly. The magnitude of the alternating stress cycles created in powertrain components, as a result of the alternating loading cycles, increases with increased combustion gas pressure and speed of motion (piston speed and engine revolutions per minute). The frequency of the alternating stress cycles may be related to each engine revolution or each combustion cycle (once every second engine revolution for four stroke engines).

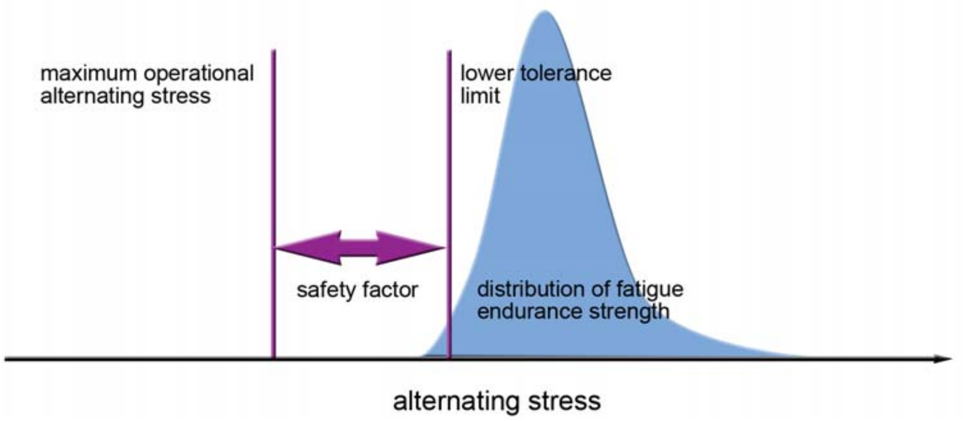
Powertrain components are subjected to an extremely high number of alternating stress cycles over the duration of their expected service life, for example, 1.5×10^7 once per rev. cycles, will be created over a period of 100 hours for an engine speed of 2,500 rpm. Because of the exposure to a very high number of alternating stress cycles, powertrain component design is based on controlling the magnitude of alternating stress cycles to a value that does not exceed the fatigue endurance strength of the component, figure 8.63.

Figure 8.63: Schematic representation of the relationship between alternating stress amplitude and number of cycles to failure showing the fatigue endurance strength



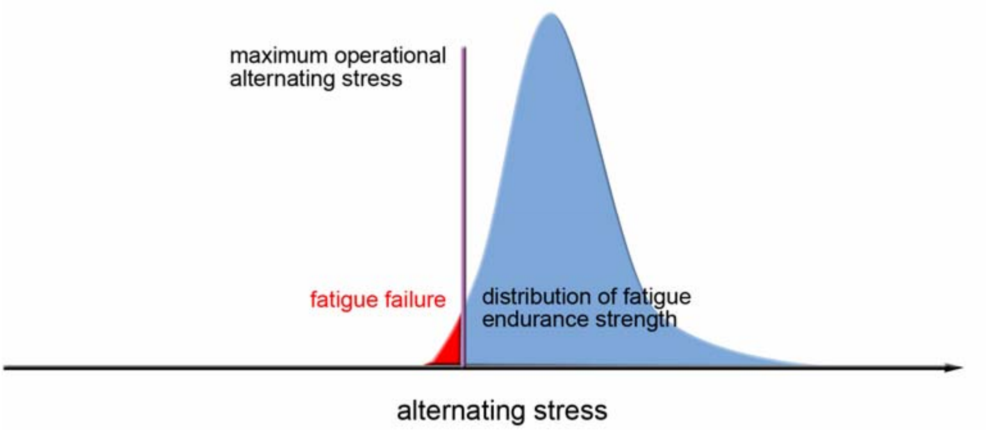
The fatigue endurance strength of a component is a function of; the material, component form, presence of stress concentrators, presence of residual stress, component surface finish, and the presence of surface hardening. It is well established that the fatigue endurance strength of a mass-produced component is not known with certainty. The scatter in endurance strength requires design to be based on knowledge of the probability distribution for the endurance strength for the component, see figure 8.64. Factors of safety are used to accommodate the uncertainties and scatter in component endurance strength.

Figure 8.64: The relationship between maximum alternating stress and the distribution of component fatigue endurance strength – infinite life



Fatigue failure will occur in some components from a batch of designed (part number) components if the magnitude of the alternating stress overlaps the distribution of endurance strength for the component, see figure 8.65.

Figure 8.65: The relationship between maximum alternating stress and the distribution of component fatigue endurance strength – finite life, component failure



For the case of component designs that have passed certification testing and have demonstrated fatigue-free operational performance, component failure indicates that:

- the component was subjected to alternating stresses that exceeded the maximum design allowable value;
- a change in the distribution of component endurance strength from the design state has occurred;

- a change in the component has occurred during operation, so that it is no longer bounded by the component fatigue endurance strength distribution parameters; or
- there was a combined reduction in component endurance strength and increase in maximum alternating stress.

The magnitude of alternating stress cycles in a powertrain component, of established design, may be a function of engine speed (crankshaft revolutions per minute and piston speed), differential thermal expansion and contraction, or the pressure of combustion gases. For the case of aircraft engine-coupled to a constant-speed propeller, the speed of the engine is tightly controlled. However, the pressure of combustion gases (bmep) may vary in response to power, speed and mixture selection.

Increases in the magnitude of alternating stress beyond the design maximum allowable value, may arise from operational factors and/or maintenance factors that act, singly or synergistically, to increase the combustion gas pressure, the engine/component speed, and thermal stresses beyond design allowable values.

Component fatigue endurance strength is affected by a lowering of material strength, the creation of additional stress concentrating features, or a lowering of designed compressive residual stress states.

8.5.1 Cylinder head fatigue failure

Cylinder heads are part of the structural assembly that, in effect, is a pressure vessel subjected to alternating pressures and heating and cooling cycles. These alternating pressures and thermal cycles are the source of alternating stresses in cylinder heads.

The location of fatigue cracking in the cylinder head, occurrence 2001/2885, VH-MJA, site of fatigue crack initiation, and plane of fatigue crack growth, see figure 8.66, indicate that fatigue cracking initiated and propagated as a result of periods of engine operation with high gas pressures in the cylinder. The cylinder head section, at the joint between the head to barrel, is subjected to longitudinal stresses each time the combustion chamber is pressurised.

Figure 8.66: Fatigue cracking features, occurrence 2001/2885, VH-MJA

Fatigue cracking initiated at several sites at the head/barrel thread root (the general regions of crack initiation are arrowed), cracking propagated on a plane normal to the cylinder wall.

It is evident that, in the case of occurrence 2001/2885, VH-MJA, the stresses created at the head-to-barrel connection, through gas pressure in the combustion chamber, exceeded the endurance strength of the cylinder head. It is important to consider the effect of localised pressure, as developed under conditions of end-gas detonation, as a factor in fatigue crack initiation. The site of fatigue crack initiation in the cylinder head from MJA is located adjacent to a site of potential end-gas detonation.

8.5.2 Cylinder attachment fastener fatigue failure

The cyclic development of combustion-gas pressure creates a condition of alternating stress in the cylinder attachment fasteners. The magnitude of alternating stresses in each fastener is controlled through the creation of a preload in the fastener during assembly. The avoidance of fatigue crack initiation is dependent on; the magnitude of the preload in the fastener, the magnitude of the load applied to the fastened joint, and the endurance strength of the fastener. For a fastener of specified endurance strength, fastener failure may occur if the combustion gas pressure exceeds the design allowable value or the fastener preload is below the design value.

Fastener preload may be reduced during engine operation through the deformation of material included in the fastened joint. The inclusion of paint under the face of the nut can result in a significant lowering of the preload in cylinder attachment studs, see for example Lycoming Service Bulletin 271A. It is evident in the case of occurrence 2002/5129, VH-TZY, that, not only had a thick paint film been applied to the cylinder base flange under the bearing face of the nuts, paint had been applied to the stud threads in the region where the nut thread engages with the stud thread, see figures 8.67 to 8.69.

Figure 8.67: An example of paint applied to the region of the stud thread that engages with the nut thread, occurrence 2002/5129, VH-TZY

Figure 8.68: Detailed view of the paint applied to the stud thread, occurrence 2002/5129, VH-TZY

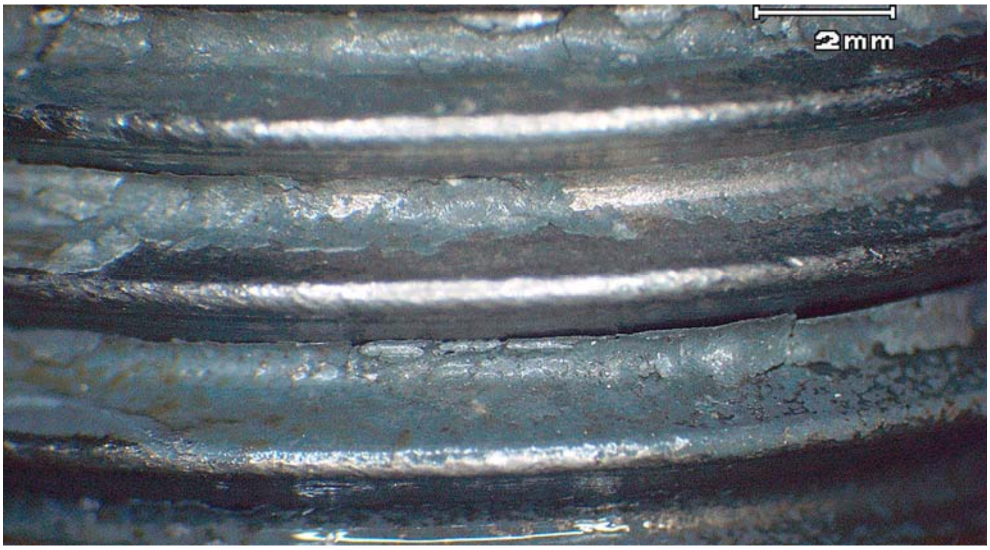


Figure 8.69: An example of the paint film applied to the cylinder base flange, occurrence 2002/5129, VH-TZY

Note the presence of grey paint on the surface of the bolthole.

8.5.3 Connecting rod bearing housing fatigue failure

The resistance of connecting-rod bearing housings may be affected by the creation of surface damage through the process of adhesive wear – galling – that occurs when there is relative movement between the piston pin and housing surface, following the breakup of the little-end bearing, or relative movement between the steel backing of the big-end bearing inserts and the big-end housing. The fracture of connecting rod little-end housings in occurrences, 2000/90, MZK, and 2003/03701, OCF, are examples of the effect of galling damage on the inner surface of bearing housings.

The connecting rod big-end housing fatigue fractures associated with occurrences, 2000/90, VH-BNN, 2001/1405, VH-LTW, 2002/3474, VH-ACZ, are characterised by fatigue initiation at the outer surface of the housing at the point of transition from the bolt boss to the connecting rod 'I' beam, see figure 8.70. Fatigue initiation in this location is associated with big-end housing flexure under conditions of connecting rod inertia loading. In practice, the degree of flexure is limited by the clearance between the crankshaft journal and the big-end bearing.

Fatigue failure, involving initiation at the outer surface of the big-end housing, is an indicator of an increase in the degree of housing flexure. The breakup of the big-end bearing inserts creates increased clearance between the journal and the connecting rod big-end allowing increased housing flexure under connecting rod inertia loading, figure 8.71.

Figure 8.70: The site of fatigue crack initiation, occurrences 2000/90, 2001/1405, 2002/3474

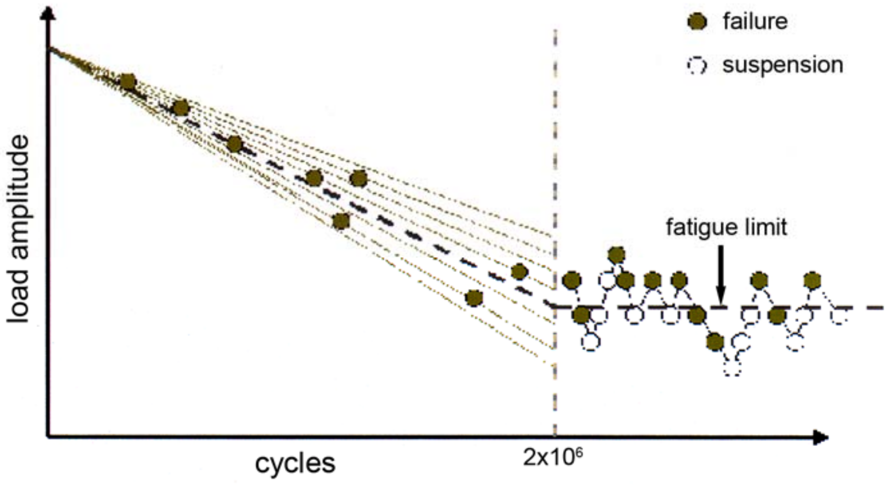
Figure 8.71: A comparison of clearance between the crankshaft journal and connecting rod big-end bearing (left) and the big-end housing without the bearing inserts (right)

The diameter of the crankshaft journal is represented by the coloured circle.

8.5.4 Crankshaft fatigue failure

Crankshafts, regardless of the end application of the engine, are designed to have an operational life not limited by fatigue. The complex interrelationships between loads, geometric stress concentrators, residual stress, surface finish, surface hardening, and material, results in scatter in fatigue behaviour. Safety factors are applied to ensure that, for a particular crankshaft design, the maximum alternating stress from engine, operation does not intersect the distribution of crankshaft fatigue endurance strength.

Figure 8.72: Schematic showing the scatter in the relationship between alternating stress magnitude and number of alternating stress cycles for a crankshaft (Lee and Morrissey, 2001)



Two dominant fatigue failure modes have been identified by the designers of crankshafts (Piraner, Pflueger and Bouthier, 2002):

- fatigue through a crankweb, associated with bending of the crank throw in its plane, with crack initiation occurring at a main or crank journal fillet; and
- fatigue through a connecting-rod journal, associated with alternating shear stresses generated by throw torsion, with fatigue cracking initiating at an oil hole.

The initiation and propagation of fatigue cracks in a crankshaft is not simply a matter restricted to the material from which the crankshaft is manufactured. It is a matter of all factors that affect the magnitude of crankshaft alternating stresses, and the crankshaft endurance strength.

Crankshaft alternating stress

External loads

The major loads imposed on a crankshaft during operation are loads created by combustion gas pressure and the loads created by the inertia of rotating and reciprocating assemblies. These loads create bending and torsional stresses in the crankshaft journals and crankwebs. The maximum stress in the crankshaft is developed when the engine is operated in a manner that results in maximum combustion chamber gas pressure and/or maximum piston speed.

A feature of the layout of horizontally-opposed engines – the placement of a main bearing between two connecting-rod journals – makes crankshaft bending a critical loading condition, see figure 8.72. The magnitude of bending stresses in crankwebs is strongly influenced by the placement of journals (Taylor, 1999, vol.2, pp.494-495). Bending stresses are increased as the length of the crankweb between neighbouring journals is increased.

Torsional stresses arise from the action of the gas pressure loads on the cranks and the transmission of torque to the engine-output flange and accessory drivetrain. A special loading case that is considered during design, and thoroughly tested during engine certification, is that of torsional resonance. Torsional resonance is a function of the frequency of gas pressure impulses and the elastic properties of the crankshaft.

Stress concentration

The distribution of stress developed within a crankshaft, through crankshaft bending and torsional, is not uniform (Taylor, 1999, vol.2, pp.496-498). Stress gradients are formed under bending and torsion loading. The stress decreases in magnitude from the surface to centre of the component. The form of a crankshaft results in non-uniform distributions of stress. Torsional stresses are concentrated in the journals and bending stresses are concentrated in the transitions between the journals and crankwebs. For the case of crankshaft bending, the distribution of bending stress in the journal fillet region is not uniform around the circumference of the fillet or around the fillet radius, figures 8.74 and 8.80. The distribution of bending stress is influenced by detailed geometry and the timing of the maximum load with respect to the angular position of the crankshaft.

Figure 8.73: **Schematic showing the typical locations for fatigue crack initiation in the forward fillet of the No.6 journal and the rear fillet of the No.5 journal, for the case of no fillet damage**

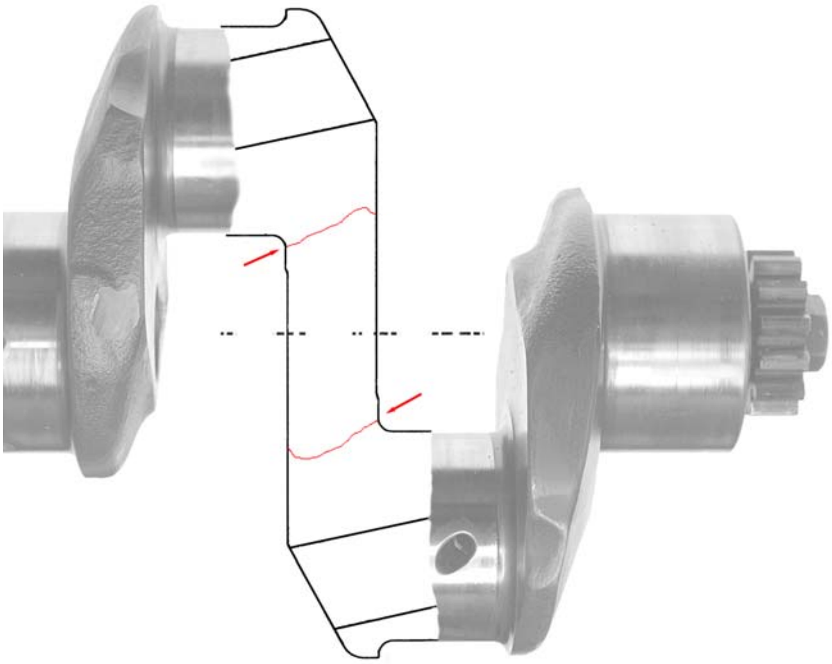
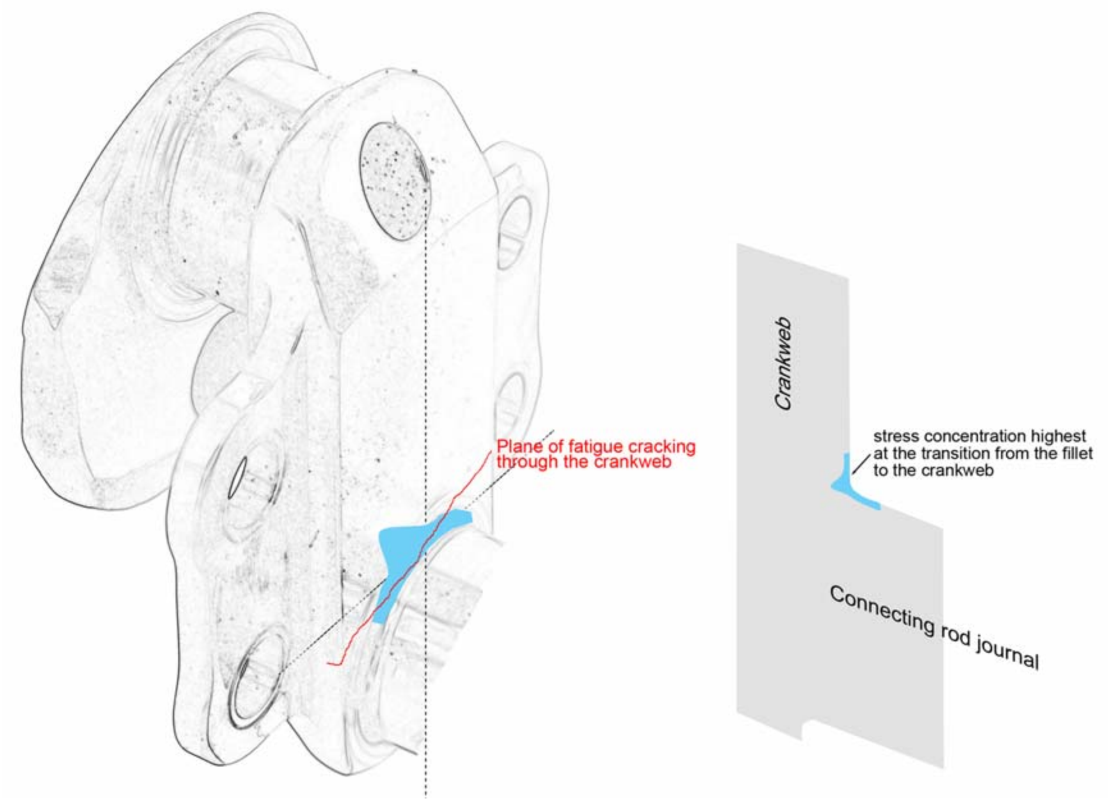


Figure 8.74: **Schematic showing the distribution of crankweb bending stress at the forward fillet of a No.6 connecting rod journal**



The orientation of the plane of fatigue cracking is related to the angular position of the crankweb at the time of maximum combustion pressure; for normal operation the peak pressure is developed approximately 20° after top centre.

Crankshaft endurance strength

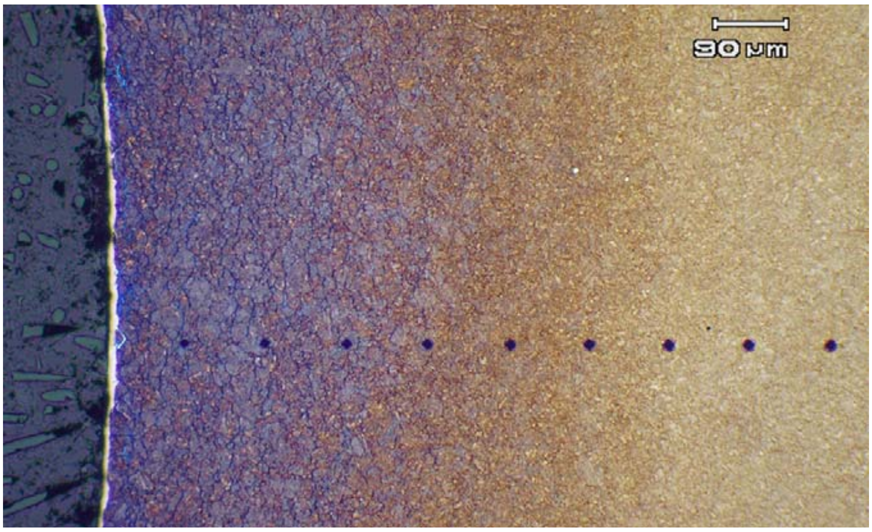
The resistance of a crankshaft to the initiation of fatigue cracking is affected by the mechanical properties of the crankshaft material and the nature of residual stresses at the sites of operational stress concentration.

Aircraft engine crankshafts are nitrided to create a hard, wear resistant, surface. An additional effect of nitriding is to create gradients of strength and compressive stress across the hardened zone. These gradients of strength and residual stress have a strong influence on resistance to bending fatigue (ASM, 1997, vol.19, p.682). The superposition of the compressive residual stress gradient, with a high compressive stress at the surface, on the applied stress gradient, with a high tensile stress at the surface, results in a reduction in the magnitude of alternating stress at the surface of nitrided crankshaft journal fillets. The gradient of material strength creates a gradient in resistance to fatigue initiation. The highest resistance to fatigue initiation is at the surface. An example of the extent of the effect of nitriding is shown in figure 8.75.

For cases where the operational alternating stresses exceed the design allowable value, the combined effect of operating stress gradient, residual compressive stress gradient, and material fatigue strength gradient, results in fatigue crack initiation below the surface of the fillet (ASM, 1997, v.19, p.612; Hertzberg, 1996 p.548;

Shigley and Mischke, 1989, pp.286-287; Forrest, 1970, p193). Subsurface initiation occurs when the magnitude of crankshaft alternating loads just exceed the endurance strength of the crankshaft. When the magnitude of alternating loads greatly exceeds the endurance strength, fatigue cracking initiates at the fillet surface.

Figure 8.75: Metallographic section taken from an aircraft crankshaft fillet showing the extent of the effect of nitriding



The plane of the section is perpendicular to the fillet radius. The extent of the effect of nitriding can be discerned by the change in colour from left to right (the unaffected core material is coloured straw on the right side of the micrograph). The square shaped features are microhardness indentations.

The initiation of fatigue cracking is further influenced by the nature of the distribution of microstructural features. The steel alloy from which crankshafts are manufactured is not a homogeneous material. The material can be described, in a general sense, as being a fine dispersion of carbides (iron and other alloying elements) in a polycrystalline ferrite matrix. In addition, there is a dispersion of non-metallic, oxide and sulphide, inclusions. Fatigue crack initiation is affected by the nature of the microstructural features at the site of highest stress concentration. Any feature that increases the magnitude of local shear stresses, for example, free surfaces associated with inclusions, or lowers the critical shear stress for plastic deformation, will lower the operational alternating stress magnitude for fatigue initiation.

The effect of non-metallic inclusions is minimised by the use of melting practices, such as vacuum-arc remelting, that reduce the number and size of non-metallic inclusions.

The effect of material variation on fatigue endurance strength, in an alloy of specified composition, state of heat treatment, and method of melting and forming, is established by testing standard test pieces. Any variation arising from material features is accommodated in the design of a component by the use of safety factors.

Crankshaft endurance strength may also be reduced by changes in component form or the creation of discontinuities during engine operation or component maintenance.

8.5.5 Crankshaft fatigue failure – examples

The features of fatigue fracture in nitrided crankshafts are affected by the non-uniform distributions of applied stress, residual stress, material endurance strength, material inclusions. They are also affected by stress concentrating features that may be created during maintenance actions or engine operation

No fillet damage, subsurface fatigue crack initiation

Example 1: Teledyne Continental GTSIO-520M engine; crankshaft p/n 635104, s/n C874; reported major defect 1992. The crankshaft connecting-rod journals had been resized 0.010 inch undersize.

Figure 8.76: Fatigue fracture forward fillet of the No.1 connecting-rod journal, fatigue crack propagation through the crankweb between the No.1 and No.2 connecting rod journals

The site of fatigue crack initiation is arrowed.

Figure 8.77: Low magnification scanning electron micrograph of the region surrounding the site of fatigue crack initiation

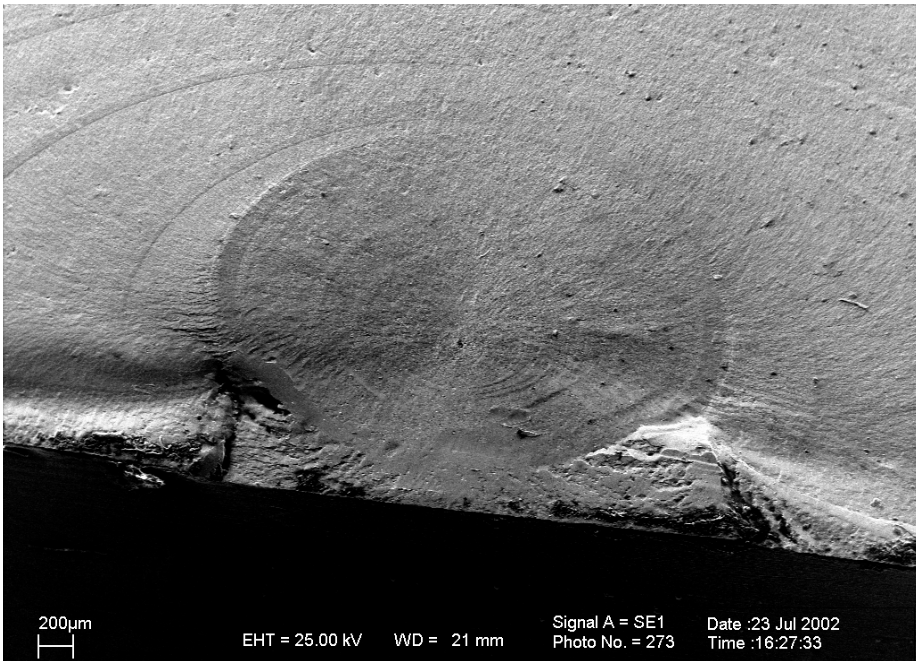


Figure 8.78: Scanning electron micrograph showing the site of fatigue crack initiation in more detail

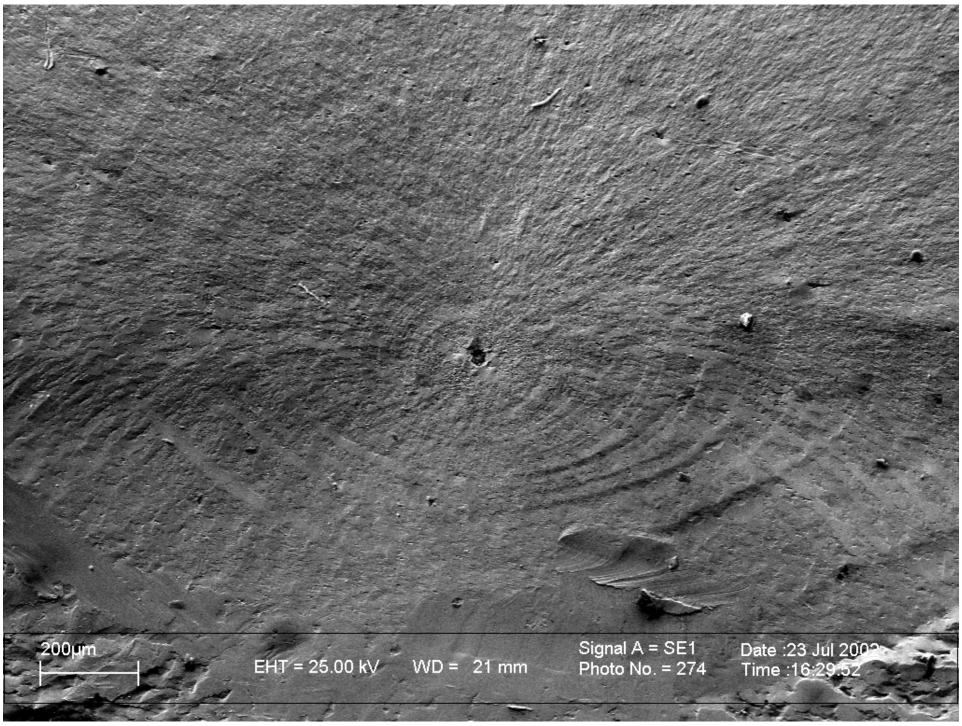


Figure 8.79: Scanning electron micrograph of the site of fatigue crack initiation at higher magnification showing that crack initiation occurred at an alumino-silicate inclusion

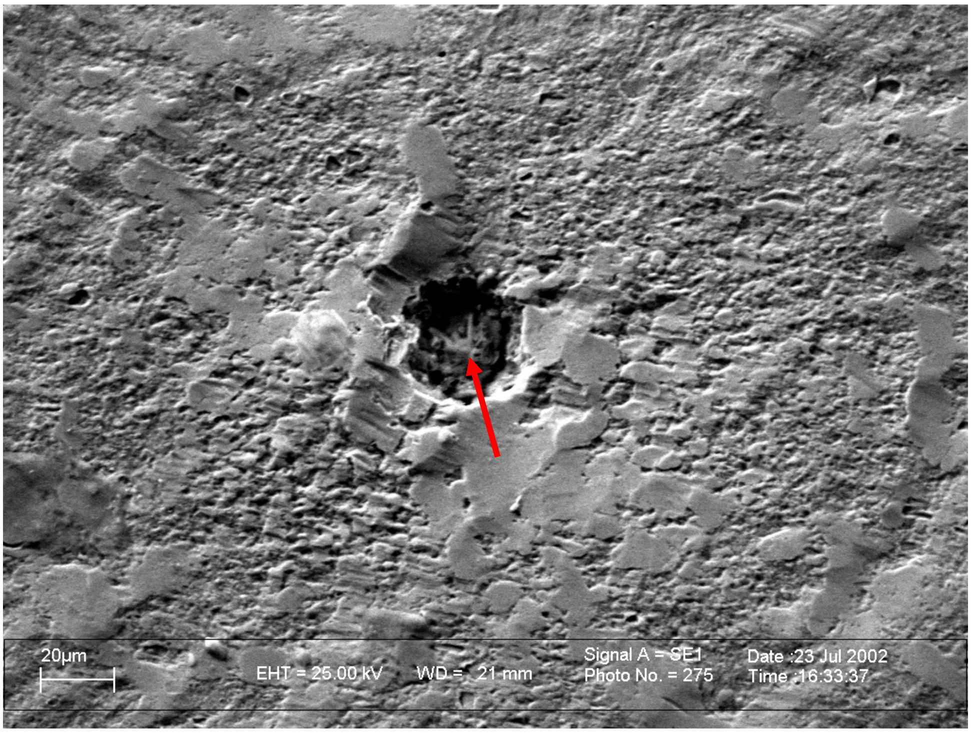
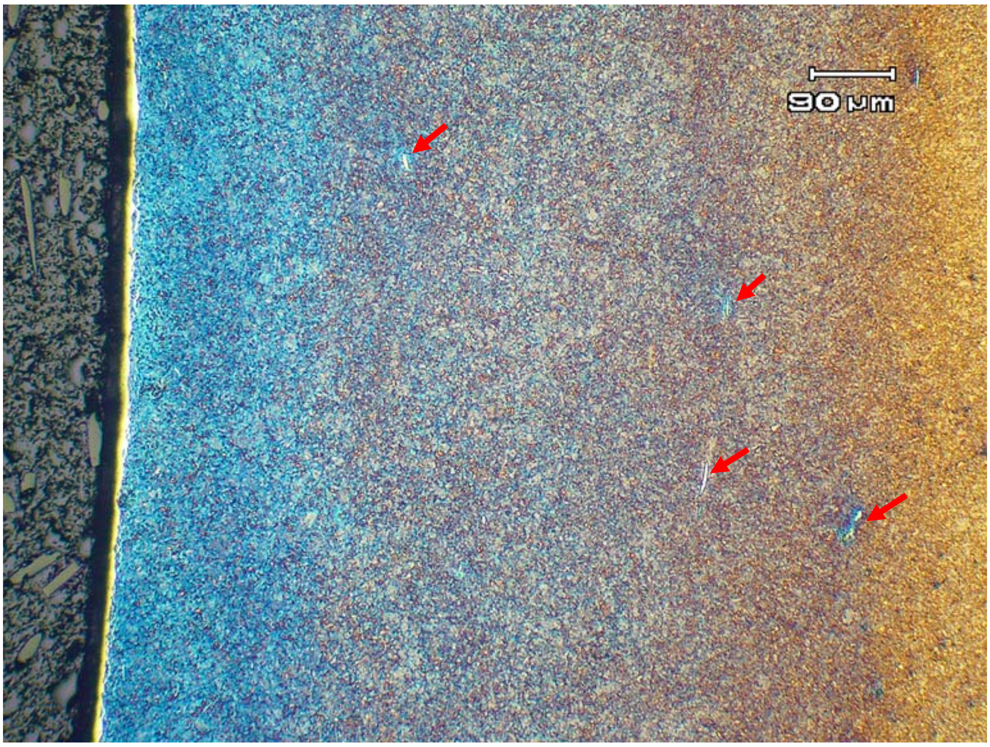


Figure 8.80: Metallographic section through the No.1 connecting-rod journal fillet



The fillet surface is at the left of the micrograph. The depth of nitriding can be distinguished by the colourisation; the core material is at the right (straw/gold). Several non-metallic inclusions are evident (arrowed).

Figure 8.81: The nature of a typical inclusion present in the crankshaft steel

It is evident that fatigue crack initiation occurred at a material inclusion located in the region of applied stress concentration, created by crankshaft bending during engine operation (the transition between the fillet and crankweb), and the location of highest residual tensile stress (the transition from the hardened surface to the crankshaft core material).

Examination of the No.1 connecting rod big-end bearing revealed that the forces created during engine operation had been sufficient to damage the bearing surface, locally, in the region that is sensitive to combustion loads, figure 8.82.

Figure 8.82: No.1 connecting rod bearing boundary lubrication damage (rod side insert)

Resolution of the issues contributing to the fatigue fracture of this crankshaft requires the consideration of, both, material factors and the magnitude of combustion loads in the No.1 cylinder.

Example 2: Teledyne Continental TSIO-520; crankshaft, s/n S789nc, inspection marking 092/u/u; occurrence 2001/4799 VH-BEM. The marking 092/u/u indicates that the crankshaft had been inspected ultrasonically, for the presence of fatigue cracking, on two occasions.

The initiation of fatigue cracking in this crankshaft is consistent with the location of highest applied stress and highest residual tensile stress when the magnitude of the combined stresses just exceeds the fatigue endurance strength of the material. There is no evidence of the presence of any abnormally large non-metallic inclusions, figures 8.84 to 8.86.

On the basis of the results of two previous ultrasonic inspections, it is apparent that fatigue initiation occurred after a long period of operation. Successful operation, over a long period of operational time, indicates that the crankshaft material is not the prime factor in fatigue crack initiation.

Resolution of the issues contributing to the fatigue fracture of this crankshaft would require the consideration of possible changes in engine operation that increase the magnitude of crankshaft bending at the No.3 main bearing.

Figure 8.83: **Scanning electron micrograph showing the region surrounding the site of fatigue crack initiation, forward fillet of the No.3 main bearing journal. Fatigue cracking propagated through the No.3 main and No.5 connecting-rod crankweb**

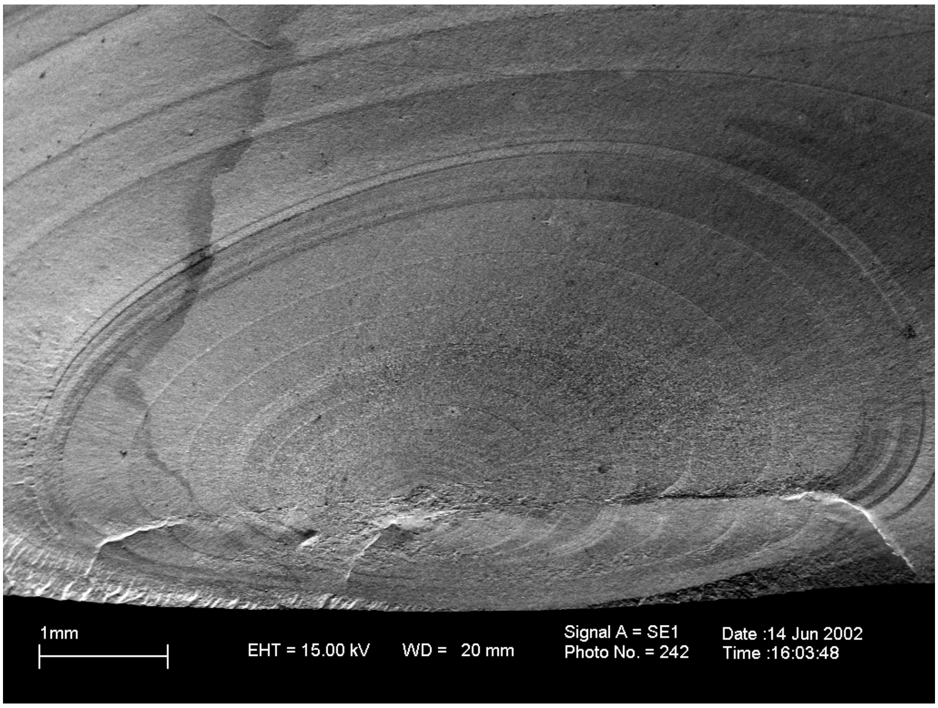


Figure 8.84: **Detailed view of the region surrounding the site of fatigue crack initiation. The features of the initiation site had been obliterated by mechanical damage after the fracture of the crankweb**

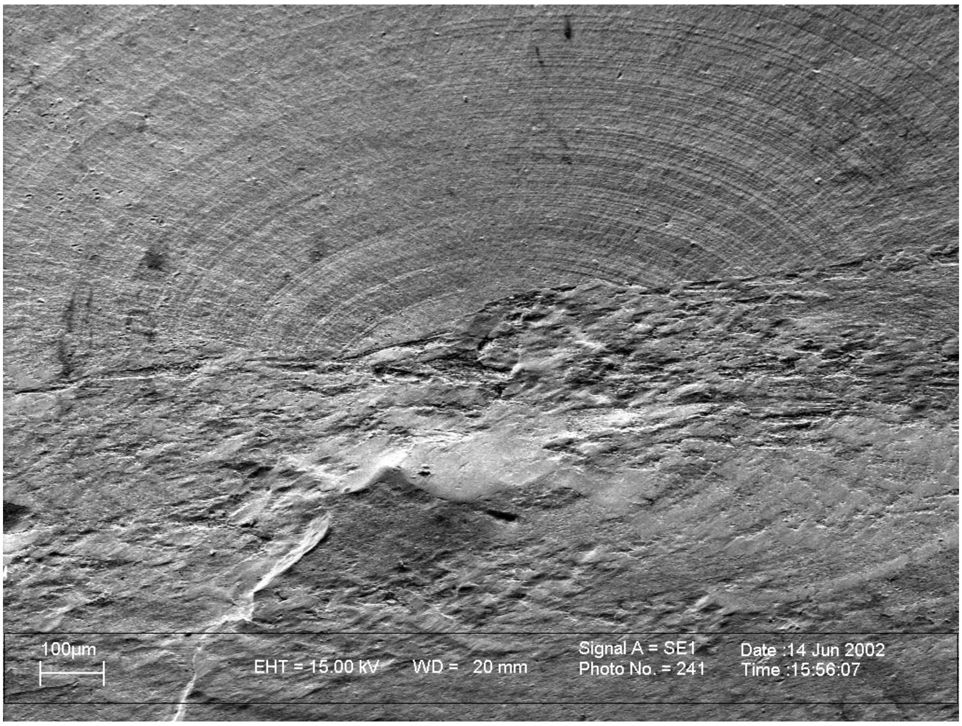


Figure 8.85: **Scanning electron micrograph showing the plane of metallographic sectioning through the site of fatigue crack initiation**

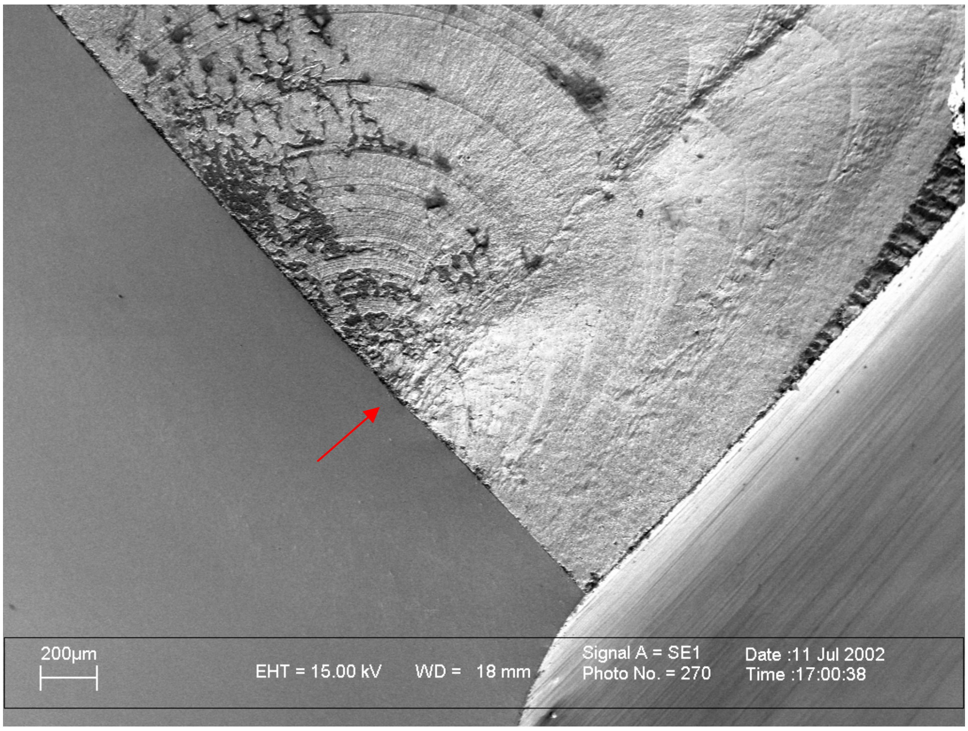
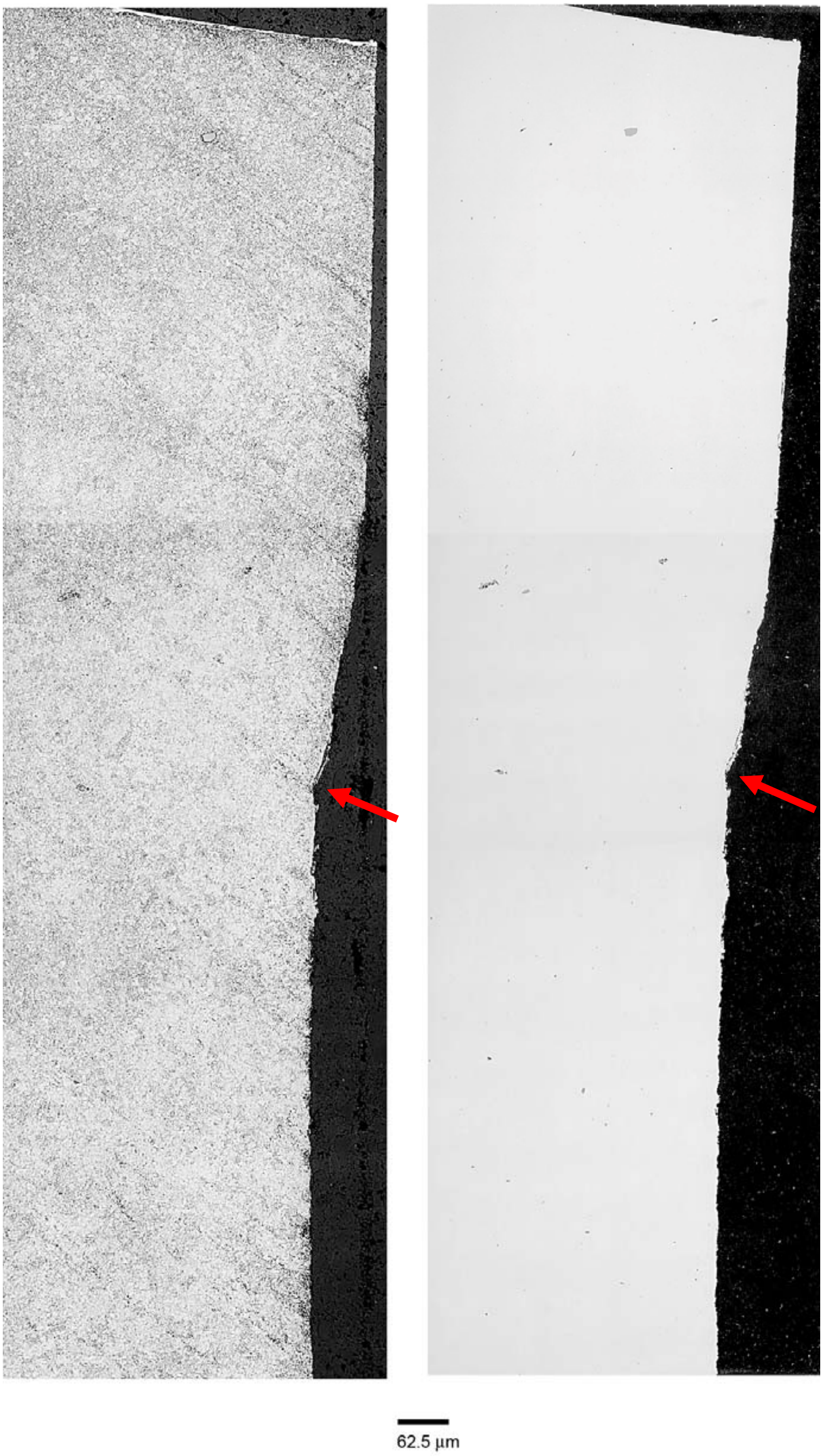


Figure 8.86: **Metallographic sections through the site of fatigue crack initiation etched (left) and unetched (right)**

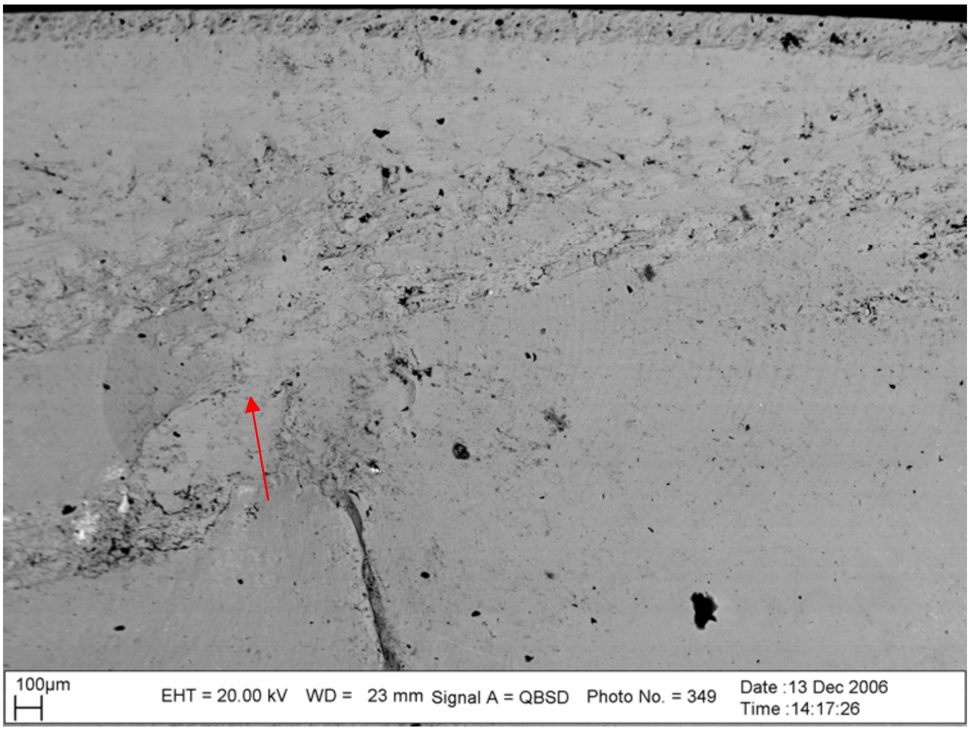


The site of fatigue crack initiation is arrowed. The unetched micrograph shows the nature and distribution of non-metallic inclusions.

Example 3: Lycoming TIO-540-J2BD; reported major defect, 96/0797.

Figure 8.87: **Fatigue crack initiation, forward fillet of the No.3 main journal, crack propagation through the crankweb between the No.3 main journal and No.2 connecting-rod journal**

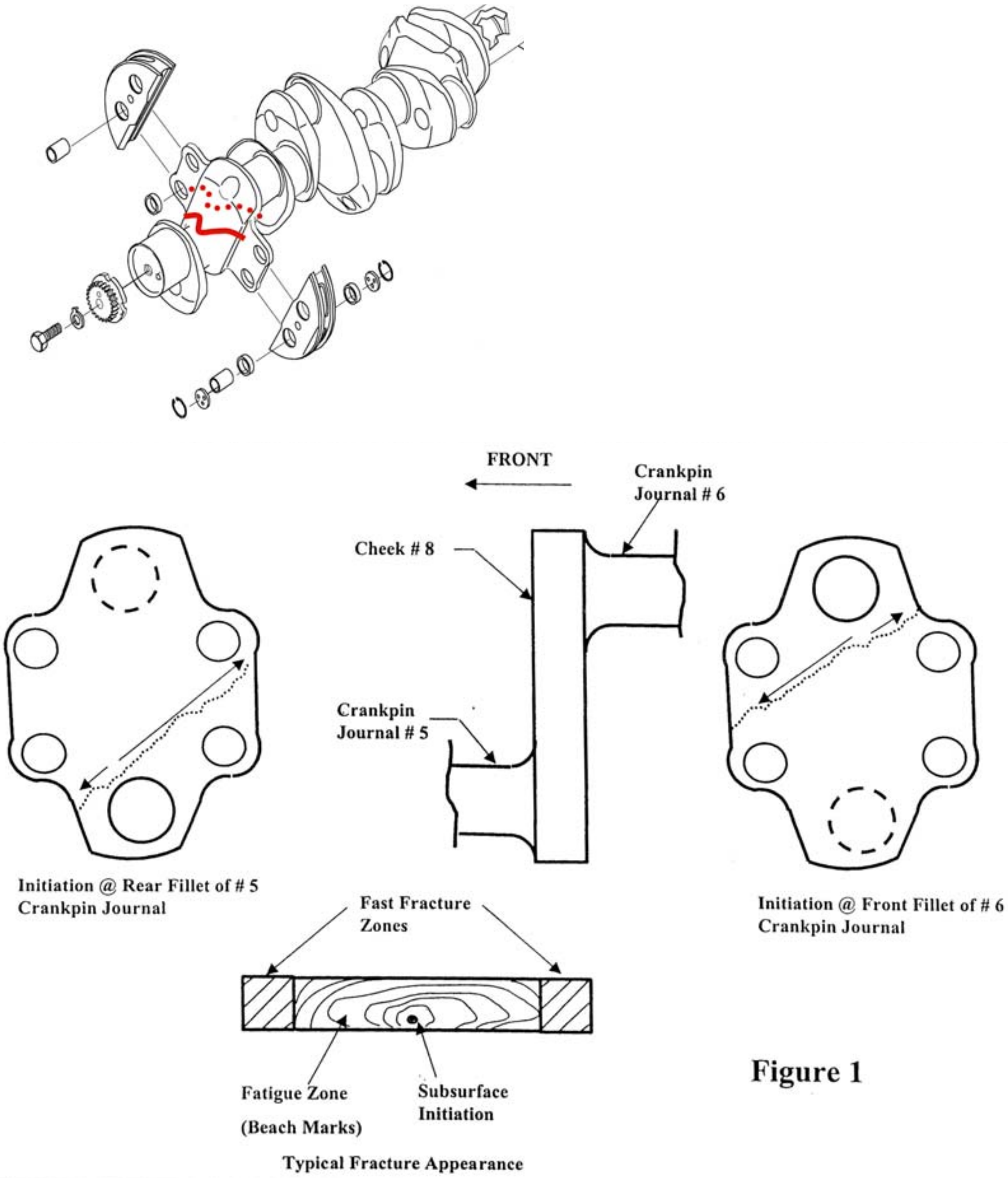
Figure 8.88: **Scanning electron micrograph showing the region surrounding the site of fatigue crack initiation**



The site of crack initiation had been damaged mechanically following the fracture of the crankweb.

Example 4: The Federal Aviation Administration (FAA) reported a series of fatigue fractures in the crankweb between the No.6 and No.5 connecting journals of Lycoming TIO (LTIO)-540 engine crankshafts. Note, however, that no fractures of this type were reported to the ATSB during the period covered by this study.

Figure 8.89: FAA diagrams showing the nature of fatigue cracking in the crankweb between the No.6 and No.5 connecting rod journals (GASIL, 2002, p.28)



The fatigue initiation sites were reported to be below the surface of the forward fillet of the No.6 connecting-rod journal or the rear fillet of the No.5 connecting-rod journal.

No fillet damage, surface fatigue initiation,

A number of crankshaft failure events involve multiple fractures. An engine can continue to operate following the fracture of a crankweb as the plane of fracture allows torque to be transmitted by continued contact between regions of the fracture surface. The initial fracture creates a condition of abnormal high bending stress at other crankshaft fillets.

Example 5: Lycoming TIO-540-V2AD, occurrence 2005/02231, VH-IGW.

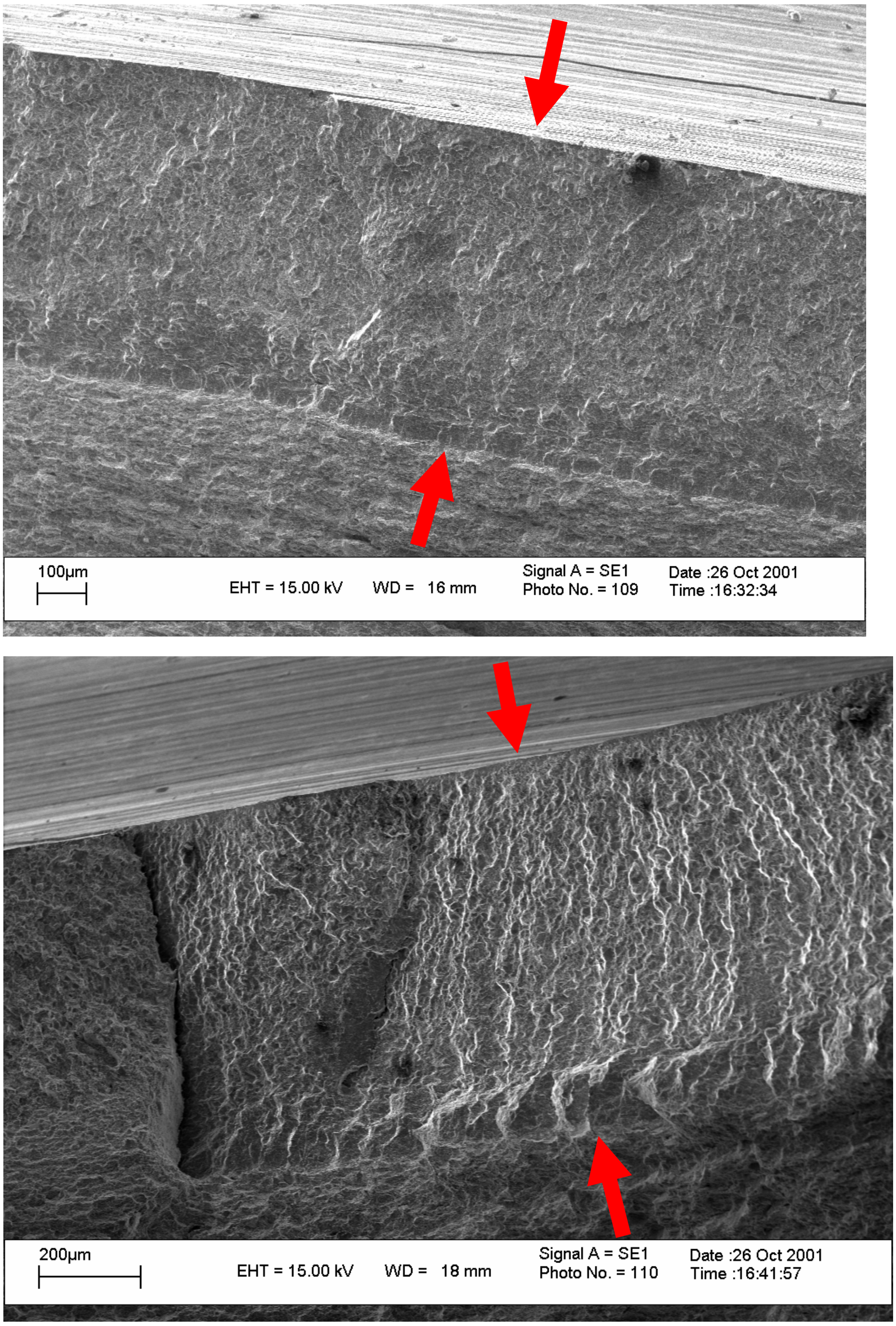
Figure 8.90: Crankweb fracture No.3 main/No.3 connecting-rod journals following the fracture of the crankweb between the No.4 main and No.4 connecting rod journals

Fatigue crack initiation occurred at the transition of the fillet to the crankweb. The lack of fatigue crack progression marks indicates that crack growth occurred within the period of one flight.

Example 6: Lycoming TIO-540-J2B, occurrence 2000/2157, VH-MZK (left).

Continued operation of the engine following the fracture of the No.6 connecting-rod journal, created a condition of abnormal loading on the No.5 connecting-rod journal and the No.4 main journal. The fatigue cracking that resulted from the abnormal loading condition (see figure 6.39), initiated at the fillet surface.

Figure 8.91: **Fatigue cracking rear fillet of the No.4 main bearing journal (top) and the forward fillet of the No.5 connecting-rod journal (bottom)**



The depth of fatigue cracking is indicated by arrows. Crack initiation was not restricted to a specific material feature.

Modification of journal fillet radius, surface initiation

Example 7: Lycoming IO-540-C4B5 engine, reported major defect 1995, crankshaft s/n 68499, connecting rod journals reduced in diameter by 0.003 of an inch by abrasive polishing.

The fillets of all connecting rod journals had been notched, at the transition from the journal bearing-surface to the crankweb fillet, during the journal polishing process. Fatigue cracking initiated at the surface of the No.6 journal where the fillet had been notched.

Figure 8.92: The nature of the plane of fatigue crack growth

Figure 8.93: Detailed view of the fatigue crack initiation site, crankweb side

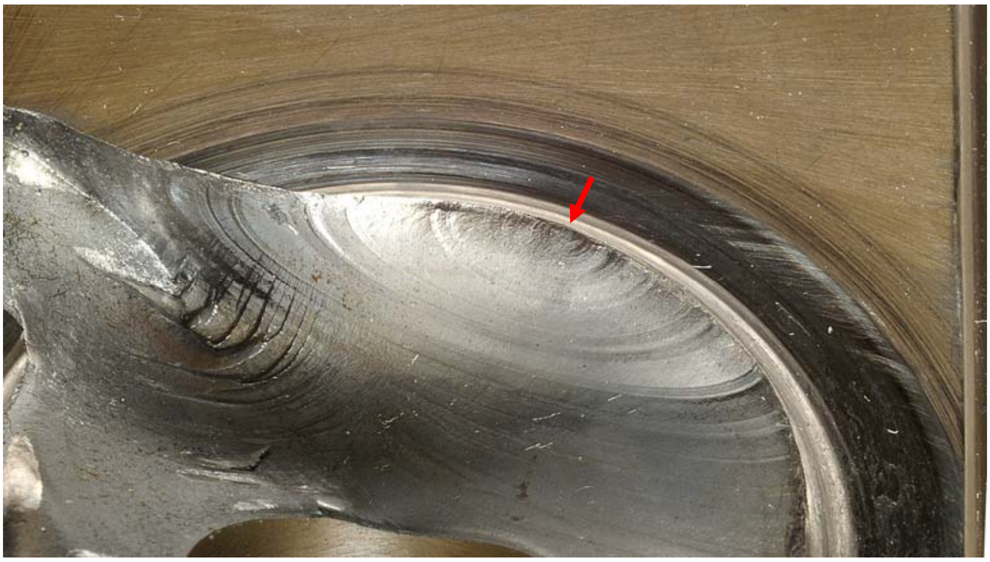


Figure 8.94: **Detailed view of the fatigue crack initiation site, journal side**

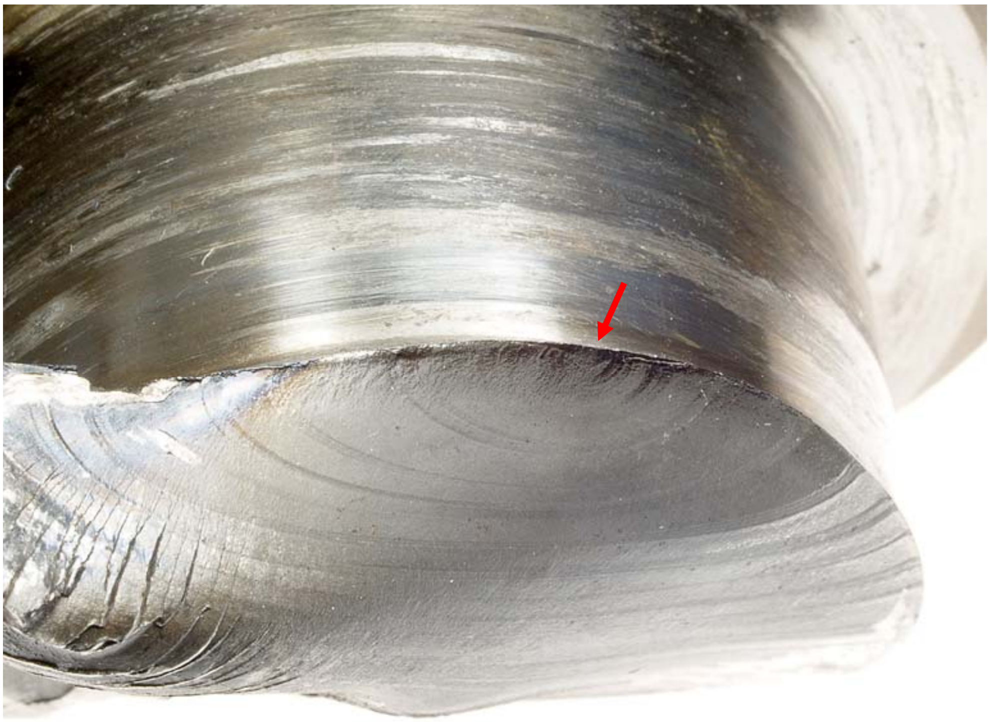
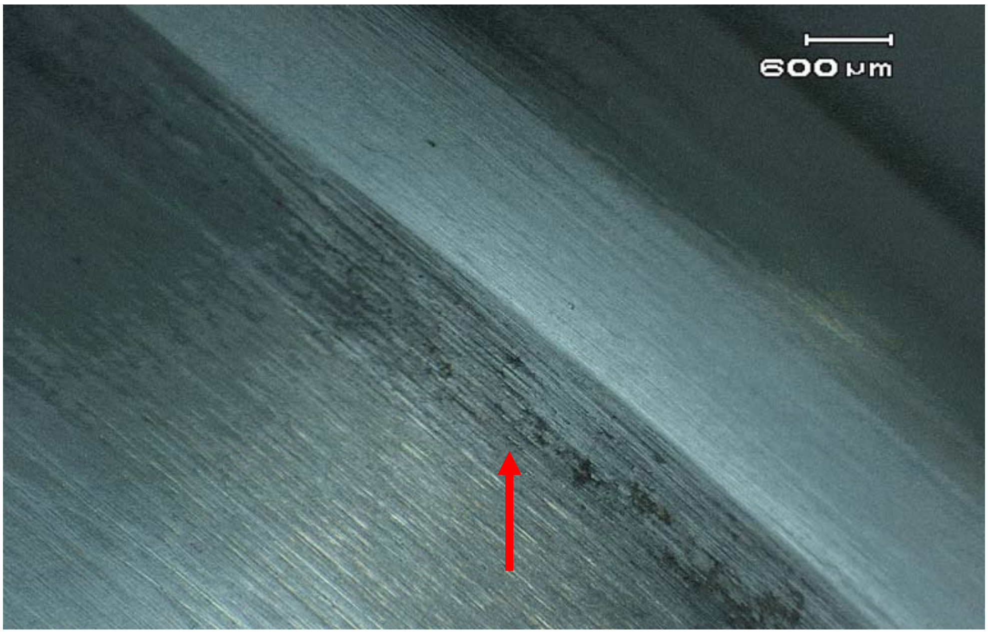


Figure 8.95: **An example of fillet notching**



It is apparent, in this example, that while the site of fatigue initiation coincided with the predicted circumferential position of highest crankweb bending stress, the severe stress-concentrating feature created at the journal-to-fillet transition, during journal polishing, influenced the radial location of the initiation site in the fillet. The change in the site of crack initiation, with respect to the fillet, affected the plane of fatigue crack growth.

Planar defects created by rubbing contact between the connecting rod and crankweb

Example 8: Lycoming TIO-540-J2BD, major defect report 94/1135.

The lack of ductility in the nitrided surface of a crankshaft creates the possibility of the development of surface cracks if the surface is subjected to localised thermal expansion stresses.

In this example, frictional heating through rubbing contact between the No.6 connecting rod big-end housing and the face of the crankweb, following the distortion of the connecting rod during engine operation, created a number of fine cracks in the nitrided surface of the crankweb.

Figure 8.96: The fatigue fracture in the crankweb

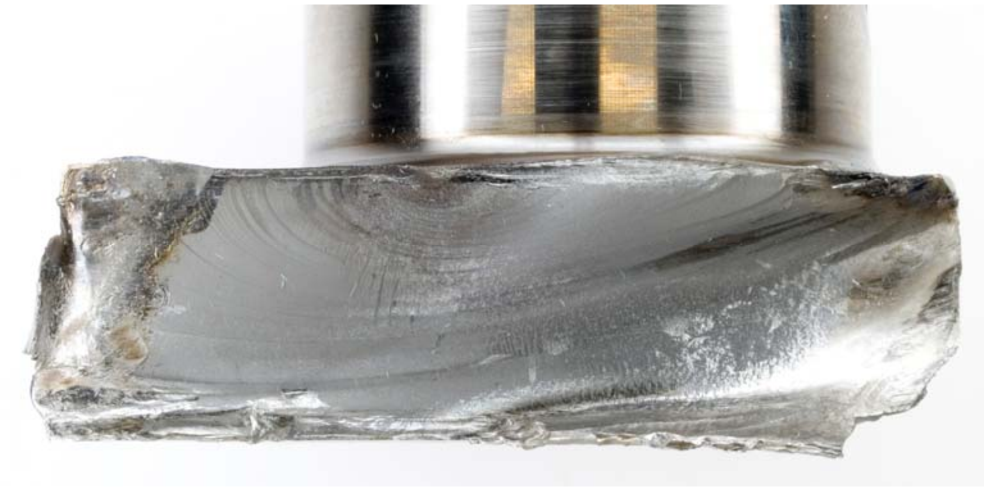


Figure 8.97: The region of rubbing contact damage, the site of fatigue crack initiation is arrowed

Examination of the connecting rod established that the sequence of events leading to the rubbing contact between the big-end housing and crankweb commenced with the fatigue fracture of a counterweight-pin retention plate in one of the counterweight assembly fitted to the crankweb. Connecting rod distortion occurred when the unrestrained counterweight pin was caught between the face of the counterweight and the connecting rod ‘I’ beam, figures 8.98 to 8.100.

Counterweight-pin retention plate fatigue indicates that the engine had been operating in a manner that induced pin shuttle. Resolution of this failure would require an investigation of the factors that contribute to counterweight pin shuttle.

Figure 8.98: Remnants of the fractured counterweight pin retention plate

Figure 8.99: The face of the counterweight showing evidence of localised deformation created as the pin was dragged between the counterweight and connecting rod

Figure 8.100: The extent of connecting rod deformation

The region of damage created by the freed counterweight pin is arrowed.

Planar defects created by journal grinding

The resizing of crankshaft journals to an undersize condition has been conducted, on occasions, by grinding. There is a risk that, during the grinding process, localised heating can lead to cracking in the hardened surface.

Example 9: Teledyne Continental IO-520F, major defect report 91/1262.

The crankshaft journal had been resized by grinding during overhaul, 25 hours prior to the fracture.

Figure 8.101: The fatigue fracture, cracking initiated at the forward fillet of the No.1 connecting-rod journal

While the nature of the initiation site of fatigue fracture had been obliterated by damage created during continued crankshaft rotation, magnetic particle inspection of the shaft revealed the presence of other small cracks in the region of journal fillets. One of these crack indications was opened to allow the examination of crack surface features, figures 8.102 and 8.103.

It is evident, from the crack surface features, that the region of cracking that extended perpendicular to the fillet was formed by the brittle fracture of the hardened zone in response to localised thermal expansion stresses. It is also evident from the crack surface features, that the region of cracking that extended parallel to the fillet, was formed as a result of fatigue crack growth and initiated as a result of the presence of the thermal expansion crack.

Figure 8.102: **Magnetic particle inspection indication (arrowed) of cracking in the rear fillet of the No.1 connecting-rod journal**

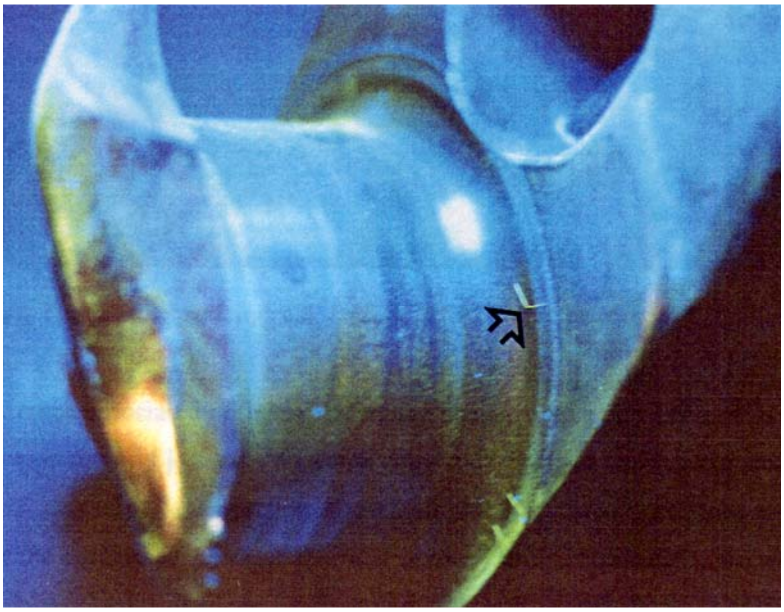
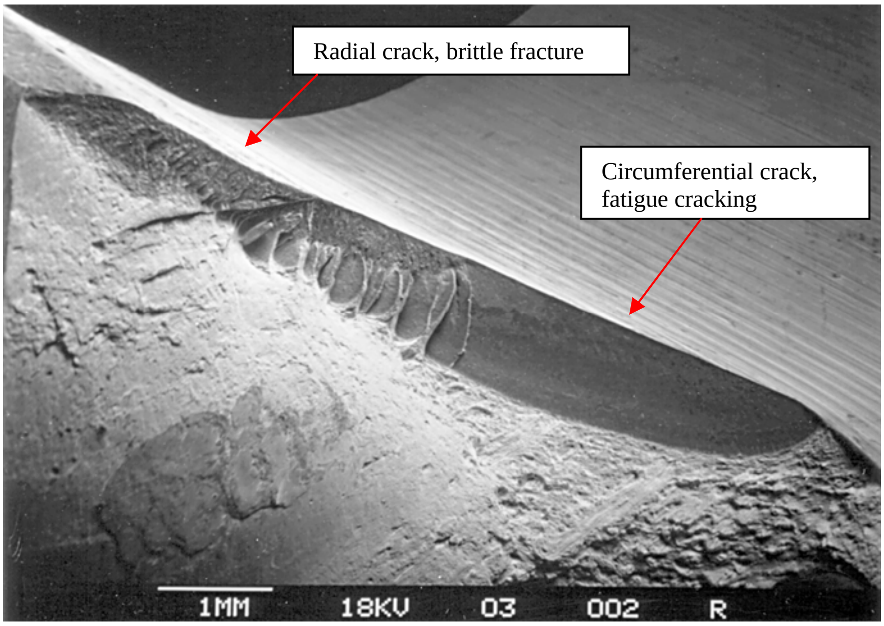


Figure 8.103: **The crack surfaces of the magnetic particle indication arrowed in figure 8.107**



Example 10: Lycoming TIO-540-J2BD, major defect report 93/0787, crankshaft p/n 10346, s/n 73Y19.

The connecting-rod journals had been resized by grinding during overhaul, 14 hours prior to crankshaft fracture.

Figure 8.104: The fatigue fracture in the crankweb between the No.5 and No.6 connecting rod journals

Fatigue cracking initiated at a number of locations in the rear fillet of the No.5 journal.

Figure 8.105: An example of cracking perpendicular to the fillet and plane of fatigue cracking (arrowed)

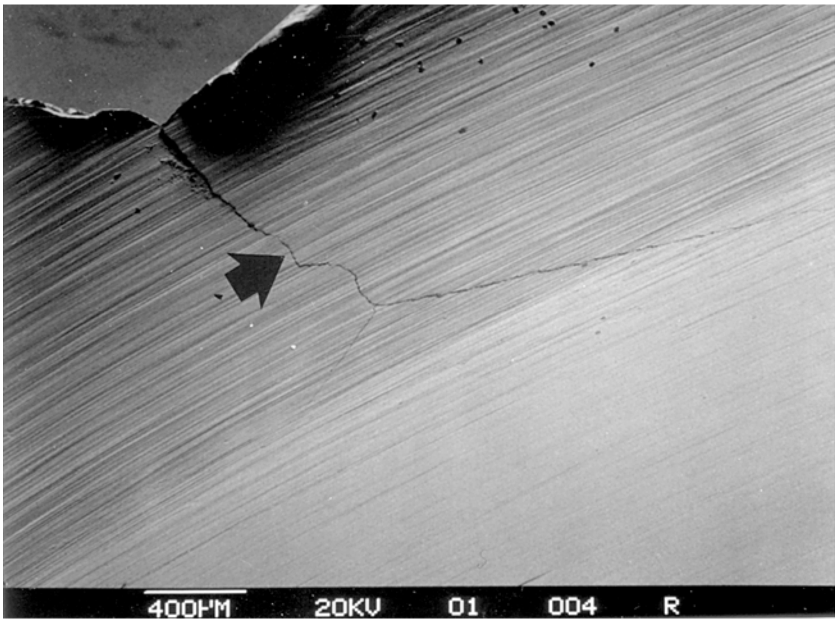
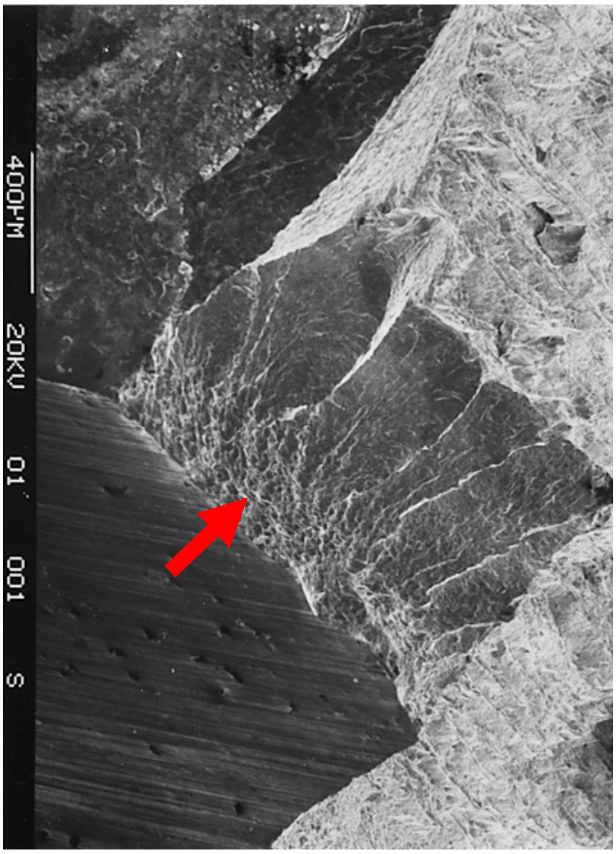


Figure 8.106: Crack surface features, region of cracking arrowed in figure 8.105



Note that the initial region of cracking, from the surface into the nitrided-zone displays the features of brittle fracture. Subsequent crack growth from the region of brittle fracture occurred as a result of fatigue crack growth.

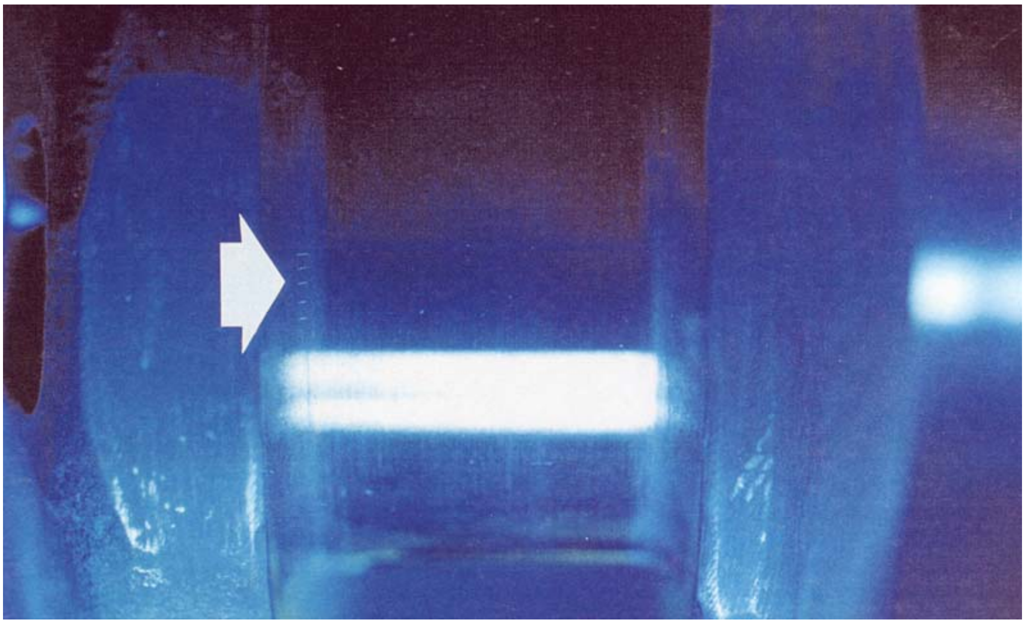
Example 11: Lycoming TIO-540-J2BD, major defect report 93/0498, crankshaft p/n LW10346, s/n 91260.

The connecting-rod journals had been resized by grinding during overhaul 56 hours prior to crankshaft fracture.

Figure 8.107: The fatigue fracture in the crankweb between the No.5 and No.6 connecting rod journals

Fatigue cracking initiated at a number of locations in the rear fillet of the No.5 connecting rod journal.

Figure 8.108: An example of magnetic particle inspection indications in the fillet of another journal (arrowed)



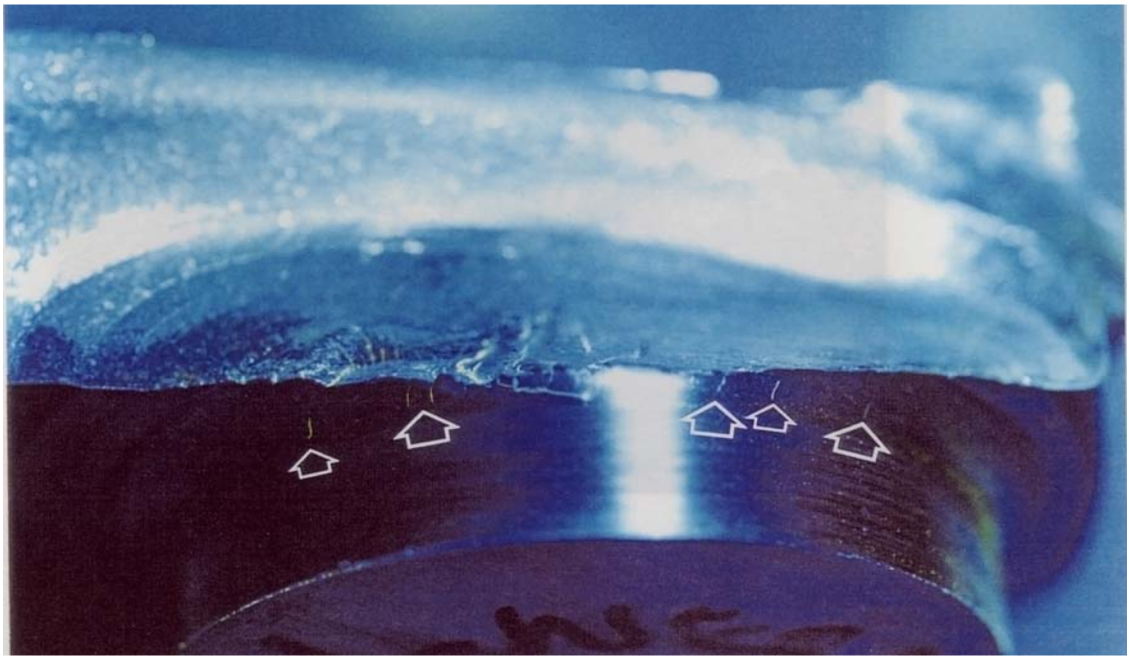
Example 12: Lycoming TIO-540-J2BD, major defect report 93/0158, crankshaft p/n LW 10346, s/n 69184.

The connecting rod journals had been resized by grinding during overhaul, 181 hours prior to crankshaft fracture.

Figure 8.109: The fatigue fracture in the crankweb between the No.5 and No.6 connecting rod journals

Fatigue cracking initiated at a number of locations in the rear fillet of the No.5 connecting rod journal.

Figure 8.110: Magnetic particle inspection indications of thermal expansion cracks (arrowed) associated with fatigue crack initiation



Example 13: Lycoming IO-360-A1B6, major defect report 92/0575, crankshaft, s/n 130583.

The connecting-rod journals had been resized by grinding.

Figure 8.111: The fatigue fracture in No.3 connecting rod journal

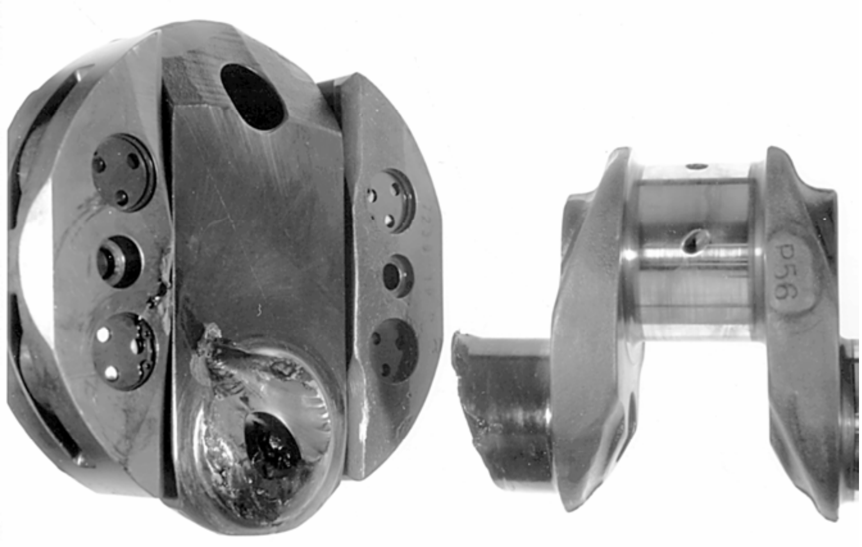
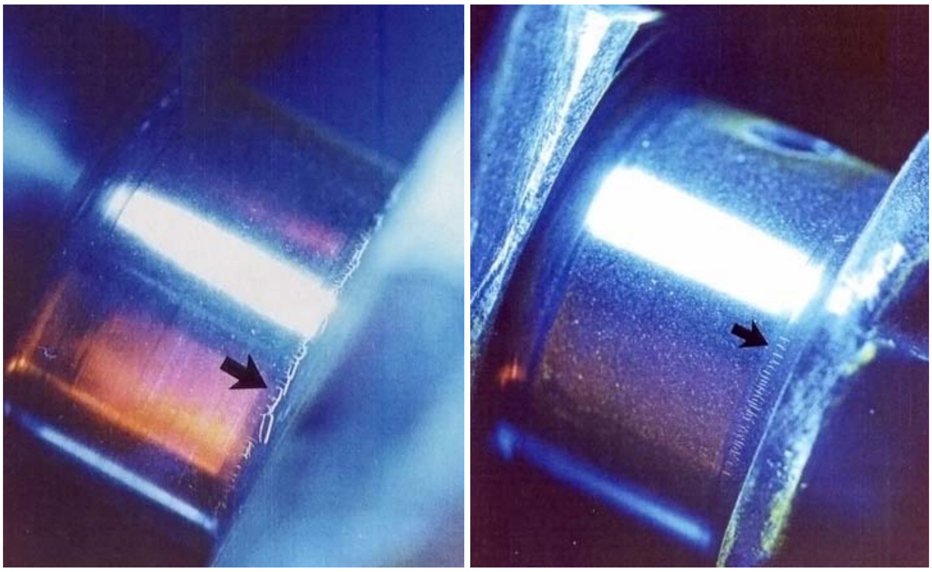


Figure 8.112: Examples of magnetic particle inspection indications of thermal expansion cracks in the fillets of the No.4 connecting rod journal



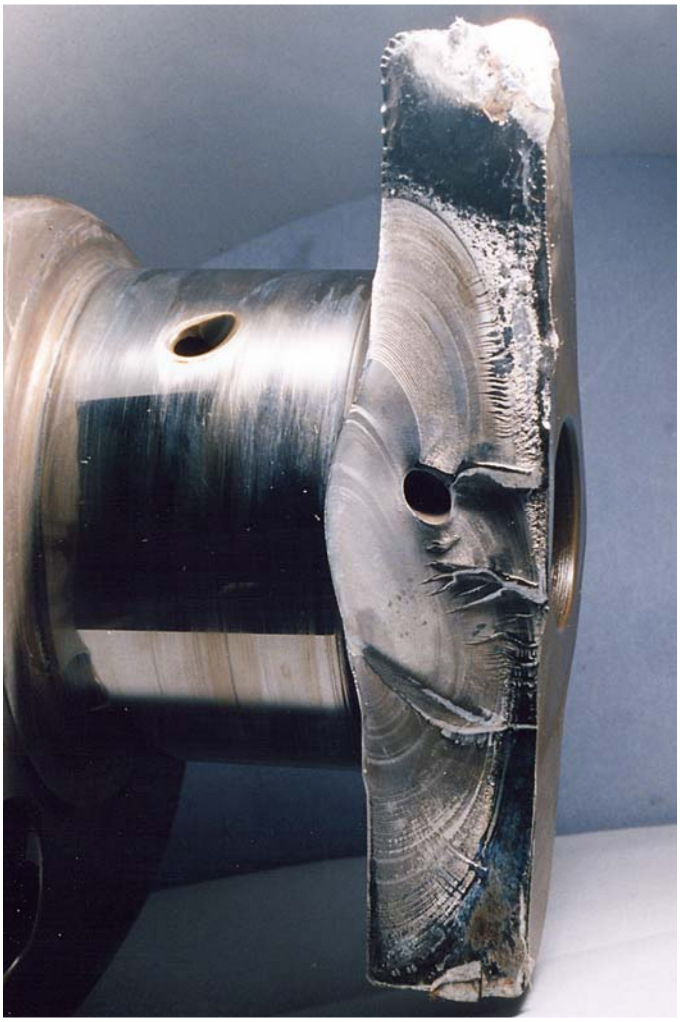
The crack indications (left) show that circumferential cracking has developed from the series of short thermal expansion cracks in the region of the No.4 journal between the crankwebs – the region of highest stress under crankshaft bending. The crack indications on the opposite side of the journal are shown on the right of the figure.

Main-bearing insert contact with journal fillet

In situations where crankshaft-bearing inserts are able to move in their housing, damage through contact between the edges of the bearing inserts and the journal fillet can occur. The nature of the localised rubbing contact has two effects. Firstly, localised heating associated with the rubbing contact can cause thermal expansion cracks to form in the hardened surface of the fillet and, secondly, wear associated with rubbing contact can create notches in the fillet. Thermal expansion cracking and wear notches in crankshaft fillets are features that can cause the initiation of fatigue cracking in surface hardened crankshafts while an engine is operated within its operational limits.

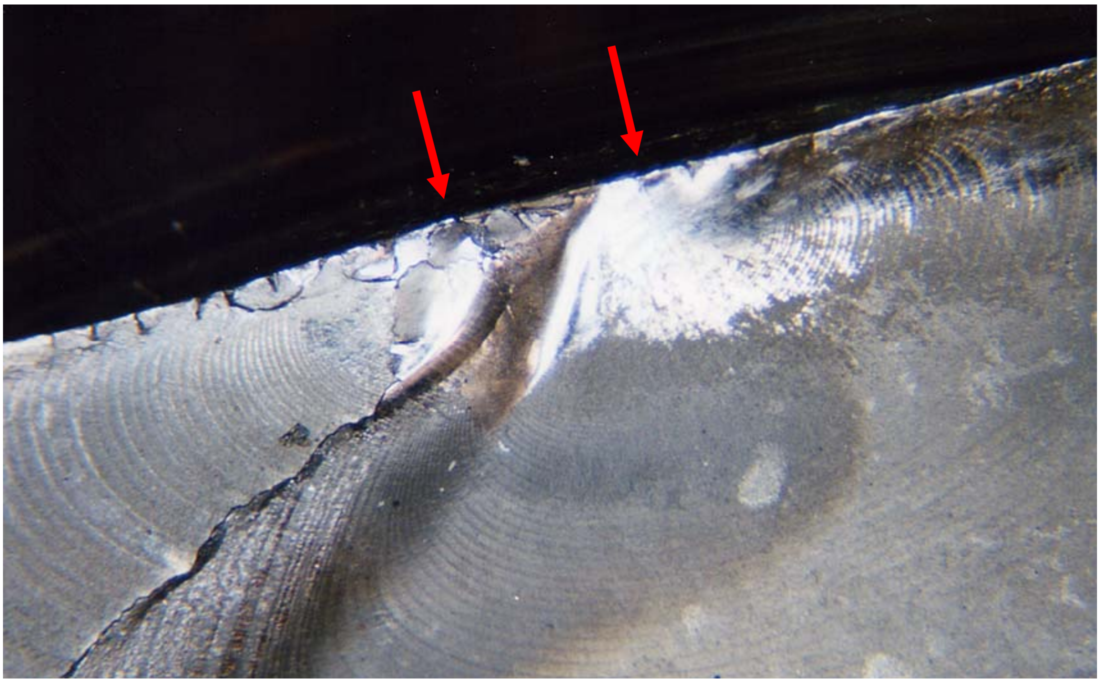
Example 14: Lycoming TIO-540-J2B, occurrence 2001/2544, VH-TTX, crankshaft p/n LW 10346, s/n 87928.

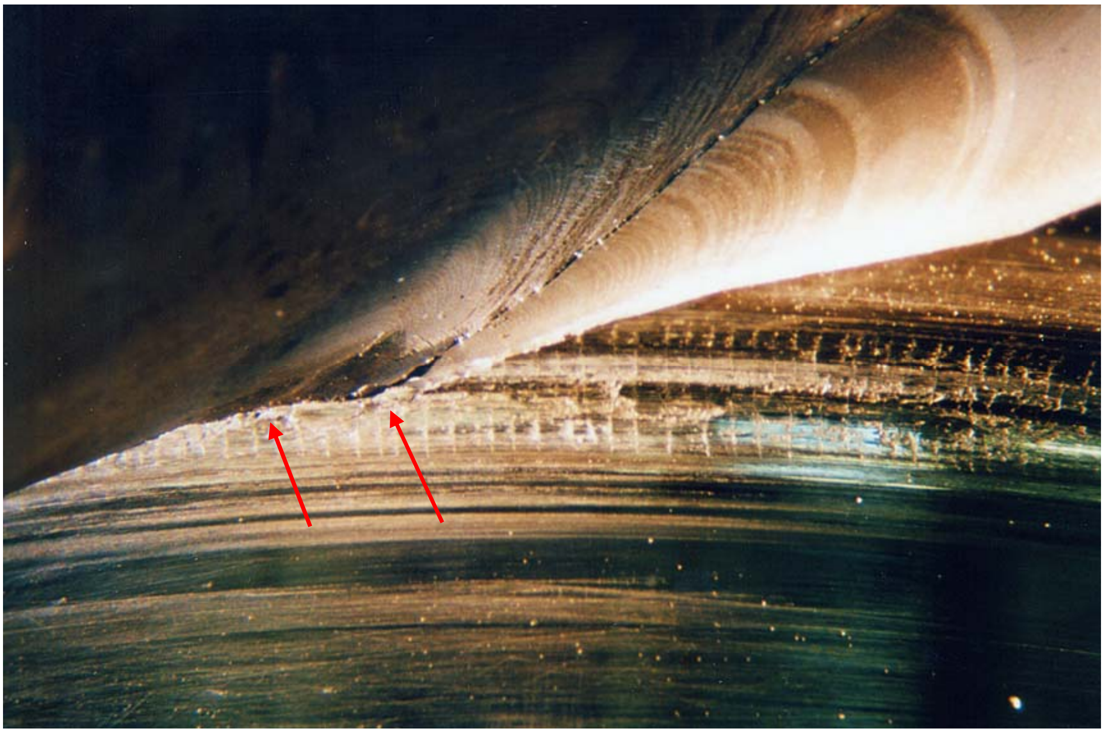
Figure 8.113: Fatigue fracture, crankweb No.4 main/No.4 connecting rod



Fatigue cracking initiated in the forward fillet of the No.4 main bearing journal.

Figure 8.114: Detailed views of the site of fatigue crack initiation



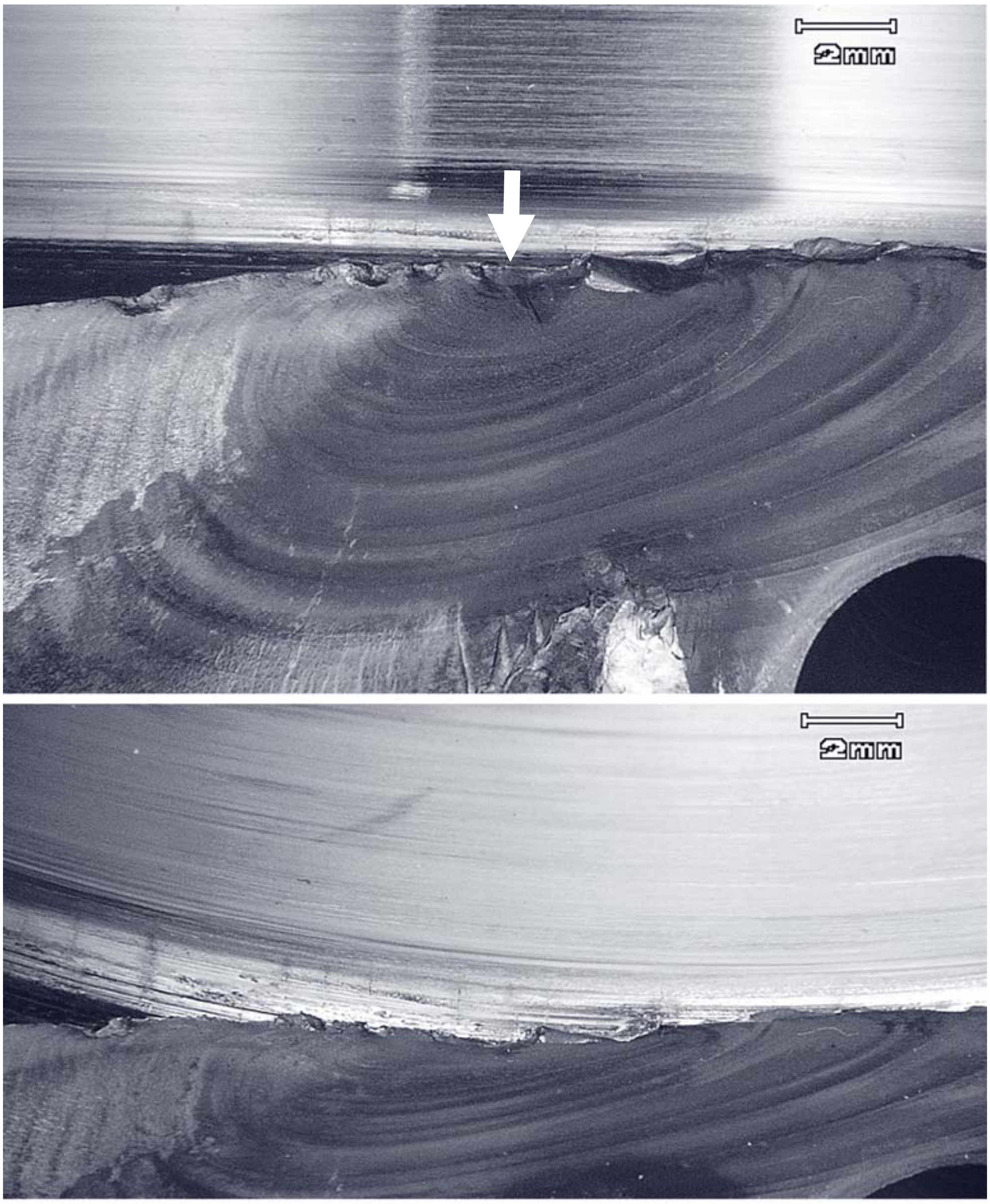


The damage created by the contact between the main-bearing inserts and the main-bearing fillet comprises of a series of thermal expansion cracks (oriented perpendicular to the fillet) and notching/scoring of the fillet.

Example 15: Lycoming TIO-540-V2AD, occurrence 2005/2231 VH-IGW, crankshaft p/n LW 17740, s/n V5311.

The crankshaft fractured through the crankweb between the No.4 main bearing journal and No.4 connecting-rod bearing journal.

Figure 8.115: The site of fatigue crack initiation, No.4 main bearing journal fillet

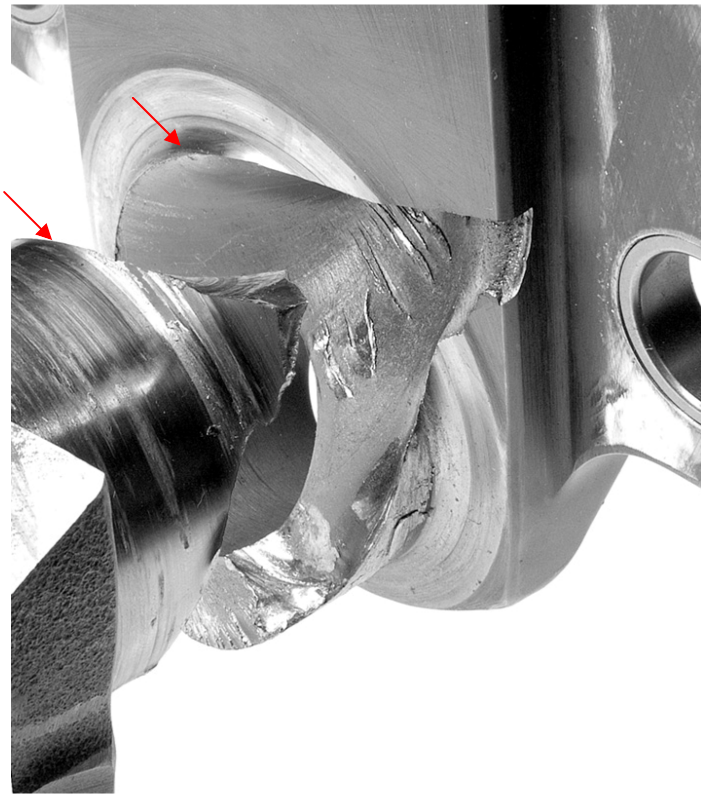


The location of the fatigue crack initiation is indicated with an arrow. Rubbing contact between the edge of the bearing insert and journal fillet created circumferential scoring and a series of short cracks (oriented perpendicular to the fillet).

Fatigue crack initiation, occurrences 2000/2157 VH-MZK (left) and 2001/5866 VH-JCH

Fatigue cracking, leading to the fracture of crankshafts in occurrences 2000/2157 VH-MZK (left engine) and 2001/5866 VH-JCH, initiated at the transition of the journal No.6 connecting-rod bearing surface to the No.5/No.6 crankweb fillet (the forward fillet of the journal). The location of the fatigue crack initiation site, with respect to the crankweb, fillet radius, and circumferential position on the journal, was similar to example 7, page 204, and example 13, page 215, examples where fatigue crack initiation was influenced by a stress concentrating feature created during maintenance. The location of crack initiation, with respect to the fillet radius, differed from other examples of crankshaft fatigue fracture where there had been no modification of the fillet radius or stress-concentrating features had been created at different radial locations in the fillet.

Figure 8.116: The general form of fatigue cracking in the No.6 connecting journals of occurrences 2000/2157 and 2001/5866, and example 7.



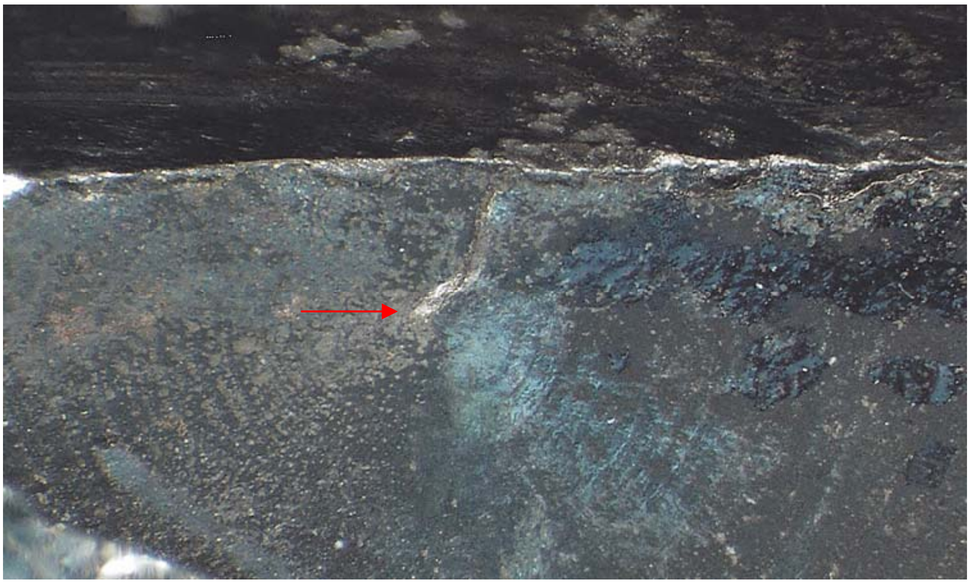
The location of the site of fatigue crack initiation is arrowed

The location of the site of fatigue crack initiation at the transition of the journal to crankweb fillet radius influenced the plane of fatigue crack growth. Crack growth has occurred in response to stress state created by the combination of crankweb bending and journal torsion.

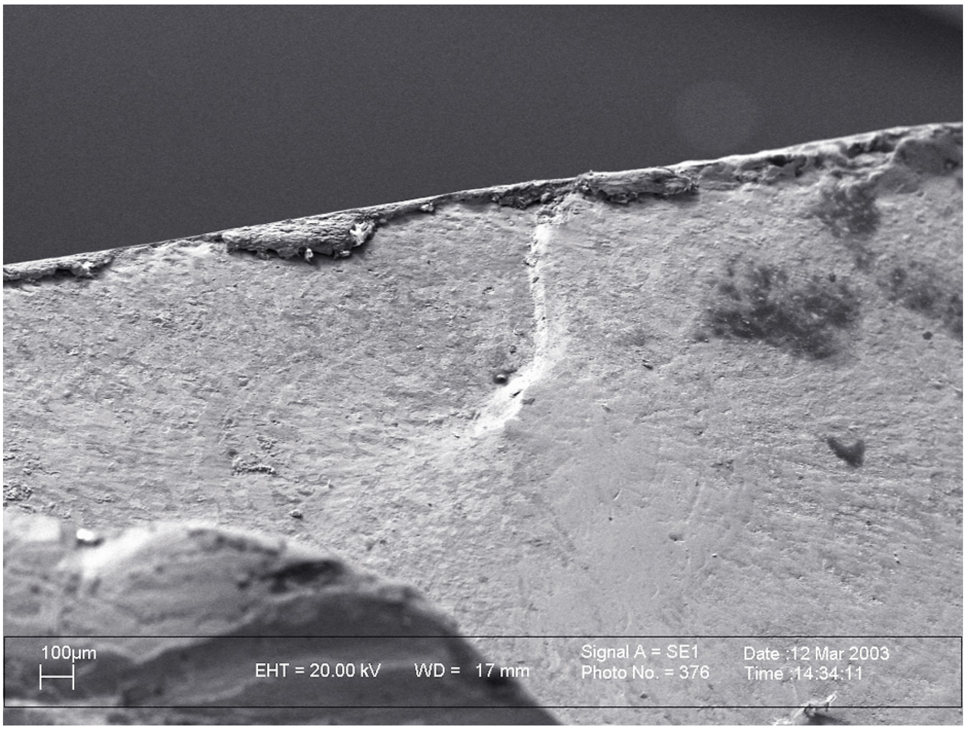
While it is clear that modification of the fillet during journal resizing created a stress concentration sufficient to initiate fatigue cracking in the crankshaft from example 7, the stress-concentrating feature associated with fatigue initiation in occurrences 2000/2157 and 2001/5866 is not so clear.

The site of fatigue crack initiation, occurrence 2000/2157, had been damaged during the period of continued operation of the engine after the fracture of the No.6 connecting-rod journal. However, it is evident that fatigue cracking initiated below the surface of the journal and that a planar feature, extending from the journal surface to the point of crack initiation, oriented perpendicular to the fillet, was present, figure 8.117.

Figure 8.117: Detailed views of the site of fatigue crack initiation, occurrence 2000/2157



Light micrograph, the site of fatigue crack initiation is arrowed.



Scanning electron micrograph.

Serial metallographic sectioning was conducted to examine the nature of the planar feature that extended to the site of fatigue initiation, see figures 8.118-8.123. It is evident, from these sections, that the original feature associated with fatigue initiation had been deformed following the fracture of the journal. It is also evident that the original planar feature was crack-like, oriented perpendicular to the fillet, and extended, approximately, 0.34 mm from the damaged journal surface into the nitrided zone.

Figure 8.118: **Serial metallographic sections, plane of sectioning parallel with the journal surface**

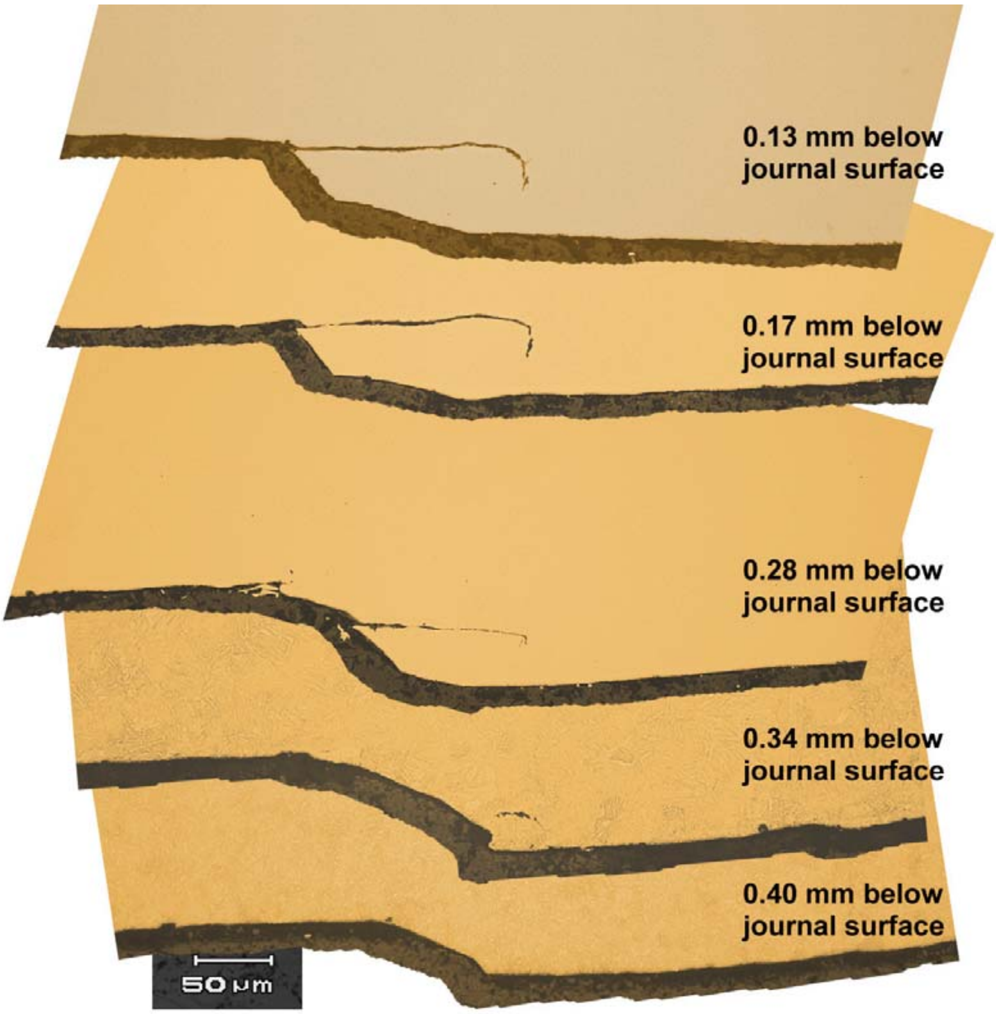


Figure 8.119: The microstructural features present in the section 0.13 mm below the journal surface

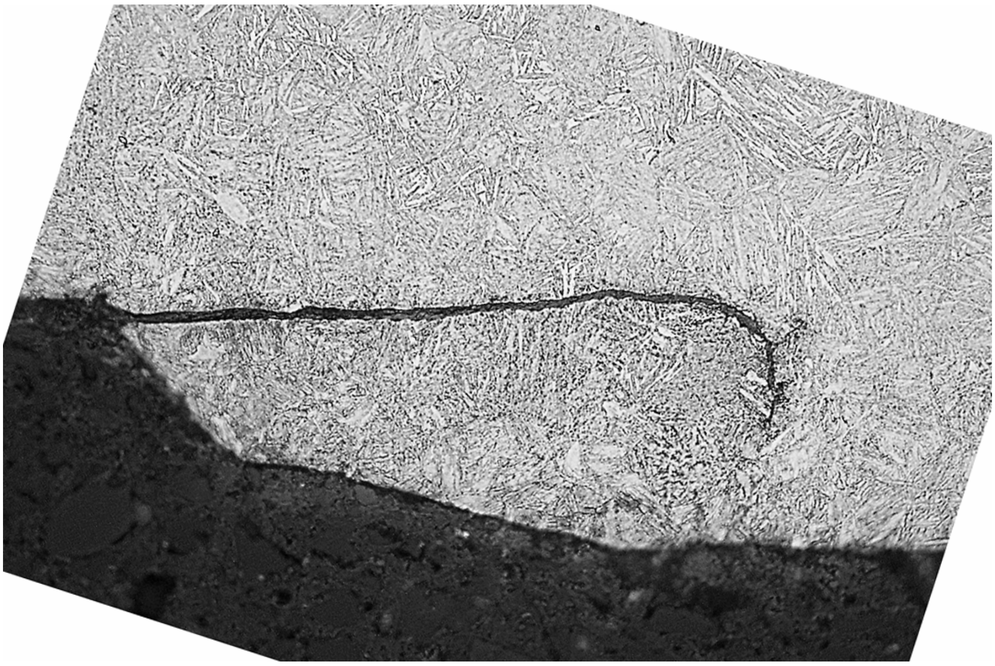


Figure 8.120: The microstructural features present in the section 0.28 mm below the journal surface

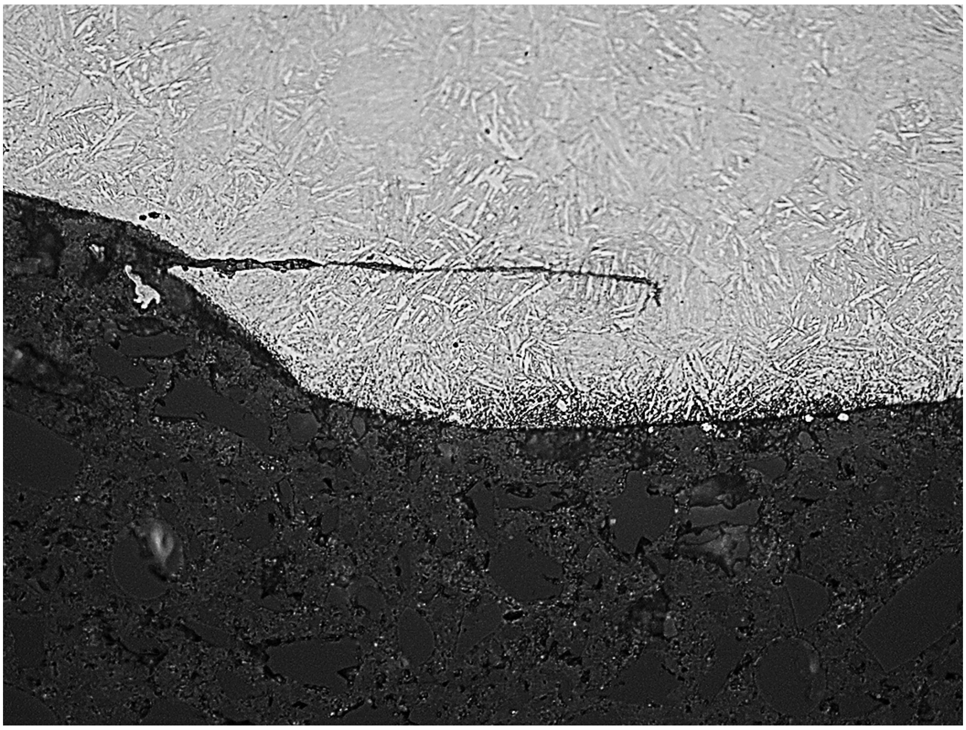


Figure 8.121: **Detailed view, section 0.17 mm below the surface, scanning electron micrograph**

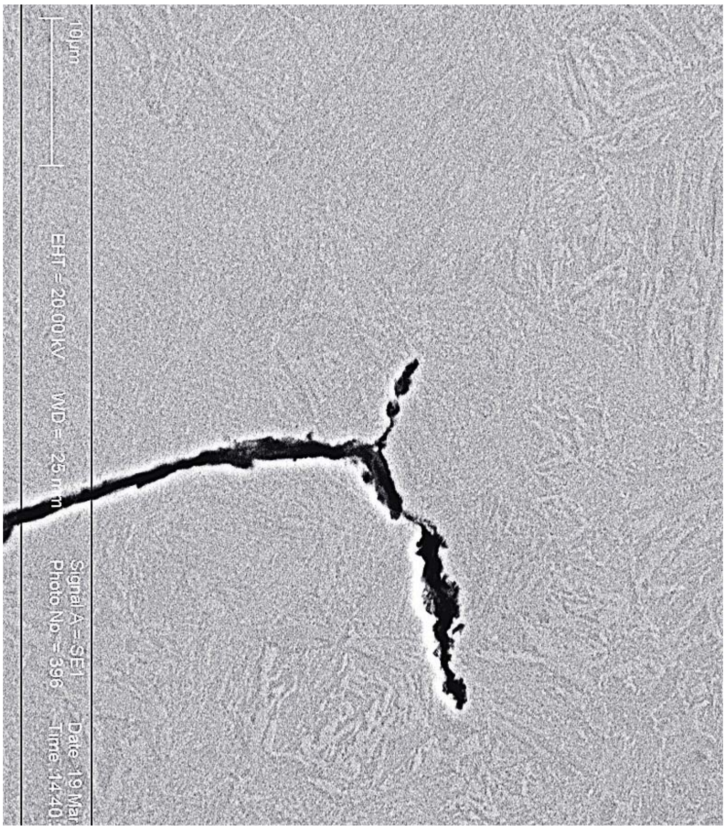


Figure 8.122: **Detailed view, section 0.28 mm below the surface, scanning electron micrograph**

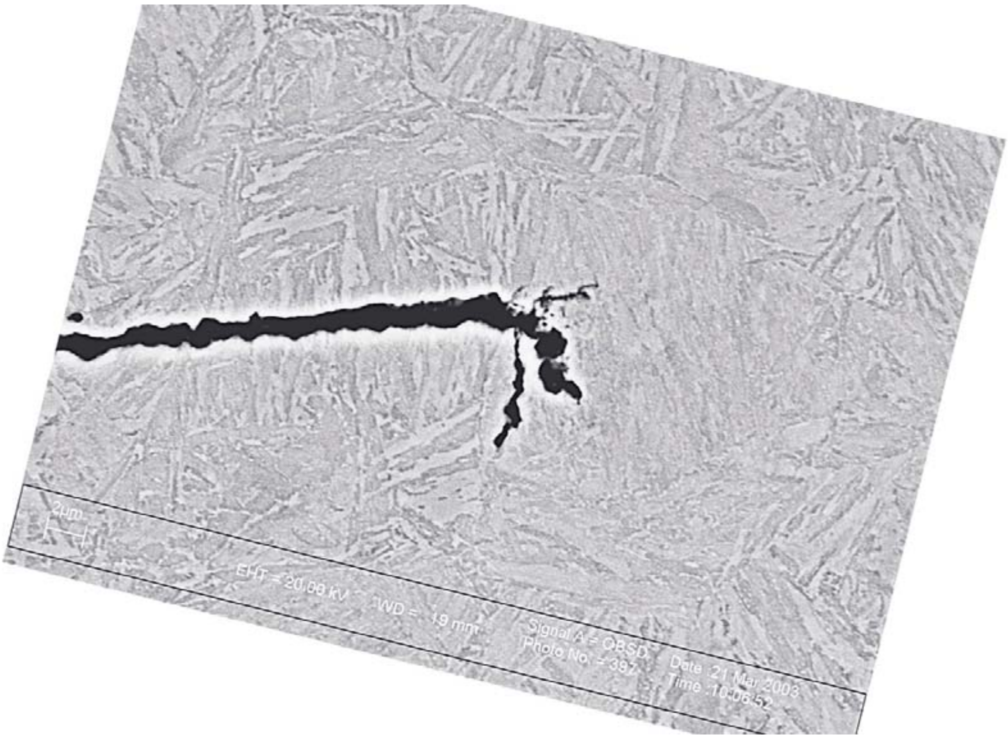
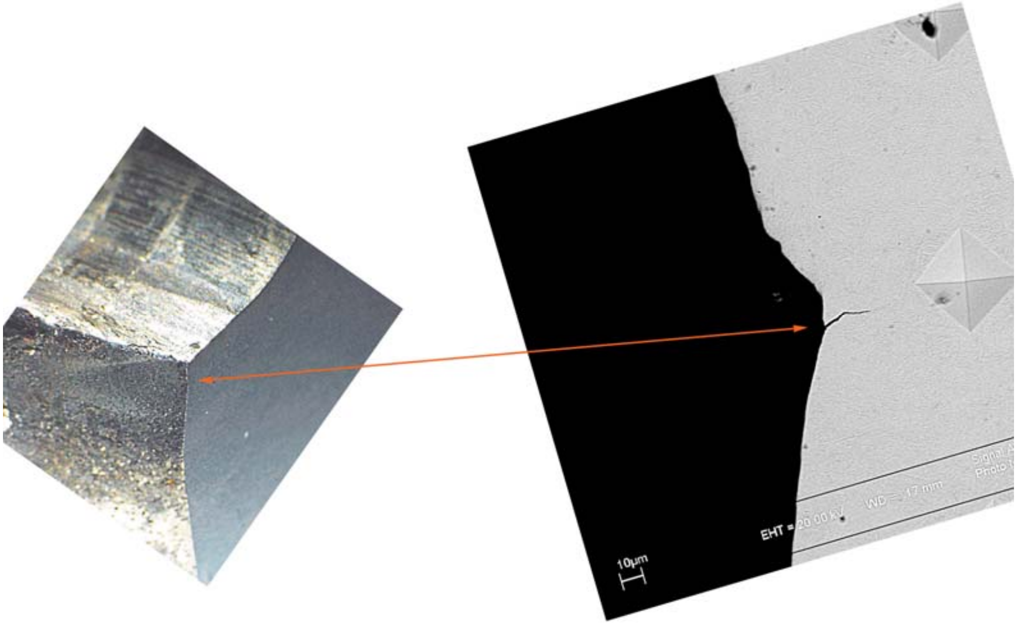


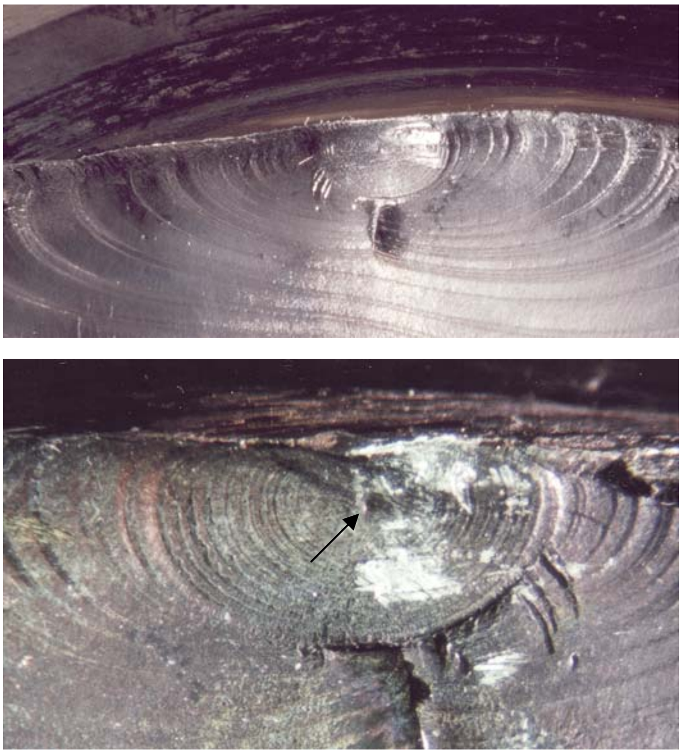
Figure 8.123: Metallographic section taken through the planar feature on the crankweb side of the fracture, perpendicular to the journal surface



The section shows a crack-like defect (oriented perpendicular to the fillet) at the site of fatigue initiation.

The site of fatigue crack initiation, occurrence 2001/5866, had also been damaged during the period of continued operation of the engine after the fracture of the No.6 connecting-rod journal. However, while the region had been damaged, it is evident that fatigue cracking initiated below the surface of the journal and that a planar feature, extending from the journal surface to the point of crack initiation, was present, figure 8.124.

Figure 8.124: Fatigue crack initiation site, occurrence 2001/5866



The crankweb side of the fracture is shown at the top of the figure, the journal side of the fracture is shown at the bottom of the figure. The site of fatigue crack initiation is arrowed.

The fatigue fracture of the crankshaft, No.6 connecting-rod journal, in the left engine, occurrence 2000/2157, and the crankshaft, No.6 connecting rod journal, in the right engine, occurrence 2001/5866, were not the only the only components in the engines affected by a progressive failure mechanism. In both cases, progressive failure mechanisms affected the No.6 connecting rod big-end assemblies.

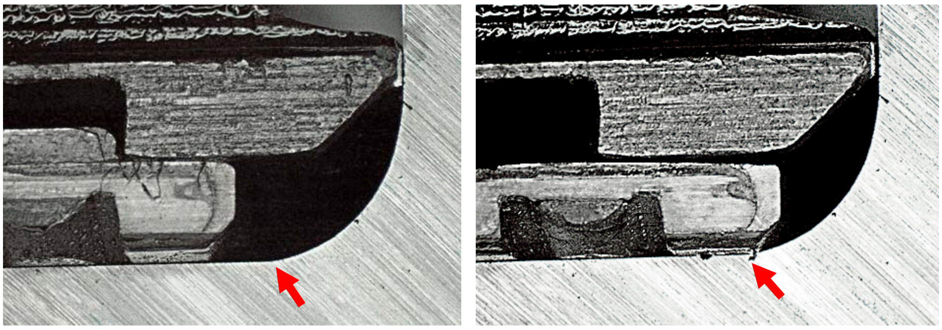
The connecting rod, big end, bearing inserts had been reduced to fragments of steel backing that had been extruded through the gap between the housing and journal. Fatigue cracking in the big-end housings initiated as a result of increased housing flexure (2000/2157) or housing surface damage (2001/5866), following bearing insert breakup. Nuts on the big-end housing bolts had loosened, as a result of the frictional heating of the bolts, when the central guide sections of the bolts contacted the crankshaft journal following bearing insert breakup. Separation of the housings from the crankshaft journals occurred prior to final engine failure – the evidence of connecting rod collision with the camshaft, fracture of the pneumatic pump drive, and pilot report of pneumatic ‘inop’ warning light illumination – as a result of fatigue fracture (2000/2157) and loss of the nut from one big-end housing bolt (2001/5866).

In addition, examination of big-end bearing inserts from other, intact, big-end assemblies from both engines, revealed; that a lubricant had been placed between the bearing inserts and their housings, evidence of relative movement between the inserts and their housings, and bearing surface wear associated with high combustion loads.

Resolution of the issues contributing to the No.6 connecting rod journal fatigue fracture of the crankshafts in occurrence 2000/2157 and 2001/5866 requires the consideration of the effects of failure processes in the No.6 connecting rod big- end bearing and the possible creation of stress concentrating features at the transition between the journal and fillet.

If a Lycoming (L)TIO-540 engine big-end bearing insert did move, axially, as a result of connecting rod out-of-plane rocking and reduced insert retention force, the particular geometry of the big-end housing and fillet would result in bearing contact damage at the transition between the journal surface and the fillet, figure 8.125.

Figure 8.125: Schematic showing the point of contact between a bearing insert that has moved in its housing and the crankshaft journal fillet



The location of fatigue crack initiation for occurrences 2000/2157 and 2001/5866, with respect to the fillet, is arrowed.

8.5.6 Summary

The factors that were found to initiate fatigue cracking and fracture of cylinder heads, cylinder attachment fasteners, connecting-rod bearing housings, and crankshaft journals may be divided into two groups: those factors that increase the magnitude of alternating stress in a component, and those factors that decrease the endurance strength of a component.

In this study, sources of increased component alternating stress were found to have been associated with the gas pressures produced by combustion, increased component flexure, and reductions in component preload. Sources of decreased fatigue endurance strength were found to have been associated with surface damage created by adhesive wear (galling), surface scoring created by rubbing contact with a closely associated component, and cracking in nitrided surfaces created by localised frictional heating.

The initiation and propagation of fatigue cracks in a powertrain component is not, simply, a matter restricted to the material from which the component is manufactured. It is a matter of all factors that affect the magnitude of component alternating stresses, and the component endurance strength.

In addition to the complex interrelationships between loads, preloads, geometric stress concentrators, residual stress, surface finish, surface hardening, and material of an individual component, there are clear interdependencies between the combustion process in individual and multiple cylinders of a horizontally-opposed engine, the physics of plain bearing lubrication, the mechanics of bearing insert retention, and the process of fatigue crack initiation.

8.6 Multiple event sequences

It is apparent that some engine failure occurrences, analysed during the course of this study, involved the failure of more than one subsystem or component. In some occurrences, the sequences of events leading to subsystem or component failure are independent, although they may have common initiating factors, figure 8.126. In other occurrences, the event sequences have clear dependencies, figure 8.127. When considering potential dependencies, it is important to realise that reciprocating engines are engineered systems and, as such, human actions, interactions and reactions can affect event sequence dependencies in addition to the dependencies associated with pure mechanical interactions.

Figure 8.126: Occurrence 2000/3675, VH-NPA

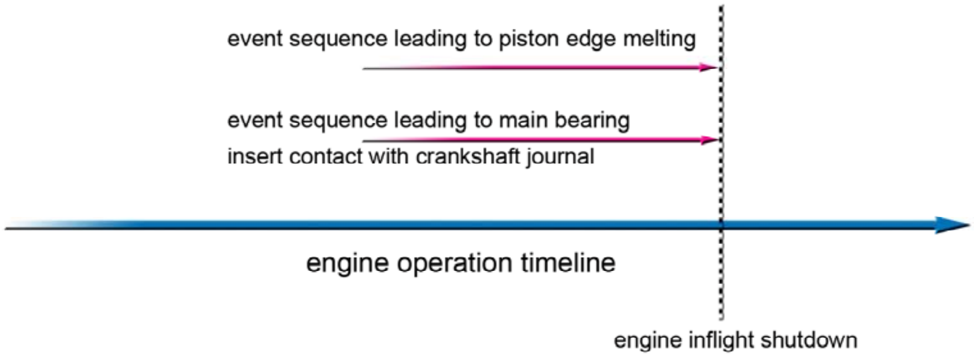
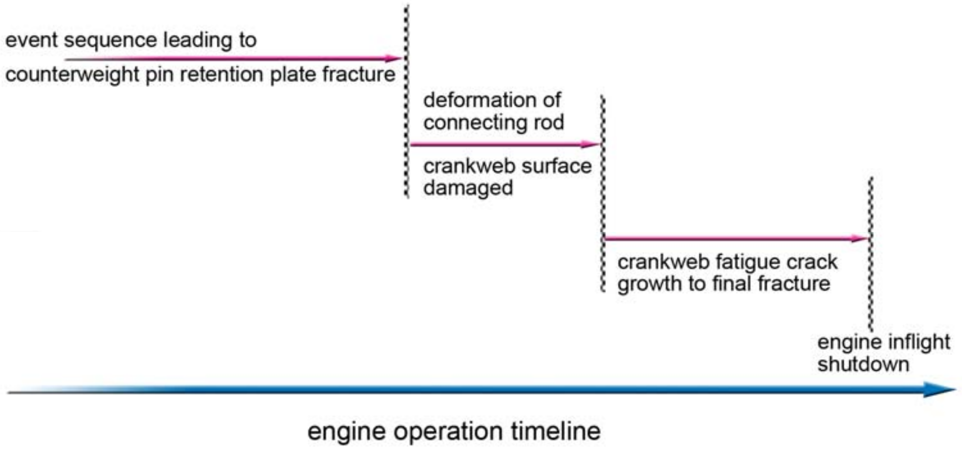


Figure 8.127: Major defect report 94/1135, example 8



Refer to figures 8.96 to 8.100.

Figure 8.128: Occurrence 2001/5866, VH-JCH

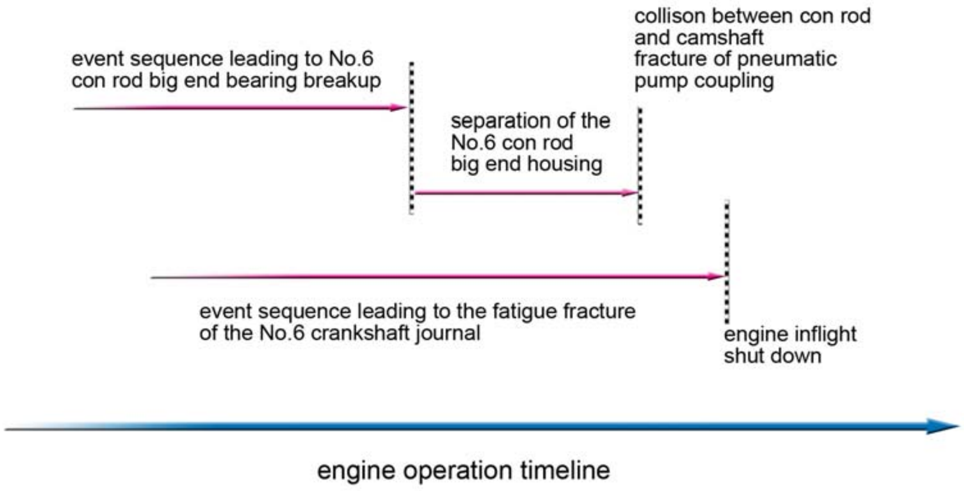
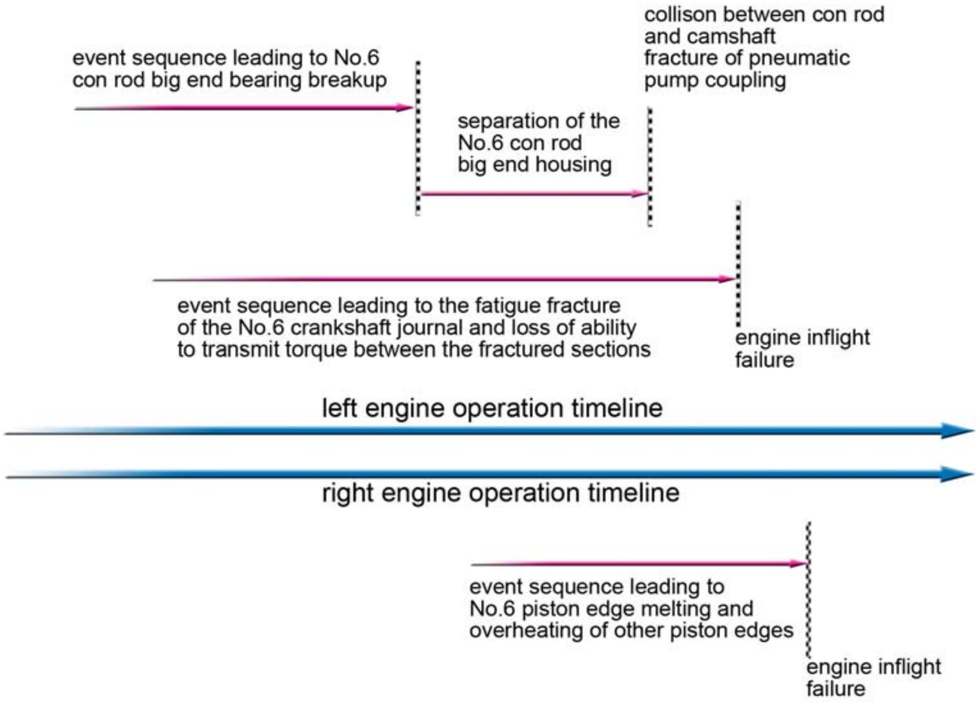


Figure 8.129: Occurrence 2000/2157, VH-MZK



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9 ANALYSIS OF AIRWORTHINESS ASSURANCE SYSTEM - AIRCRAFT PROPULSION

9.1 Introduction

Airworthiness is the term used to describe the continuing capability of an aircraft to operate safely within its designed limits. It is based on the expectation that flight operations will be performed with acceptable reliability in respect of flight crew workload, flight handling characteristics, flight performance/envelope availability, safety margins, welfare of occupants, punctuality, and economics (Leaflet 13-4, CAAP 418). Airworthiness is an essential ingredient of safe air transport.

The issues associated with airworthiness management have evolved in parallel to the issues associated with the broader field of quality management. Airworthiness management has evolved from control, through checking for conformance with specified processes and procedures, to assurance that the systems created to prevent threats to safe aircraft operation continue to function. In keeping with the principles upon which quality management standards are based, the airworthiness assurance system should provide confidence that safety-critical aircraft systems are:

- well understood and effective; and
- action is taken to correct problems within a system, prior to system failure, rather than reacting to system failure.

The focus of this chapter is the performance of the safety assurance system that is concerned with the safe operation of propulsion systems.

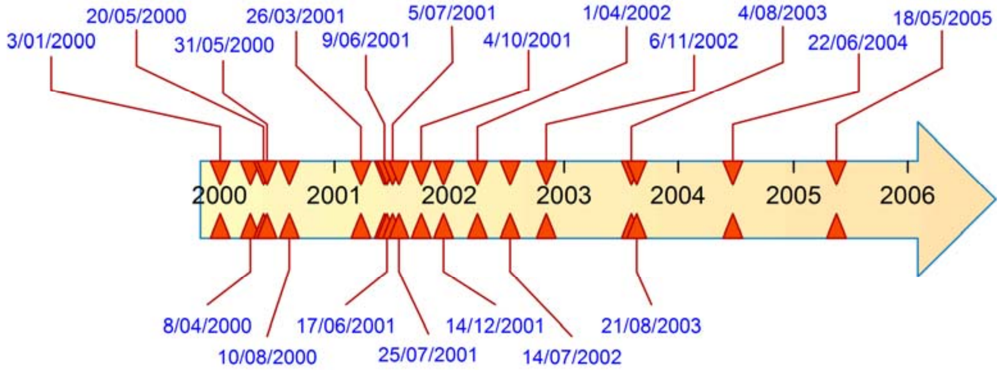
9.2 Condition monitoring of propulsion systems

In the context of airworthiness assurance, condition monitoring is the term commonly applied to the process of assessment of the effectiveness of systems, sub-systems and elements. Condition monitoring plays an important role in the airworthiness assurance system for aircraft propulsion. Engine in-flight shutdowns, engine unscheduled removals, and engine component failures, reported in safety investigations or service difficulty reporting schemes, may provide the basis for changes to be made to propulsion system design, manufacturing processes, operational limitations, or maintenance actions.

The principle behind data collection is that the data has to be to be of sufficient quality and quantity to ensure that any adverse defect rate, trend, or reduction in failure resistance, is identified quickly to control failure rates or prevent recurrence. The analysis of failure events should, initially, consider each event individually to determine if any immediate corrective action is appropriate. Further analysis of a series of events may result in other corrective actions. The effectiveness of corrective actions is measured by the data trends gained through the continued process of condition monitoring.

The frequency of aircraft reciprocating-engine structural failure during the period 2000 to 2005 (in particular between 2000 and 2003), figure 9.1, suggests that there was a breakdown in the systems created to ensure engine reliability, in particular, the systems created to ensure that structural failure of engine components does not occur during flight.

Figure 9.1: **Powertrain structural failure frequency distribution, 2000 - 2005**



9.3 Corrective actions

A number of safety actions, addressing reciprocating engine component structural failure, have been implemented by the ATSB, CASA, FAA, and Lycoming during the period 2000 - 2005.

9.3.1 ATSB safety recommendations

As a result of the investigation of the fatal accident involving VH-MZK on the 31 May 2000, occurrence 2000/2157, the ATSB issued a number of recommendations to FAA, CASA and Lycoming.

Fuel-air mixture leaning practices (issued 30 October 2000)

Safety recommendation R20000250

The Australian Transport Safety Bureau recommends that the Civil Aviation Safety Authority alert operators of aircraft equipped with turbo-charged engines to the potential risks of engine damage associated with detonation, and encourage the adoption of conservative fuel mixture leaning practices.

CASA response

The following response was received from the Civil Aviation Safety Authority on 22 March 2001:

> CASA also accepts Recommendations [sic] R20000250 and has published an article in the January/February aviation safety magazine Flight Safety Australia. Furthermore, CASA is considering further action on this matter and is consulting the aeroplane and engine manufacturers with a view to them improving their engine leaning procedure.

Response status: CLOSED - ACCEPTED

Engine reliability (issued December 2001)

High power variants of horizontally opposed, six-cylinder, air-cooled reciprocating engines power many aircraft employed in low capacity public transport operations in Australia. At the time of publication of this report, there were 107 Piper Chieftains on the Australian aircraft register and a much greater number in operation worldwide. Many other single and multi-engine aircraft are equipped with high-powered reciprocating engines. The engine failure analysis presented in this report highlighted a number of issues that affect the reliability of these engines. Accordingly, the following recommendations are issued:

Safety recommendation R20010254, Combustion deposits

The Australian Transport Safety Bureau recommends that the Federal Aviation Administration (Piston Engine Certification Directorate) review the certification requirements of piston engines with respect to the operating conditions under which combustion chamber deposits that may cause preignition are formed.

FAA response

The following response was received from the FAA on 20 August 2002:

> Preignition, like detonation, is a form of uncontrolled combustion that occurs in piston engine cylinders. The symptoms and consequences of both these events are very similar, differing only in the sequence of occurrence. Preignition occurs before scheduled ignition, and detonation occurs after ignition.
>
> Current FAA certification requirements and guidance provide for margin against detonation. The current FAA certification regulation that addresses piston engine detonation is (Regulations)33.47. FAA guidance describing acceptable methods of compliance with this regulation is contained in Advisory Circular (AC) 33.47-1.
>
> To meet these acceptable methods, the applicant must test the engine at worst-case conditions for detonation, which are also the most critical conditions for preignition. Instrumentation used to monitor for detonation, such as pressure sensors or pieziolectric vibration sensors, will identify all types of uncontrolled combustion, including both detonation and preignition.
>
> To pass the test, the applicant must substantiate that a 12% margin exists between the leanest fuel mixture and the onset of uncontrolled combustion. This margin is intended to accommodate the deteriorating resistance of the engine to detonation and preignition as it ages and accumulates combustion chamber deposits during the overhaul interval.
>
> The FAA is currently conducting an extensive evaluation of the detonation characteristics of high performance reciprocating engines at the FAA Technical Centre. The relationship between deposit formation and octane rating increase of the engine will be investigated. Data from this evaluation will be used to assess the adequacy of the current regulation and advisory material.
>
> Service experience with certificated reciprocating engines will also be monitored for detonation incidents and appropriate corrective action will be taken if a service problem is revealed.

ATSB response

> The ATSB appreciates the consideration that the FAA has given the recommendations and investigation report. A great deal of work and thought went into the engine failure analysis, but it was beyond the resources of the ATSB to delve too much further into the issues that we have raised. In this regard, we were pleased to learn that the FAA considered that further evaluation of the issues we had identified was justified. We are in the process of preparing a case study that will include detailed information on 10 other failures of high-powered reciprocating engines that we have investigated. We will forward a copy of that document to you upon its release, as it may assist your ongoing testing and other activities in this area.
>
> The ATSB is greatly interested in the outcome of the work you will be undertaking with respect to the two recommendations. We would appreciate any advice you are able to provide, such as progress reports or other information as it becomes available.

Subsequent ATSB response on 9 October 2003

> I refer to two safety recommendations that the ATSB issued to the FAA in December 2001 that arose from the ATSB's investigation into the Whyalla Airlines PA3l-350 accident that occurred on 31 May 2000.
>
> In your letter of 5 August 2002, you advised that an FAA Safety Recommendations Review Board had classified responses to recommendations 02.141 and 02.142 as "Closed -Acceptable Action". The memorandum attached to your letter outlined the action that the Aircraft Certification Service, Engine and Propeller Directorate intended to take concerning the recommendations. As it is now over 12 months since receiving your correspondence, I wanted to check with you regarding the progress the FAA has made in examining those issues.
>
> Further, our investigation into the engine malfunctions in the accident aircraft, as well as engines that had malfunctioned in other aircraft, revealed clear evidence of corrosion damage to the aluminium alloy layer in the bearings where the alloy was exposed at the bearing insert ends. The ATSB's report on the accident stated that the formation of lead oxy bromides instead of lead bromide would affect the quantity of free bromine remaining after the scavenge process. Excess bromine can find its way into the lubricating oil and form hydrobromic acid. The ATSB would also be interested in any observations or data the FAA might have gained regarding excess bromine from the evaluation of piston engine performance characteristics it was conducting.

Response status: CLOSED –PARTIALLY ACCEPTED

Safety recommendation R20010255, Use of anti-galling compounds

The Australian Transport Safety Bureau recommends that the Federal Aviation Administration FAA (Piston Engine Certification Directorate) review the practice during assembly of applying anti-galling compounds to the backs of connecting rod bearing inserts with respect to its affect on the safety margin for engine operation of the bearing insert retention forces achieved.

Subsequent ATSB response on 9 October 2003

> I refer to two safety recommendations that the ATSB issued to the FAA in December 2001 that arose from the ATSB's investigation into the Whyalla Airlines PA3l-350 accident that occurred on 31 May 2000.

> In your letter of 5 August 2002, you advised that an FAA Safety Recommendations Review Board had classified responses to recommendations 02.141 and 02.142 as "Closed -Acceptable Action". The memorandum attached to your letter outlined the action that the Aircraft Certification Service, Engine and Propeller Directorate intended to take concerning the recommendations. As it is now over 12 months since receiving your correspondence, I wanted to check with you regarding the progress the FAA has made in examining those issues.
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> Further, our investigation into the engine malfunctions in the accident aircraft, as well as engines that had malfunctioned in other aircraft, revealed clear evidence of corrosion damage to the aluminium alloy layer in the bearings where the alloy was exposed at the bearing insert ends. The ATSB's report on the accident stated that the formation of lead oxy bromides instead of lead bromide would affect the quantity of free bromine remaining after the scavenge process. Excess bromine can find its way into the lubricating oil and form hydrobromic acid. The ATSB would also be interested in any observations or data the FAA might have gained regarding excess bromine from the evaluation of piston engine performance characteristics it was conducting.

Nil response

Response status: CLOSED-NO RESPONSE

Safety recommendation R20010256

The Australian Transport Safety Bureau recommends that Textron Lycoming review the practice during assembly of applying anti-galling compounds to the backs of connecting rod bearing inserts with respect to its affect on the safety margin for engine operation of the bearing insert retention forces achieved during assembly.

Textron Lycoming response

The following response was received from Textron Lycoming on 12 February 2002:

> Textron Lycoming did not specifically respond to recommendation R20010256, but on 12 February 2002, in comment with respect to the content of the ATSB's final report stated; "Lycoming does not concur with the specific findings in ATSB report 200002157 that attribute the failure of the left engine to the presence of anti-seize compound between the bearing and the connecting rod journal."

Repose status: CLOSED-NOT ACCEPTED

Safety recommendation R20010257, Reliability of aircraft propulsion systems within Australia

The Australian Transport Safety Bureau recommends that the Civil Aviation Safety Authority review the operating and maintenance procedures for high-powered piston engines fitted to Australian registered aircraft, to ensure adequate management and control of combustion chamber deposits, preignition and detonation.

CASA response

The following response was received from Civil Aviation Safety Authority on 06 March 2002:

CASA acknowledges the intention of the safety recommendation and advises that the Authority has taken significant steps to address this issue with the Federal Aviation Administration in relation to the, certification of the Piper aircraft and engine.

In discussions with the Federal Aviation Administration (FAA) New York Aircraft Certification Office and the FAA Atlanta Aircraft Certification Office, CASA advised that one of the primary issues identified in the Whyalla accident was aggressive fuel leaning.

CASA advised the New York and Atlanta FAA Offices of the discrepancies identified between the Engine Operating Manual approved by the New York Office and the Aircraft Flight Manual approved by the Atlanta Office.

Following these discussions, the Atlanta Office has responded with advice that the FAA is of the opinion that fuel mixture leaning procedures were not a contributing factor in the events of May 2000.

This response is not consistent with the findings of the ATSB in regards to the resulting combustion chamber deposits, preignition and detonation.

CASA's actions in regards to this recommendation are ongoing, and discussions are being held with the engine manufacturer. CASA undertakes to advise the ATSB of the outcomes of these discussions as they progress.

In relation to the maintenance procedures for all high-powered piston engines fitted to Australian registered aircraft, CASA advises that action in relation to this matter is ongoing.

CASA intends to review current maintenance procedures applied to all high-powered piston engines fitted to Australian Registered aircraft to ensure compliance with manufacturer's published procedures, and in the opinion of the Authority, this action will provide timely notice of engine distress resulting from combustion chamber deposits.

In relation to the operating procedures for all high-powered piston engines fitted to Australian Registered aircraft, CASA advises that the Authority has notified all operators of Textron Lycoming and Teledyne Continental Motors piston engines aircraft of reports of crankshaft bearing failures.

To minimise the risk of combustion chamber deposits resulting in abnormal loading of the bearings, CASA has recommended the operators adopt conservative fuel mixture leaning procedures.

A copy of this letter is provided for the information of the ATSB.

The following is a copy of the letter

To all operators of Textron Lycoming and Teledyne Continental Motors piston engines with a take off power rating greater than 250 horsepower

And aircraft maintenance organisations

Subject: Lycoming and TCM Crankshaft Bearing and Connecting Rod Bearing Failures

Since August 2001, CASA has received 9 major defect reports relating to crankshaft and connecting rod bearing failures. Six of the failures occurred in Lycoming engines and three in TCM engines. All of the failures have occurred at a low bearing time in service. All but one of the reports involved large, high horsepower engines. A preliminary examination of a number of the failed bearings indicates evidence of delamination of the bearing shell layers. That examination result is consistent with undocumented reports of warranty claims against engines exhibiting bearing material in the oil filters of low time in service engines.

Textron Lycoming, Teledyne Continental Motors, Superior Air Parts and the FAA have been advised. of the bearing defects being reported in Australia CASA is conducting on-going discussions with Lycoming, TCM and Superior Air Parts on the reported failures. `However, CASA, has been advised; crankshaft bearings can also be supplied by non original equipment manufacturers each with a unique prefix to the original part number. Air Support and Engine Components Incorporated are two such suppliers. An Air Support supplied bearing will have the prefix "AS", eg; AS 13884-M03

Textron Lycoming has advised; bearing delamination detects should not present a safety of flight concern if the engine oil pressure filter and oil pressure screen are inspected for metal contamination at each oil and filter change. Cutting open the filter and examining the filter element as detailed in Lycoming Service Bulletin Number 480D will provide ample opportunity to detect an impending bearing failure. The FAA supports the Lycoming response.

Aggressive fuel mixture leaning may be relevant to the reported bearing defects.' The Australian Transport Safety Bureau, in investigating the dual engine failures associated with the fatal Whyalla Airlines Piper PA31-350 accident, noted a relationship between bearing failures and aggressive fuel leaning procedures. The ATSB lists engine operating practices as a contributing factor in that accident. A copy of the ATSB report can be found on the internet at www.atsb.gov.au. The CASA Flight Safety Australia Jan/Feb 2001 "Lean and Mean" article advising of the real costs of aggressive fuel mixture leaning also provides useful information on this subject.

Until a full understanding of the causes of the crankshaft bearing failures is obtained, CASA recommends all Lycoming and TCM piston engine powered aircraft operators and applicable maintenance organisations carry out the following precautionary procedures.

1. Fuel mixture leaning procedures detailed in the aircraft manufacturer's flight manual or pilot operating handbook may be different to the procedures recommended by the engine manufacturer. The engine manufacturer may recommend the use of richer fuel mixtures than those approved by the aircraft manufacturer. To limit crankshaft bearing exposure to abnormal combustion loads occurring during aggressive leaning procedures, observe the fuel mixture leaning procedure limits detailed in the engine manufacturer's operators manual.

2. At each engine oil change and filter change, if applicable to the engine model, inspect the oil pressure screen, oil suction screen and cut open the oil filter and inspect the filter element for evidence of metal contamination, Lycoming SB 480D and TCM SB M87-12 Rev.l refer; and

3. Carry out an engine oil change and, if applicable, an oil filter change, at intervals as published by the engine manufacturer, Lycoming SB 480D and TCM SB M87-12 Rev. l refer; and
4. At each engine oil change, drain the oil whilst the engine is still hot and strain the oil through a fine mesh screen filter. If a bearing defect is present, hot oil will flush out bearing material 'flakes.

> Defects found in carrying out the above recommendation should be reported to CASA on the Major Defect Form available from the CASA website, www.casa.gov.au. CASA is continuing to seek an understanding on the primary cause of the bearing defects, in submitting such defect reports, please include all available information on the supplier and part number of the bearings fitted.

The following response was received from Civil Aviation Safety Authority on 21 November 2003:

> The Australian Transport Safety Bureau (ATSB) has requested that the Civil Aviation Safety Authority (CASA) seek further clarification from the Federal Aviation Administration (FAA) on detonation limiting conditions and examine what steps CASA can take to ensure that operating procedures used by operators of fleets of more than one aircraft type take account of the requirements contained in varying operating manuals and handbooks.
>
> In response to the first issue, the FAA has been advised of CASA's specific concern with the fuel mixture leaning procedures being different in the three Pilot Operating Handbooks (POHs) for the PA31-350 Chieftain. Despite all serial numbers of PA31-350 aircraft having identical fuel systems, engines and performance, a fleet operator may operate a mix of aircraft serial number ranges, and yet, in ignorance, operate all aircraft to the one manual. CASA is writing a follow up letter to the FAA reiterating our concerns on this issue and CASA undertakes to advise the ATSB of the FAA's response.
>
> In response to the second issue, CASA's auditing of fleet operators now requires the approved Operating Procedures Manual be reviewed with consideration given to the operating procedure document detailed in the aircraft Type Certificate Data sheet (TCDS).
>
> This review is carried out on each individual aircraft in the fleet by type, model and the aircraft's manufacturer's serial number, and CASA believes that this step will assist in ensuring that operators of fleets including more than one model of a particular aircraft type take account of different versions of operating manuals and handbooks.
>
> Thank you for bringing these matters to the attention of the Authority.

Response status: CLOSED-ACCEPTED

9.3.2 Lycoming mandatory service bulletins - crankshafts

MSB 550

DATE:	February 1, 2002 Service Bulletin No. 550
SUBJECT:	Crankshaft Replacement in Lycoming TIO and LTIO-540 Engines Rated at 300 Horsepower and Higher

Lycoming has received several field reports of broken crankshafts in six-cylinder turbocharged engines. Lycoming believes the problem is related to the material used in these crankshafts.

Due to the nature of the problem, there is no field process currently available to identify crankshafts potentially affected. Therefore, Lycoming requires that all the engines listed below be returned to the factory for crankshaft replacement within 10 hours of operation.

MSB 552, and supplement 1 (SB552S-1)

DATE: August 16, 2002 Service Bulletin No. 552 (Supersedes and Replaces Service Bulletin No. 550)

SUBJECT: Crankshaft Replacement in Lycoming TIO and LTIO-540 Engines Rated at 300 Horsepower and Higher

Service Bulletin No. 552 applies only to TIO and LTIO-540 engines rated at 300 horsepower or higher.

Engines that previously complied with Service Bulletin No. 550 are also affected by Service Bulletin No. 552.

Lycoming has received several field reports of broken crankshafts in six-cylinder turbocharged engines rated at 300 horsepower or higher. The problem is related to the material used in these crankshafts. Due to the nature of the problem, there is no field process currently available to identify crankshafts potentially affected.

MSB 553 and supplement 1 (SB553S-1)

DATE: September 16, 2002 Service Bulletin No. 553 Engineering Aspects of this Service Bulletin are FAA Approved

SUBJECT: Crankshaft Inspection for Lycoming Six Cylinder Turbocharged Engines

Lycoming has received a field report of a broken crankshaft in a six-cylinder turbocharged engine. The report affected a product outside of the range recalled by Service Bulletin No. 552. Metallurgical testing indicates that the cause is material related. Lycoming requires that affected crankshafts be inspected. During the inspection, three core samples will be removed from the crankshaft propeller flange by a Lycoming authorized representative.

MSB 566 and supplement 1 (SB566S-1)

DATE: July 11, 2005 Service Bulletin No. 566

SUBJECT: Crankshaft Replacement in Lycoming Engines.

MODELS AFFECTED: Any Lycorning engine model specified below manufactured, rebuilt, overhauled or repaired after March 1, 1999:

Engines that have complied with Service Bulletin No. 552 or Service Bulletin No. 553 are not affected by this Service Bulletin.

Lycoming has continued to analyze crankshafts in service. This analysis indicates that replacement of certain crankshalts is warranted. Therefore, Lycoming is recalling certain crankshafts in the specified four and six cylinder engines.

All affected Lycoming crankshafts have a serial number format of "V5379" followed by a 3 to 5 digit number.

Please note that not all "V5379" crankshafts are affected. The crankshaft serial number is marked on the O.D. of the propeller mounting flange.

MSB 566, Supplement 1

DATE: November 30, 2005 Supplement No. 1, To Service Bulletin No. 566

SUBJECT: Crankshaft Replacement in Lycoming Engines

MODELS AFFECTED: Any Lycoming engine model specified below manufactured, rebuilt, overhauled or repaired after March 1, 1999:

Lycoming has continued to analyze crankshafts in service. This analysis indicates that replacement of certain crankshafts is warranted. Therefore, Lycoming is recalling certain crankshafts in the specified four cylinder engines.

MSB 569

DATE: February 21, 2006 Service Bulletin No. 569

SUBJECT: Crankshaft Retirement for Certain Lycoming Engines

MODELS AFFECTED: Any Lycoming engine model specified below manufactured, rebuilt, overhauled, or repaired after March 1, 1997:

Lycoming has continued to analyze crankshafts in service. While there have been no failures in the crankshafts which are the subject of this Service Bulletin, as part of our commitment to quality, Lycoming is initiating a crankshaft retirement program. This crankshaft retirement program requires the removal of the subject crankshafts when the crankcase is separated or at overhaul, whichever occurs first, not to exceed three calendar years from the date of this Service Bulletin, no later than February 21, 2009.

MSB 569A

DATE: April 11, 2006 Service Bulletin No. 569A (Supersedes Service Bulletin No. 569)

SUBJECT: Crankshaft Retirement for Certain Lycoming Engines

MODELS AFFECTED: Any Lycoming engine model specified below manufactured, rebuilt, overhauled, or repaired after March 1, 1997:

Engine models, engine serial numbers, and crankshaft serial numbers have been added. Therefore, all owners of the engine models listed above need to check this revised Service Bulletin even if it was previously determined that you were not affected by Service Bulletin No. 569.

NOTE

1. Engines that have complied with Service Bulletin No. 552, Service Bulletin No. 553, Service Bulletin No. 566, or Supplement No. 1 to Service Bulletin No. 566 and have not had another crankshaft replacement in the field after such compliance with one of the above Service Bulletins are not affected by this Service Bulletin.

2. Any new, rebuilt, overhauled, or repaired (example: prop strike) engines received from Lycoming after July 11, 2005 (logbook date of manufacture) that have not had a crankshaft replaced in the field are not affected by this Service Bulletin.

9.3.3 Airworthiness directives, Federal Aviation Administration - crankshafts

AD 2002-04-51

Subject: EMERGENCY AIRWORTHINESS DIRECTIVE U.S. Department of Transportation, Aircraft Certification Service, Federal Aviation Administration, Washington, DC

DATE: February 11, 2002

Send to all U.S. owners and operators of Textron Lycoming LTIO-540 and TIO-540 engines. These engines are installed on, but not limited to Piper Navajo (PA 31, PA 31-350, and EMB-820), Piper Saratoga (PA 32-301T, PA 32R-301T, and PA 31-325), Piper Aerostar (PA 60-700P), Piper Malibu Mirage (PA 46-350P), Piper Mojave (PA 31P-350) El Gavilian (EL-1), and Cessna T-206.

This Emergency Airworthiness Directive (AD) is prompted by reports of 14 crankshaft failures in LTIO540 and TIO-540 engines, rated at 300 HP or higher, that were assembled with crankshafts manufactured from March 1, 1999, through December 31, 1999. This condition, if not corrected, could result in crankshaft failure, which could result in total engine power loss, in-flight engine failure and possible forced landing.

Since an unsafe condition has been identified that is likely to exist or develop on other Textron Lycoming LTIO-540 and TIO-540 engines, rated at 300 HP or higher, that are listed by serial number (SN) in this AD, this AD requires removal of the crankshaft within 10 hours time-in-service (TIS) after receipt of this AD.

AD 2002-17-53

Subject: EMERGENCY AIRWORTHINESS DIRECTIVE Aircraft Certification Service U.S. Department of Transportation Federal Aviation Administration, Washington, DC

DATE: August 16, 2002

Emergency distribution is required.

This Emergency Airworthiness Directive (AD) supersedes Emergency AD 2002-04-51. Send to all U.S. owners and operators of Textron Lycoming LTIO-540 and TIO-540 engines. These engines are installed on, but not limited to Piper Navajo (PA 31, PA 31-350, and EMB-820), Piper Saratoga (PA 32-301T, PA 32R-301T, and PA 31-325), Piper Aerostar (PA 60-700P), Piper Malibu Mirage (PA 46-350P), Piper Mojave (PA 31P-350) El Gavilian (EL-1), and Cessna T-206. This Emergency AD is prompted by reports of 17 crankshaft failures in LTIO-540 and TIO-540 engines, rated at 300 HP or higher, that were assembled with certain crankshafts that were manufactured using a hammer-forged process. The FAA is continuing the investigation into the cause of the crankshaft failures, and further regulatory action will follow. This condition, if not corrected, could result in crankshaft failure, which could result in total engine power loss, in-flight engine failure and possible forced landing.

FAA's Determination of an Unsafe Condition and Proposed Actions

Since an unsafe condition has been identified that is likely to exist or develop on other Textron Lycoming LTIO-540 and TIO-540 engines, rated at 300 HP or higher, with a crankshaft installed that is listed by serial number (SN) in this AD, this AD requires removal of the crankshaft before further flight after receipt of this AD.

AD 2002-19-03

Subject: [Docket No. 2002-NE-03-AD; Amendment 39-12883; AD 2002-19-03] RIN 2120-AA64

Airworthiness Directives; Textron Lycoming I0-540, LTIO-540 and 'I' I0-540 Series Reciprocating Engines

Date: September 20, 2002

SUMMARY: This amendment supersedes emergency airworthiness directive (AD) 2002-17-53 that was sent previously to all known U.S. owners and operators of Textron Lycoming LTIO-540 and TIO-540 series engines, rated at 300 horsepower (HP) or higher. That action requires, before further flight, replacing certain serial-numbered crankshafts that were hammer forged with crankshafts that were press forged. That AD was prompted by reports of crankshaft failures in LTIO-540 and TIO-540 engines, rated at 300 HP or higher. This amendment expands the suspect population of engines to include engines with crankshafts that were manufactured between March 1997 and the present and all 10-540 engines with crankshafts that were manufactured between March 1997 and the present that have been modified by supplemental type certificate (STC) by installing a turbocharger system. The actions specified by this AD are intended to prevent failure of the crankshaft, which could result in total engine power loss, in-flight engine failure and possible forced landing.

DATES: Effective September 20, 2002.

AD 2005-19-11

Subject: [Docket No. FAA-2005-21864; Directorate Identifier 2005-NE-29-AD; Amendment 39-14276; AD 2005-19-11] RIN 2120-AA64

Airworthiness Directives; Lycoming Engines (Formerly Textron Lycoming) AEIO-360, IO-360, 0-360, LIO-360, LO-360, AEIO-540, IO-540, 0-540, and TIO-540 Series Reciprocating Engines

ACTION: Final rule.

Date: October 21, 2005

SUMMARY: The FAA is adopting a new airworthiness directive (AD) for certain Lycoming Engines (formerly Textron Lycoming) AEIO-360, IO-360, O-360, LIO-360, LO-360, AEIO-540, IO-540, O-540, and TIO-540 series reciprocating engines rated at 300 horsepower (HP) or lower. This AD requires replacing certain crankshafts. This AD results from reports of 12 crankshaft failures in Lycoming 360 and 540 series engines rated at 300 HP or lower. We are issuing this AD to prevent failure of the crankshaft, which could result in total engine power loss, in-flight engine failure, and possible loss of the aircraft.

DATES: This AD becomes effective October 21, 2005. The Director of the Federal Register approved the incorporation by reference of certain publications listed in the regulations as of October 21, 2005.

AD 2006-06-16

Subject: [Docket No. FAA-2005-23269; Directorate Identifier 2005-NE-50-AD; Amendment 39-14525; AD 2006-06-16] RIN 2120-AA64

Airworthiness Directives; Lycoming Engines (Formerly Textron Lycoming) AEIO-360, IO-360, 0360, LIO-360, and LO-360 Series Reciprocating Engines

Date: April 27, 2006

SUMMARY: The FAA is adopting a new airworthiness directive (AD) for certain Lycoming Engines (formerly Textron Lycoming) AEIO-360, IO-360, 0-360, LIO-360, and LO-360 series reciprocating engines. This AD requires replacing certain crankshafts. This AD results from a crankshaft failure in a Lycoming LO-360-A1H6 reciprocating engine. We are issuing this AD to prevent failure of the crankshaft, which could result in total engine power loss, in-flight engine failure, and possible loss of the aircraft.

AD 2006-20-09

Subject: [Docket No. FAA-2006-24785; Directorate Identifier 2006-NE-20-AD; Amendment 39-14778;] RIN 2120-AA64

Airworthiness Directives; Lycoming Engines (L)O-360, (L)IO-360, AEIO-360, 0-540,10-540, AEIO-540, (L)TIO-540, IO-580, and IO-720 Series Reciprocating Engines.

Date: November 3, 2006

SUMMARY: The FAA is adopting a new airworthiness directive (AD) for certain Lycoming Engines (L)O-360, (L) IO-360, AEIO-360, O-540, IO-540, AEIO-540, (L)TIO-540, IO-580, and IO-720 series reciprocating engines. This AD requires replacing certain crankshafts. This AD results from reports of 23 confirmed failures of similar crankshafts in Lycoming Engines 360 and 540 series reciprocating engines. We are issuing this AD to prevent failure of the crankshaft, which will result in total engine power loss, in-flight engine failure, and possible loss of the aircraft.

DATES: This AD becomes effective November 3, 2006. The Director of the Federal Register approved the incorporation by reference of certain publications listed in the regulations as of November 3, 2006.

9.3.4 Civil Aviation Safety Authority Australia airworthiness directives - crankshafts

The following series of Airworthiness Directives where issued by the Civil Aviation Authority Australia in response to the mandatory service bulletins issued by Lycoming.

AD/LYC/107 Amdt 1, 21 August 2002: Crankshaft Material

AD/LYC/107 Amdt 2, 2 October 2002: Crankshaft Replacement

AD/LYC/108, 2 October 2002: Crankshaft Material Inspection

AD/LYC/112, 28 October 2005: Lycoming Crankshaft Replacement

AD/LYC/115, 11 May 2006: Lycoming Crankshaft Replacement

AD/LYC/117, 23 November 2006: Lycoming Crankshaft Replacement

9.3.5 Safety advisory publications – mixture control

An article titled, ‘Chieftain investigation leads to safety recommendations’, published in the ATSB supplement of Flight Safety Australia (Flight Safety Australia, Nov.-Dec. 2000), introduced safety recommendation R 20000250 and another recommendation relating to the carriage of life jackets for over-water flight.

The article drew attention to the apparent correlation between the leaning of the fuel-air mixture during cruise to within 50°F of peak EGT (rich or lean side) and engine component failure. It also drew attention to the extensive reliable performance of Lycoming TIO-540 engines achieved by a number of public transport operators when fuel-air mixture leaning during cruise was restricted to 100°F rich of peak EGT.

An article titled, ‘Lean and mean, best economy or false economy, what are the costs of long-term aggressive leaning?’, written by CASA staff and published in Flight Safety Australia (Flight Safety Australia, Jan.-Feb.) discusses detonation, aggressive leaning, high power engines, and leaning procedures.

This article has created some confusion through its attribution of ‘aggressive leaning’ as the dominant factor in the process of detonation.

> Detonation: By definition, detonation is the uncontrolled explosion of the fuel/air mixture, as distinct from an even and progressive burning. Detonation occurs when the anti knock rating of the fuel is lower than required by the pressure and temperature generated during engine operation. There are a number of factors which combine to create detonation. Using fuel with an octane number (anti-knock rating) less than that required for the engine is the most obvious. However, more common is overleaning of the fuel/air mixture.
>
> Leaning the mixture lowers the anti-knock rating of the fuel. Most high performance engines require full rich during high power settings such as take-off and climb. The reason? To ensure the fuel anti-knock rating is appropriate for the combustion pressure and temperatures being developed at the high power setting.
>
> Conversely, an engine may be leaned when operating at low power settings when the temperature and pressure is less severe. It is the level of leaning that requires caution.

> Aggressive leaning: Aggressive leaning is adjusting the fuel/air mixture to the lean side of peak EGT. Aggressive leaning reduces the fuel anti-knock rating to a level where the engine is susceptible to detonation. That is, the margin between normal combustion and detonation is minimal.
>
> When running lean of peak, a defect such as a defective spark plug, fuel nozzle etc, is not the real issue of concern, it is the deliberate reduction of the available detonation margin by aggressive leaning
>
> Pre-ignition: the presence of a static hot spot in a cylinder, such as a lump of carbon or cracked spark plug ceramic, can lead to pre-ignition. A static hot spot and aggressive leaning can lead to pre-ignition detonation, which almost always results in destructive detonation. Detonation may destroy a piston or con-rod bearing before the pilot could detect the damage occurring. Again, the destruction is avoidable. The static hot spot is a minor defect, but aggressive leaning turns it into induced destructive detonation.

Confusion arises from the failure to explain that the detonation-limited fuel-air mixture is a function of engine power setting. Normally, the fuel-air mixture adjustment of a high-power aircraft engine is detonation limited at take-off and climb power settings but not at cruise power settings, see for example, figures 8.4 and 8.27. Mixture leaning close to peak exhaust gas temperature (EGT), or to the lean side of peak EGT, is only performed at cruise power settings. Mixture adjustment does not affect the anti-knock rating of the fuel.

For the situation where operating conditions are favourable for end-gas detonation, the intensity of detonation depends on the mass of end gas that auto-ignites (Taylor, 1999, vol.2, p.56). Throttling an engine to cruise power reduces the total mass of fuel-air mixture and, as a consequence, reduces the mass of end gas and the potential intensity of end-gas detonation.

9.3.6 Safety advisory publications - bearings

The Federal Aviation Administration published a special airworthiness information bulletin alerting operators of bearing surface delamination that had affected several front main bearings of high-power (greater than 300 HP) Lycoming engines.

> SPECIAL AIRWORTHINESS INFORMATION BULLETIN
>
> U.S. Department of Transportation, Federal Aviation Aircraft Certification Service Administration, Washington, DC
>
> No. NE-01-37 August 16, 2001
>
> Applicability
>
> This Special Airworthiness Information Bulletin (SAIB) alerts you, an owner or operator of Textron Lycoming IO-540 and TIO-540 series engines with 300hp or greater, that had Textron Lycoming Front Main Bearings P/N LW-13885 installed after August 24, 2000. These bearings were shipped to Textron Lycoming between August 24, 2000 and January 31, 2001 as standard size bearings with a date code of "6-00" (without an "M" suffix after the part number). Most were installed in new engines, and some were sold as spare replacements or shipped from Textron Lycoming installed in rebuilt or overhauled engines after August 24, 2000.
>
> Introduction

> Textron Lycoming has reported 6 events of front main bearings delaminating and liberating metal particles into the oil system that ultimately accumulate in the oil filter. Textron Lycoming found one delaminated bearing after the routine disassembly of a new production engine and five other delaminated bearings from routine oil filter checks at times varying between 25 hours and 350 hours. If this condition goes undetected, you could experience engine seizure and an in-flight shutdown.
>
> Textron Lycoming advised the FAA that delamination of front main bearings is a relatively slow process that you can detect through routine oil filter inspections. Field inspections have verified this method of detection (oil filter inspections). The current Textron Lycoming oil filter replacement recommendation for a new, overhauled or rebuilt engine is contained in Textron Lycoming Mandatory SB 480D and specifies the oil filter inspection intervals and oil filter inspection procedures.

The Civil Aviation Authority (CASA) Australia published an article titled ‘Check your bearings’ that discusses issues relating to bearing material and reliability (Flight Safety Australia, Jul.-Aug., 2003). CASA also issued an airworthiness bulletin (AWB 85-1 issue 3, 1 November 2004), titled ‘Textron Lycoming Engine Bearings’ which discusses issues relating to bearing construction, engine operations, maintenance, assembly/overhaul practices, and a service difficulty reporting program.

9.4 Performance of the feedback process

The formal actions of the regulatory authorities and the engine manufacturer, during the period 2000 to 2005, have been concentrated on crankshaft material and manufacturing issues, and have touched lightly upon the behaviour of plain bearings manufactured with an aluminium-tin layer.

It is evident, however, in this study of powertrain structural failure, over the period 2000 – 2005, that threats to fight safety have been created by cylinder head fatigue, piston melting, connecting rod little-end fracture, connecting rod big-end fracture, the movement of main bearing inserts, and cylinder attachment fastener fracture. The actions taken to address crankshaft material issues will have no effect on these other types of powertrain structural failure.

A timeline of safety actions, promulgated during the period 2000 – 2005, combined with timelines for the various types of powertrain structural failure is shown in figure 9.2.

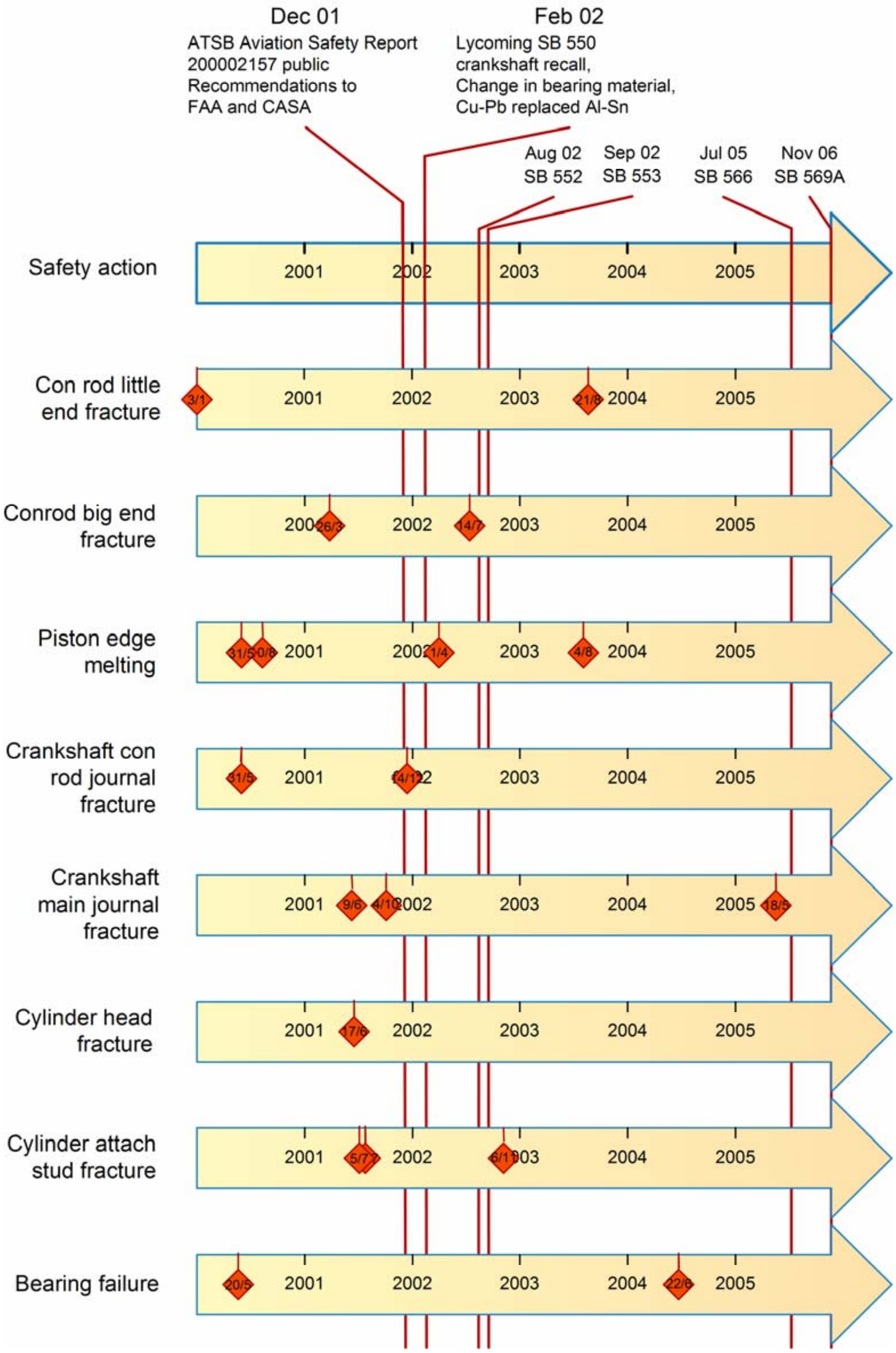
An important function of the airworthiness assurance system is the adjustment or correction of the propulsion system following system malfunction events. System correction relies on the process of feedback. Unlike simple feedback processes, such as temperature control, in which cause-and-effect linkages are clearly defined and ‘hard wired’, feedback processes that form the basis of airworthiness assurance systems, do not have clearly delineated cause-and-effect linkages and rely on the human processes of investigation, analysis and communication (Romeyn, 2006).

The resolution of differences between the operational reliability and design reliability, is achieved by appropriate adjustment or correction of the sub-systems and components that form the propulsion system. Recurrent propulsion system failures are an indication that system adjustment or correction, through an effective feedback process, is not occurring.

Feedback is an important component in the airworthiness assurance system. Its purpose is to ensure that defect information is received, analysed, and acted on in a timely manner. For the system to succeed, complete and accurate defect analysis must be provided to all those involved in the implementation of the system; regulators, manufacturers, operators, maintainers. The importance of feedback in the airworthiness assurance system was previously highlighted in the ATSB’s 2002 report *Investigation into Ansett Australia maintenance safety deficiencies and the control of continuing airworthiness of Class A aircraft.* The investigation found that:

> The CASA Canberra central office database for major defect reports was incomplete, partly due to deficiencies in reporting, and the information received was not fully analysed. In addition, feedback to the initiators of major defect reports, and to other operators, was limited. As a result, the potential safety benefit of the major defect reporting system was not fully achieved (ATSB, 2002, p.118).

Figure 9.2: **Safety actions in the context of powertrain structural failure type**



9.4.1 Feedback barriers

Barriers to feedback may arise at a various levels in a system hierarchy; individual interactions, organisational goals and interactions, and societal influences. For feedback, in response to system malfunction to be effective, information must be sensed, perceived, put into context, evaluated, analysed, and communicated. Feedback in a complex engineered-system is a function that relies on human performance. Potential barriers to feedback may occur as a result of poor communication, complacency, lack of knowledge, distraction, lack of teamwork, fatigue, lack of resources, pressure, lack of assertiveness, stress, lack of awareness, and accepted norms.

The complexity of systems has an important effect on the feedback process through the inability to predict, with complete certainty, the consequences of interactions between physical, chemical, mechanical and human processes.

The resolution of differences between operational and design reliability, in situations where the feedback process is ineffective, results in a change in expectation of propulsion system performance and an acceptance of a lower level of reliability. The management of threats to the wellbeing of passengers and crew becomes more dependent on system redundancy and the ability of pilots to manage periods of abnormal operation. However, for some aircraft types, for example those certified to FAR part 23, the defence of propulsion system redundancy is not present for all phases of flight. It is also evident that the structural failure of propulsion systems may create damage and an associated period of abnormal operation beyond the capability of the pilot to complete the flight safely. In these cases, the acceptance of a lower level of reliability increases the threat to wellbeing.

The issue of over reliance on system failure defences is noted in the UK CAA’s handbook on condition-monitored maintenance.

> In the case of a system designed to a multiple redundancy philosophy it has been a common misunderstanding that, as redundancy exists, an increase in failure rate can always be tolerated without corrective action being taken. (leaflet 13-4 CAAP 418, p.7)

The tendency to accept deviations from initial performance standards is not restricted to the operation of aircraft reciprocating engines. The subtle, insidious, unpredictable effect of accepting deviations from agreed performance standards has been highlighted in the reports of investigations into the Challenger and Columbia space shuttle accidents.

> The initial Shuttle design predicted neither foam debris problems nor poor sealing action of the Solid Rocket Booster joints. To experience either on a mission was a violation of design specifications. These anomalies were signals of potential danger, not something to be tolerated, but in both cases after the first incident the engineering analysis concluded that the design could tolerate damage. These engineers decided to implement a temporary fix and/or accept the risk, and fly. For both O-rings and foam, that first decision was a turning point. It established a precedent for accepting, rather than eliminating, these technical deviations. As a result of this new classification, subsequent incidents of O-ring erosion or foam debris strikes were not defined as signals of danger, but as evidence that the design was now acting as predicted. (Columbia accident investigation, 2003, p.196)

The means of overcoming the barriers to effective feedback lies in developing an awareness of the factors that: prevent the seeing of evidence clearly and in context, result in incorrect classification, result in incorrect cause and effect linkages, and interfere with communication at all levels. Feedback is highly dependent on viewing the system in its entirety, and viewing its elements in detail. Feedback to ensure continued safe operation should be based on the potential consequences of a sequence of events.

9.5 References

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10 CONCLUSIONS

The reliability of reciprocating engines is an issue for a significant portion of the Australian civil aviation fleet. Over the six-year period of this study, 2000 – 2005, 1,270 reciprocating-engine powered aircraft on the Australian register operated for about 220,000 hours. Of these aircraft, around 200 were employed in the low-capacity regular public transport class of operation, providing public transport connections throughout regional Australia.

A threat to the safe operation of these aircraft can be created by the structural failure of powertrain components – combustion chamber assemblies, pistons, connecting rods, and crankshafts.

Although propulsion system redundancy may be provided in this class of aircraft through designs that employ two independent, wing-mounted, propulsion systems, it is acknowledged that, following the failure of one propulsion system; the remaining propulsion system is not capable of providing the thrust required for all phases of flight. In addition to the safety threat created by the loss of thrust at critical phases of flight, powertrain structural failure has the potential to create a condition of high drag through the disruption of engine cowls, the potential to fracture engine mounts, and the potential to affect wing structures through the effects of fire.

In view of the potential consequences of powertrain structural failure, the reliability of powertrain components is of critical importance and should not be diminished through an over reliance on propulsion system redundancy and pilot response. The number and frequency air safety occurrences involving powertrain structural failure events during the six year period 2000 to 2005 suggests that there was a breakdown in the system created to ensure the reliable operation of reciprocating engines.

The twenty events of powertrain component failure studied could be grouped into several categories:

- piston edge and cylinder head melting
- connecting rod little-end bearing housing and big-end bearing housing fatigue fracture
- plain bearing surface breakup
- movement of plain bearings within their housings
- cylinder head fatigue
- cylinder attachment fastener fatigue fracture
- crankshaft fatigue fracture.

These failure events were not restricted to one engine model or one engine manufacturer.

The event sequences stemming from powertrain component failure were found to vary in nature and consequence. The inherent complexity of the chemical, physical and mechanical processes, and behaviours and interactions between the component parts of assemblies affect the nature of failure sequences and, ultimately, the consequence of the failure sequence – service difficulty, serious incident, or fatal accident.

Analysis of each failure mode revealed that factors that contribute to the failure ranged from:

- a change in combustion from normal flame propagation to end gas auto-ignition (detonation);
- a change in plain bearing lubrication regime;
- a change in the force acting to retain bearing inserts in their housings;
- a change in the force acting to move bearing inserts in their housing; and
- the initiation of fatigue cracking in components designed to have a life not limited by fatigue cracking.

While a major variation in an initiating factor from the designed state, may cause the failure of a powertrain component, for example, the development of heavy detonation through the use of incorrect fuel or gross exceedence of operating limitations will lead to the rapid melting of combustion chamber components, it is evident that synergistic interactions between factors, with smaller variations from the norm, can also cause component failure.

A change in the combustion process – from flame propagation throughout the fuel-air mixture to the auto-ignition of some part of the mixture – has the potential to affect the reliability of powertrain components. The effect of detonation is related to the intensity of detonation, which in turn, is dependent on the volume of end-gas that undergoes auto-ignition. Light to medium detonation may result in some mechanical damage. The actual nature of mechanical damage is dependent on the robustness of powertrain components and assemblies to abnormal loading. Heavy detonation results in the melting of aluminium alloy combustion chamber components.

Detonation-free operation, for a fuel of known detonation resistance, is based on limiting the operator-controlled engine parameters of manifold pressure (power), speed, mixture, and engine load. Additionally, detonation-free operation is based on designed limits for; combustion chamber surface temperatures (spark plugs, piston crown and cylinder head inner surface, the presence of deposits), inlet air temperature, and rate of pressure rise (spark ignition advance, ignition from sites other than spark plugs). Variations in any of these factors, beyond designed limits, will increase the likelihood of detonation during engine operation. In addition, the cumulative effect of variations in a number of factors may also act to increase the likelihood of detonation.

For the engine failure occurrences investigated in this study, it is clear that leaning at climb power settings increases the likelihood of detonation. It is also evident that the fuel-air mixture settings – lean climb and lean cruise, resulted in the deposition of a non-volatile lead compound on combustion chamber surfaces. The presence of non-volatile deposits also increases the likelihood of detonation.

The effects of end-gas detonation, non-uniform pressure development on piston crowns, and the propagation of shockwaves across piston crowns, have an effect that is dependent on the layout of the engine (horizontally opposed or radial). The location of the regions of end-gas detonation in a horizontally-opposed engine combustion chamber (dual spark plugs) results in rocking of the piston pin in the connecting rod little-end bearing and rocking of the connecting rod big-end bearing about the crankshaft journal. The location of the regions of end-gas detonation in a radial-engine combustion chamber (dual spark plugs) results in the rotation of the piston about the piston pin.

Plain bearings in high-powered aircraft reciprocating engines are an example of a complex subsystem operating within a complex engineered-system. Complexity brings with it a variety of failure modes and a sensitivity of the failure process to initial conditions.

The failure of bearings in aircraft horizontally-opposed engines can be related to factors that affect hydrodynamic oil film stability, factors that lead to an increase in the temperature of bearing materials, factors that control the magnitude of the bearing insert retention force, and factors that control the magnitude of forces which act to displace the bearing insert. The functioning of other engine subsystems and the actions of operators and maintainers influence these factors.

A change in plain bearing lubrication from hydrodynamic to boundary conditions is affected by factors that increase the bearing load, or decrease the bearing clearance. This analysis found that bearing surface damage created by boundary lubrication was associated with loads arising from combustion. It was also established that there were instances where bearing clearances had been reduced by maintenance actions undertaken to resize crankshaft journals.

Factors that were found to increase the temperature of bearings were high engine power operation combined with boundary lubrication, the presence of an adherent nickel layer between the lead-tin and aluminium-tin bearing layers exposed after bearing surface wear, and the loss of metal-to-metal contact between the bearing insert and housing through the inclusion of a lubricant.

The response of plain bearings to increases in bearing temperature is dependent on the nature of the various metallic layers that are used in their construction. It was established that the differing behaviour of plain bearings constructed with an intermediate bearing layer of an aluminium-tin alloy or a copper-lead alloy, was a result of the microstructural changes that occur in the aluminium-tin alloy when the bearing is heated, and the consequent lowering of the endurance strength of the aluminium-tin layer.

Factors that result in bearing insert movement were found to be those factors that affect the magnitude of the friction force created by the interference fit and the magnitude of forces acting to move the insert circumferentially and axially.

Factors that affect the magnitude of the coefficient of friction between the backs of bearing inserts and bearing housings have an important effect on insert retention. It was evident in this analysis that lubricants had been placed between the backs of connecting rod big-end bearing inserts and their housings during assembly.

The magnitude of the forces acting to move an insert in its housing are affected by increases in sliding surface friction (boundary lubrication and, in particular, the sliding of a steel journal against an adherent nickel bearing surface) and the nature of loading created by combustion. Combustion may have an effect through an increased load on the bearing surface, increased bending moments on the main bearings of crankshafts, and increased big-end bearing edge loads associated with non-uniform gas loads on the piston and the propagation of shock waves in the combustion gases during combustion with light to medium detonation.

The factors that were found to initiate fatigue cracking and fracture of cylinder heads, cylinder attachment fasteners, connecting-rod bearing housings, and crankshaft journals may be divided into two groups: those factors that increase the magnitude of alternating stress in a component, and those factors that decrease the endurance strength of a component.

In this study, sources of increased component alternating stress were found to have been associated with the gas pressures produced by combustion, increased component flexure, and reductions in component preload. Sources of decreased fatigue endurance strength were found to have been associated with surface damage created by adhesive wear (galling), surface scoring created by rubbing contact with a closely associated component, and cracking in nitrided surfaces created by localised frictional heating.

The initiation and propagation of fatigue cracks in a powertrain component is not, simply, a matter restricted to the material from which the component is manufactured. It is a matter of all factors that affect the magnitude of component alternating stresses, and the component endurance strength.

In addition to the complex interrelationships between loads, preloads, geometric stress concentrators, residual stress, surface finish, surface hardening, and material of an individual component, there are clear interdependencies between the combustion process in individual and multiple cylinders of a horizontally-opposed engine, the physics of plain bearing lubrication, the mechanics of bearing insert retention, and the process of fatigue crack initiation.

The formal actions of the regulatory authorities and the engine manufacturer, during the period 2000 to 2005, have been concentrated on crankshaft material and manufacturing issues, and have touched lightly upon the behaviour of plain bearings manufactured with an aluminium-tin layer.

It is evident, however, in this study of powertrain structural failure, over the six-year period 2000 – 2005, that threats to fight safety have been created by cylinder head fatigue, piston melting, connecting rod little-end fracture, connecting rod big-end fracture, the movement of main bearing inserts, and cylinder attachment fastener fracture. The actions taken to address crankshaft material issues will have no effect on these other types of powertrain structural failure.

The resolution of differences between the operational reliability and design reliability of reciprocating-engine powered propulsion systems is achieved by appropriate adjustment or correction of the sub-systems and components that form the propulsion system. Recurrent propulsion system failures are an indication that system adjustment or correction, through an effective feedback process, may not be occurring.

Barriers to feedback may arise at a various levels in a system hierarchy: individual interactions, organisational goals and interactions, and societal influences. For feedback in response to system malfunction, to be effective, information must be sensed, perceived, put into context, evaluated, analysed, and communicated. Feedback in a complex engineered-system is a function that relies on human performance. Potential barriers to feedback may occur as a result of poor communication, complacency, lack of knowledge, distraction, lack of teamwork, fatigue, lack of resources, pressure, lack of assertiveness, stress, lack of awareness, and accepted norms.

The complexity of propulsion systems powered by reciprocating engines has an important effect on the feedback process through the inability to predict, with complete certainty, the consequences of interactions between physical, chemical, mechanical and human processes.

The means of overcoming the barriers to effective feedback lies in developing an awareness of the factors that: prevent the seeing of evidence clearly and in context, result in incorrect classification, result in incorrect cause and effect linkages, and interfere with communication at all levels. Feedback is highly dependent on viewing the system in its entirety, and viewing its elements in detail. Feedback to ensure continued safe operation should be based on the potential consequences of a sequence of events.

Analysis of failure events in complex engineered-systems should be undertaken with regard to component failure control plans and the safety assurance system as it is applied to the aspects of design, manufacture, operation, and maintenance.