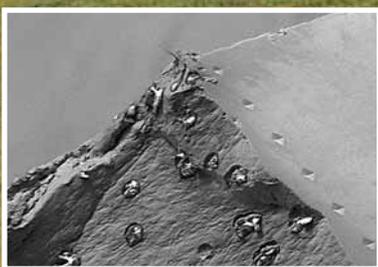


Piper PA31-350 Chieftain VH-MZK Spencer Gulf SA



31 May 2000



Department of Transport and Regional Services

Australian Transport Safety Bureau

SUPPLEMENTARY
AVIATION SAFETY INVESTIGATION REPORT
200002157-A

Piper PA31-350 Chieftan VH-MZK
Spencer Gulf SA
31 May 2000

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EXECUTIVE SUMMARY

Since the release by the ATSB on 19 December 2001 of Report 200002157 on the fatal accident involving Piper Chieftain VH-MZK in Spencer Gulf in South Australia on 31 May 2000, further events have taken place, and additional information has become available, regarding issues that were examined in ATSB Report 200002157. The ATSB formally re-opened its investigation in November 2002 under the provisions of Part 2A of the Air Navigation Act in order to test the significance of the new evidence.

From July 2002 until July 2003, the South Australian Coroner conducted a public inquest into the accident. The Coroner delivered his findings on 24 July 2003 and disagreed with the conclusions in ATSB Report 200002157 and was critical of the ATSB investigation. The Coroner concluded that the left and right engines had failed independently. He found that the right engine overheated and was damaged during the climb from Adelaide, and developed a hole in the No 6 piston 8 minutes into the cruise phase of the flight. He concluded that the left engine subsequently independently failed because of fatigue cracking initiated by a sub-surface manufacturing defect in the crankshaft.

Between 1 February and 16 September 2002 (after ATSB Report 200002157 was released), the engine manufacturer issued Mandatory Service Bulletins 550, 552, and 553 concerning potential crankshaft defects. The serial number of the MZK left engine crankshaft appeared in Service Bulletin 553. It has been reported that of the crankshafts that were subject to that service bulletin, almost 70 percent of those tested were not defective and were permitted to continue in service after testing.

As stated in ATSB Report 200002157, initial examination of the crankshaft by the ATSB indicated that it complied with the proprietary standards set by the engine manufacturer. Based on their examination of a sample that had been cut from the crankshaft by the ATSB and stored for 18 months, academics from a local university commissioned by the Coroner, along with a US firm acting for the plaintiffs in civil damages litigation, reported the existence of 'massive' high temperature oxide 'inclusions' in the crankshaft material. However, later examination by the same experts and destructive testing of the crankshaft in the vicinity of the fatigue crack origin did not reveal any evidence of massive inclusions. Nevertheless, the opinion of the US firm concluded that a manufacturing defect (rather than a thermal crack as suggested in ATSB Report 200002157) was responsible for initiating the fatigue crack. They stated that while no large foreign body manufacturing inclusion was found at the crack initiation site, it may have 'fallen out' as the crack propagated. Detailed examination of the crankshaft material and the fracture area, including both sides of the fracture surface by the ATSB (in the presence of independent observers) in March 2003 did not reveal any irregularity in the crankshaft steel that could have initiated the fatigue fracture under normal engine operating conditions. No evidence of any large inclusions or of any 'honeycomb feature' as suggested in material associated with the service bulletins was found. Without receiving expert advice, the Coroner in his findings stated that the ATSB's 50 page test report 'takes the matter no further' and chose to rely on earlier opinion and circumstantial evidence.

The ATSB does not agree with the Coroner's findings and is strongly of the view that the engine failure mechanisms and the sequence of events contained in ATSB Report 200002157 remain the most likely explanation of the circumstances of the accident, based on the limited factual information that was available. This Supplementary Aviation Safety

Investigation Report includes the ATSB's detailed response to the Coroner's findings. The report also includes further explanation of the main issues addressed in ATSB Report 200002157, as well as matters of major interest that arose during the inquest, including:

- The possibility that the failure of the VH-MZK left engine crankshaft was linked to a manufacturing defect,
- The possibility of an engine failure sequence that differed from that advanced in Report 200002157,
- The extent and timing of the left engine No 6 connecting rod big end bearing 'failure',
- The operation of the turbocharger on the Textron Lycoming TIO-540 engine,
- The maximum single engine speed the aircraft could achieve.

In summary, the ATSB explanation for the initiation of the fatigue crack in the left engine crankshaft about 50 flights before the accident was a thermal crack caused by localised surface heating when a bearing insert failed to operate as designed and a bearing edge interfered with the crankshaft surface. This resulted from some combination of excessive engine pressures probably caused by preignition from incandescent lead oxybromide deposits (linked to fuel leaning, eg in the climb but within the aircraft manufacturer's guidelines) and bearing slippage assisted by an anti-galling lubricant. In addition to MZK, this was based on the ATSB's observations of damage in a number of engines (now more than a dozen) including two from another engine manufacturer. The ATSB concluded that the holing of the right engine No. 6 piston was the result of detonation in response to the left engine failure (the right engine damage was therefore a dependent failure). As the ATSB stated when releasing Report 200002157 on 19 December 2001, it is not appropriate to 'blame' the young pilot in this scenario given the paucity of evidence and the ATSB did not do so.

The ATSB does not agree with the Coroner that MZK's pilot was likely to have allowed, ahead of any stressful situation, his right engine to overheat to a point 8 minutes into the cruise of melting a hole in a piston (especially as the temperature probe is atop the melted No. 6 piston cylinder) and then be unlucky enough that a deep-seated long-term progressive fatigue crack problem in the left engine crankshaft would have suddenly caused that engine to independently fail.

Following the release of ATSB Report 200002157, the ATSB received responses from the US FAA concerning Recommendations R20010254 and R20010255 that dealt with combustion chamber deposits and anti-galling compounds. The FAA advised that it would review the effect of anti-galling compounds on bearing insert retention, and that it was conducting an extensive evaluation of the detonation characteristics of high performance reciprocating engines and would include an examination of deposit formation as part of that evaluation.

In July 2002, the ATSB issued Safety Recommendation R200220149 for CASA to examine the potential safety benefits of devices that monitor aircraft fuel and engine system operation and whether those systems should be fitted to general aviation aircraft engaged in air transport operations. CASA advised that it did not consider the safety benefits of those devices warranted their fitment being made mandatory. However, CASA did not have any concern with operators voluntarily fitting such equipment.

While maintaining that the engine failure mechanisms and the sequence of events contained in ATSB Report 200002157 remain the most likely scenario, the Bureau examined carefully a range of scenarios. In particular, an assessment was made of any safety action that might be required if an accident as a result of a less likely scenario was to be prevented in the future.

The Coroner included five recommendations in his findings:

1. As suggested in the ATSB's submissions, the Coroner sought clarification of engine operating procedures between different versions of pilot operating handbooks and flight manuals for piper Chieftain aircraft to ensure that engine detonation limits are not exceeded. The ATSB has written to CASA supporting the Coroner's recommendation and requesting that CASA seek clarification of detonation limits from the US FAA, and examine how engine operating procedures for operators of more than one model of a particular aircraft type take proper account of differences in versions of operating manuals and handbooks.
2. The Coroner sought improved lines of communication between international aviation regulation and safety investigation agencies, even where litigation might be threatened. The ATSB already enjoys close working international relationships, but agrees that the flow of information could be improved in some instances. However, there are practical limitations that apply in other countries and through multilateral agencies over which the ATSB has no control.
3. The Coroner sought that CASA mandate the fitment of on-board recorders in aircraft carrying fare-paying passengers. The ATSB considers that its Safety Recommendation R200220149, referred to above, addressed that issue.
4. The Coroner sought the carriage of life jackets and/or life rafts in fare-paying passenger operations over water, which is supportive of earlier ATSB recommendations. ATSB Report 200002157, Section 4.4, detailed Safety Recommendations R20000248 and R20000249 concerning the carriage of life jackets and emergency and life saving equipment. R20000248 was accepted by CASA and Civil Aviation Order 20.11 amended to require life jackets to be carried on all passenger flights over water. As regards R20000249, CASA has advised that it was considering a number of issues regarding emergency and life saving equipment in twin engine aeroplanes in the context of the proposed CASR Part 121B, Air Transport Operations – Small Aeroplanes. The draft regulations included in a Notice of Proposed Rule Making (NPRM) released by CASA in July 2003 for this Part includes various requirements for emergency cabin lighting and carriage of items such as of life jackets and other flotation devices, life rafts, ELTs (Emergency Locator Transmitters) or EPIRBs (Electronic Position Indicating Radio Beacons) and other survival equipment, including provisions.
5. The Coroner proposed a research program concerning self-deploying ELT units. The ATSB's recommendation to CASA R20000249 encompasses enhanced emergency and life saving equipment such as ELTs and the Bureau believes that CASA, AusSAR (AMSA) and Defence are best placed to progress the issue.

1 BACKGROUND

Since the release by the ATSB on 19 December 2001 of the Bureau's report on the fatal accident involving Piper Chieftain VH-MZK in Spencer Gulf in South Australia on 31 May 2000, further events have taken place, and additional information has become available, regarding issues that were examined in ATSB Report 200002157. This Supplementary Aviation Safety Investigation Report has been compiled since the ATSB formally re-opened its investigation in November 2002 and is released to address the most significant among those issues, namely:

- The possibility that the failure of the VH-MZK left engine crankshaft was linked to a manufacturing defect,
- The suggestion of an alternative engine failure sequence,
- The extent and timing of the left engine No. 6 connecting rod big end bearing 'failure',
- Operation of the aircraft density controller as part of the engine turbocharger,
- The maximum single engine speed the aircraft could achieve, and
- Actual and proposed additional safety action to help ensure such an accident doesn't happen again.

In addition, the South Australian State Coroner has conducted an inquest into the accident. The Coroner delivered his findings on 24 July 2003 and was critical of the ATSB and its report. Attachment A to this report includes the ATSB's response to the Coroner's findings and criticisms.

The ATSB had an obligation to test any significant new evidence that arose after its Report 200002157 was released and a responsibility to ensure that any safety action that should be undertaken to prevent a future accident had not been overlooked. Under the operative Australian legislation, the relevant terms of Section 19DF of Part 2A of the Air Navigation Act provided that 'If, after an investigation of an accident has been completed, new and significant information relating to the accident becomes available, the [ATSB Executive] Director must conduct further investigation of the circumstances surrounding the accident'. The mandatory provisions of the Australian law picked up an international obligation accepted in paragraph 5.13 of Annex 13 to the Chicago Convention.

2 FAILURE OF THE VH-MZK LEFT ENGINE CRANKSHAFT

As part of its initial investigation into the accident, the ATSB undertook and commissioned tests in relation to the fractured left engine crankshaft's compliance with the engine manufacturer's proprietary standards concerning steel quality (chemistry, strength, non-metallic inclusion content), journal surface nitriding and journal diameter (page 62, ATSB Report 200002157). The ATSB also reached conclusions regarding the nature and cause of the fatigue crack in the crankshaft: in short, that it was initiated, in the region of the transition from the nitride hardened surface zone (case) to the crankshaft core, around 50 flights before the accident flight and consistent with thermal expansion of the nitrided layer when the metal edge of a bearing insert made contact with the crankshaft journal fillet radius (see Section 1.17.3 of ATSB Report 200002157).

The ATSB did not conduct destructive examination on the crankshaft fracture surfaces during its initial investigation. That decision was in line with normal ATSB practice not to destroy evidence unless it is essential to the investigation because of the interest other parties might have in examining damaged components first hand. The ATSB considered that the information available on the crankshaft fracture at that time did not indicate the need for such destructive testing. If, during the investigation, the ATSB had become aware of any advice from the engine manufacturer or regulator regarding any particular issue with a component of the aircraft, then that issue would have been considered and, if necessary, additional (including destructive) testing conducted.

During 2002, and subsequent to the release of ATSB Report 200002157 in December 2001, the engine manufacturer, Textron Lycoming, issued three 'mandatory' service bulletins concerning 'Crankshaft Replacement in Lycoming TIO and LTIO-540 Engines Rated at 300 Horsepower and Higher':

- Service Bulletin No. 550 was issued on 1 February 2002. It stated that 'Lycoming had received several field reports of broken crankshafts in six-cylinder turbocharged engines' and believed that the problem was related to 'the material used in these crankshafts'. The service bulletin included, by serial number, a list of engines that were to be 'returned to the factory for crankshaft replacement within 10 hours of operation'. The left engine of MZK was not included in that list.
- Mandatory Service Bulletin No. 552 was issued on 16 August 2002. It superseded and replaced Service Bulletin No. 550 and required compliance before further flight. It included a more expansive list of engine serial numbers that were to be returned to the factory for crankshaft replacement, as well as crankshaft serial numbers that were not to be used in engine assembly. Neither the left engine of MZK, nor its crankshaft, was included in the list.
- Mandatory Service Bulletin No. 553 was issued on 16 September 2002. Lycoming advised that it had received a report of a broken crankshaft in a six-cylinder turbocharged engine that affected the product outside the range of Service Bulletin No. 552. The service bulletin said that the problem was material related and required three core samples from the propeller flange of the affected crankshafts to be tested. If the core test results were acceptable, the crankshaft could be returned to service. The left engine of MZK was included in the list of serial numbers subject to the service bulletin. Avflash bulletin, 3 April 2003 reported that 601 engines were tested in

accordance with Service Bulletin No. 553 and 184 crankshafts were removed from service. The remaining 417 (69.4 per cent) were allowed to continue in service.

In the course of the coronial inquest, in August 2002 both engines from the aircraft were sent to the US for further testing and examination. Once in the US, the engines were part of civil damages proceedings. The South Australian State Coroner and parties had agreed to a protocol regime to allow for further testing including destructive testing if required. On that basis, the ATSB was prepared to await the outcome and formally re-open the ATSB investigation only if a significant material defect was established.

The Coroner had also engaged a number of local academic experts including two metallurgists, a chemical engineer and a mechanical engineer to examine various aspects of the accident. As part of the metallurgical testing, significant reliance was placed on the examination of a small sample taken from the No. 5 main bearing journal by the ATSB some two years previously. In particular, the Coroner's expert metallurgists asserted that the sample showed evidence of clusters of 'massive' high temperature oxide inclusions. Such features were not evident when the sample was originally examined by the ATSB and the Bureau has concluded that it is most likely that what was observed was surface corrosion that had occurred during storage. After light grinding and re-polishing by the metallurgists retained by the Coroner removed about 55 microns from the specimen surface, no features were evident.

Destructive testing had not been performed in the US as had been expected when the Coroner and parties, including the ATSB, travelled to the US in October 2002. A report dated mid October 2002 was provided by the US firm engaged on behalf of the parties seeking damages through the US litigation. That report included opinion that agreed with the purported high temperature oxide inclusions in the No. 5 main bearing journal sample as asserted by the Coroner's metallurgists, and placed significant weight on the release of Service Bulletin No. 553. The report contained preliminary opinion that the failure of the left crankshaft of MZK was due to a microstructural anomaly/inclusion at the fatigue crack origin.

Further delays subsequently arose regarding destructive testing in the US to establish with more certainty the characteristics of any anomaly or inclusion at the fatigue crack origin. To seek to expedite the further testing, the ATSB formally re-opened its investigation on 21 November 2002¹.

Subsequently, the US testing organisation conducted destructive testing of the crankshaft from 13–16 January 2003. In accordance with an order made by the Coroner on 3 January that the ATSB (among others) were 'entitled to attend any testing which takes place on 13th January 2003 or thereafter', the ATSB sent a specialist investigator to the US to observe the testing. For reasons that remain unclear, that testing was halted at lunchtime on 16 January before examination back to the fatigue crack initiation site had been completed. The examination that had been conducted did not reveal any evidence of massive high temperature oxide inclusions. However, despite the fatigue crack origin not having been fully examined, it was reported by the US testing organisation that sufficient

¹ Clause 5.13 of Annex 13 to the Chicago Convention, as enacted in Australia through section 19DF(1) of the Air Navigation Act includes the requirement that: 'If, after an investigation of an accident, serious incident or incident has been completed, new and significant information relation to the accident, serious incident, or incident becomes available, the Director must (a) if the investigation was conducted by the Director - conduct a further investigation of the circumstances surrounding the accident serious incident or incident'.

testing had been undertaken to establish the existence of an 'inclusion' at the fatigue crack origin that could explain the initiation of the fracture. The ATSB did not agree with that report. The ATSB specialist who observed the testing reported that:

- The examination was incomplete at the time it was discontinued and that the overall objective was not met (this being the determination of the presence or otherwise of non-metallic inclusions at the fatigue initiation site by actually sectioning through the site and the surrounding material).
- There was no evidence of 'massive iron-oxide inclusions' found on the fracture surface or within the material examined in cross-section.
- To the extent that the examination allowed, there was no discovery of evidence that established the presence of any other anomalous non-metallic inclusions (or other discontinuities) within the crankshaft steel.
- The examination became rushed and therefore less effective during the latter stages. (This was the time when ideally, the examination should have been most thorough and methodical.)
- There was no evidence found to suggest the mechanism by which the step-like feature at the fatigue origin had formed.
- At no time during the progress of the examination or after its discontinuation was there any general discussion about the findings made, nor was there any consensus agreement about the likely mechanism/s of fatigue crack initiation.

On 17 January, the ATSB formally objected to the US process and sought, through Counsel Assisting the Coroner, the Coroner's assistance for the engine parts to be returned to Australia so that the ATSB could complete the metallurgical examination. However, on 27 and 28 January 2003, despite the Coroner's order of 3 January and the concerns the ATSB had raised on 17 January, without the ATSB's knowledge and without an independent observer being present, further destructive testing of the fatigue crack initiation site by the US testing organisation was undertaken. On 28 February 2003, Counsel representing the families advised the Coroner that completion of the final report on that testing 'has been quite a lengthy task, it has many hundreds of, I am told, exhibits to it and photographs' and that it was 'a voluminous document' and that 'the pictures themselves take up two volumes'. The ATSB was subsequently provided with a copy of the final report dated 7 March 2003, comprising five pages of text and 11 pages of photographs/figures. The report essentially summarised the background to the accident as detailed in ATSB Report 200002157 and concluded that no indications of large oxide inclusions or of an oxide inclusion seam were observed and that there was no evidence of an inclusion at the fatigue crack origin. However, the US report maintained that a manufacturing defect and not a thermal crack was responsible for initiating the fatigue crack. The US report conclusions, along with the ATSB response to each, is at Attachment B.

ATSB ADDITIONAL TESTING OF THE LEFT ENGINE CRANKSHAFT

As the ATSB did not have the opportunity to observe the latest destructive testing in the US, and because of the lack of conclusive evidence of a material defect in the crankshaft, the ATSB formally sought the VH-MZK left engine crankshaft from the Coroner. The crankshaft was subsequently provided to the ATSB.

On 10 March 2003, testing by the ATSB of the left engine crankshaft and fatigue crack initiation site began. The ATSB invited all parties to the inquest to attend the testing. Representatives from Lycoming, CASA, Whyalla Airlines, and one private individual did attend, but for reasons that remain unclear, the Coroner chose not to send a representative. The parties were permitted to observe all testing and associated activities conducted by the ATSB. A comprehensive ATSB technical report on the testing, including destructive examination and external laboratory testing, is at Attachment C. A copy of that report was sent to the Coroner on 24 April 2003. Key results included:

- None of the testing or physical evidence indicated any significant irregularities or defects in the crankshaft steel that could have initiated the fatigue fracture under normal engine operating conditions.
- The types of inclusions present throughout the crankshaft, including in the immediate vicinity of the site of fatigue crack initiation, were typical of the steel type.
- No material processing abnormality was observed in the immediate vicinity of the fatigue initiation site.
- There is evidence that supports the hypothesis that a planar discontinuity was created in the hardened surface zone of the No. 6 journal surface. The features of the planar discontinuity that could be deduced from the non-destructive and destructive examination are consistent with the expected and observed features of aircraft crankshaft journal surface cracks created by localised thermal expansion following contact with other engine components or inadequate cooling during crankshaft grinding. Planar discontinuities of this type have been observed to result in the initiation of fatigue cracking in crankshaft journals.
- Within the bounds of fracture surface secondary damage and its disruption of the fine detail at the site of fatigue crack initiation, it is likely that a planar discontinuity (a small crack) in the surface hardened zone created by localised thermal expansion provided the site of stress concentration from which fatigue cracking was initiated subsurface.
- As the Textron Lycoming drawing notes for part number 13F27708 crankshafts state that no grinding is allowed on any connecting rod journal after nitriding, the most likely source of localised heating where the thermal crack was located was contact between the bearing insert and the No. 6 connecting rod crankshaft journal.

Those findings were in accord with the findings contained in ATSB Report 200002157 that was released on 19 December 2001.

Surprisingly, the Coroner concluded that the ATSB's 50 page documented test report 'takes the matter no further'. The ATSB had been advised by the Coroner's Solicitor in May 2002 that the metallurgists engaged by the Coroner during the inquest were

reviewing the technical report. However, the ATSB was not privy to any such review. In the interests of aviation safety and to ensure all evidence had been considered before finalising the ATSB's re-opened investigation, the ATSB wrote to the Coroner seeking copies of any written advice or file notes relating to the left engine crankshaft and to the engine failure sequence which had not already been made available to the ATSB during the inquest. Despite several exchanges in correspondence, the Coroner's Solicitor refused to provide any information on what, if any, specialist advice on the ATSB technical report had been provided to the Coroner.

The ATSB also sought information from the Coroner's metallurgists. Little of substance was received in response and it was stated that no report was provided to the Coroner due to the incomplete nature of the work done and because time and costing prohibited further investigation. The Coroner's Solicitor subsequently confirmed that advice and stated that no such material was provided to the Coroner. As such, it appears that the Coroner's conclusion regarding the ATSB's technical report was not based on any specialist review or advice.

It therefore seems that the Coroner relied on earlier opinion, including from the US firm acting for the parties to US civil damages litigation, that there may have been a significant non-metallic 'inclusion' in the steel that had 'dropped out', concluding that 'such an inclusion was not found at the origin of the fracture site but this does not exclude the possibility that it was lost during the fracture process'. The Coroner also relied upon the circumstantial evidence of the 2002 service bulletins indicating a potential manufacturing defect without acknowledging that a substantial majority of potentially affected crankshafts tested were not defective.

As previously noted, the assertion that the ATSB's March 2003 destructive testing and April report 'takes the matter no further' is incorrect given that the ATSB examined both fracture surfaces thoroughly and found no manufacturing defect in the left crankshaft steel that could have caused the fatigue fracture under normal operating conditions. There was no 'honeycomb feature' in the steel of the type suggested in material associated with the service bulletins.

FURTHER EXPLANATION OF THE ENGINE FAILURE SEQUENCE IN ATSB REPORT 200002157

ATSB Report 200002157 concluded that, based on the limited factual information available (recorded radar and air traffic control audio data, and metallurgical information from the left and right engines, but without the benefit of survivors, cockpit voice recordings or flight data recordings), the most likely engine failure sequence was that the left engine began to malfunction early in the cruise segment of the flight when the crankshaft fractured, but remained dogged, allowing the engine to continue to operate for a further 8 to 10 minutes before final crankshaft separation and engine stoppage. In response to the failure of the left engine, the pilot most likely would have increased power on the right engine. The nature of the damage to the right engine indicated that it had operated under conditions of severe detonation, probably for a number of minutes, causing the crown of the number six piston to melt and develop a hole and heat damage to other cylinders. The resultant erratic operation of the right engine (via oil venting and the turbocharger, see below), with reduced power and controllability, left the pilot with little alternative but to ditch the aircraft.

Key points supporting that failure sequence include the following:

- The failure of the left engine was, in effect, predetermined some 50 flights or so before the accident flight when the fatigue cracking was initiated.
- The likelihood of two independent engine failures in an aircraft on a particular flight is extremely remote. In particular, the chances of the right engine malfunctioning independently within minutes of the predetermined crack in the left engine proceeding to separation are extraordinarily unlikely.
- The type of malfunction within the right engine could not in any significant way have influenced the failure of the left engine (which resulted from the long term progressing fatigue crack).
- Heat damage in other cylinders in the right engine weigh against any notion that an ignition or fuel flow problem affecting only the No. 6 cylinder led to the piston melting.
- The available evidence indicated that the performance achieved by the aircraft during the takeoff and climb was normal.
- Although the engine climb power settings used by the operator could have induced mild detonation (but they were consistent with relevant manufacturer's operating requirements), combustion chamber temperatures would not have risen sufficiently from this to cause the type of damage evident in the right engine. Further, over many years of operation, there was no pattern of melted pistons in the operator's Chieftain aircraft as a result of the settings used and post-accident borescope inspections of engines on the other three Chieftains showed no damage. In any event, had the No. 6 piston been holed during the climb, oil would have been vented overboard and turbocharger operation become erratic at that stage. Examination of the right engine revealed that it had not seized and was probably providing some power at impact, supporting the likelihood that the piston was holed late in the flight.

- The fluctuations and general reduction in groundspeed evident from the recorded radar data from about 8 minutes after the top of climb are most unlikely to have been caused by wind conditions. The Bureau of Meteorology (BoM) recorded stable atmospheric conditions through the time and area of the flight. The very stable recorded radar track and groundspeed data from other flights by MZK and other Chieftain aircraft during the period before and after the accident reinforced the BoM information.
- Information from the crew of another Chieftain aircraft (VH-JCH) who shut down the right engine during flight after observing RPM fluctuations and other instrument abnormalities (it was later established that its crankshaft had failed in a manner very similar to that involving MZK, but had remained dogged) suggested that speed fluctuations and a general reduction in ground speed would be expected in the case of MZK if after fracture, the left engine crankshaft remained dogged for a period with continued engine operation.
- It is logical that a further sudden reduction in MZK's ground speed at time 1847:15 (see fig. 1 on page 13) was associated with a reduction in engine power. However, the recorded radar track evidence is not sufficient to conclude the extent of the power loss or which engine the loss was associated with. The radar evidence does not show the orientation of the aircraft in space; rather, it records the position of the aircraft relative to the ground. Any change in aircraft attitude does not immediately cause a deviation in track. Therefore, it would be overly simplistic to suggest that, because the aircraft track deviated approximately 19 degrees right over a period of some 30 seconds, the only explanation is that there was a power reduction or loss within the right engine. Any analysis of the likely combined response of an aircraft, autopilot and pilot following an engine failure is difficult as there are numerous possibilities, including the nature of the engine failure itself. Also, the radar data should be considered not in isolation, but in conjunction with the recorded audio data and the metallurgical facts. The absence of any information regarding the actions of the pilot at this time also bears importantly on any conclusions that might be drawn. It was for all those reasons that ATSB Report 200002157 did not consider the track deviation to be persuasive of either a right first or left first engine failure scenario. Rather, the ATSB placed greatest weight on the factual metallurgical evidence from each engine and the engine operating conditions required to produce that evidence.
- Advice from the BoM as reported in ATSB Report 200002157 was that the actual wind at 6,000 ft during the period of the accident flight was 160 degrees T at 20 kts. Later advice provided by the BoM, after ATSB Report 200002157 was released, was that the wind was 150–170 degrees T at 15–20 kts. That meant that for a groundspeed of 167 kts, the true airspeed was 147–152 kts. The groundspeed of the aircraft reduced from 177 kts to 167 kts after 1847:15. Performance data provided by the engine and aircraft manufacturers indicated that the aircraft could achieve a true airspeed greater than 147 knots on one engine, but that at least 375 brake horsepower engine output was required. This power could be achieved only if the engine was operated beyond the normal limits and in conditions where heavy detonation was likely. (As indicated earlier in this report, the damage to the right engine could only have arisen if that engine was operated beyond the normal limits.) The rated maximum power output of the Lycoming L/TIO-540-J2B engine is 350 brake horsepower. However, it is possible for the engine to produce greater than rated output when it is operated at certain

combinations of manifold pressure, RPM and fuel mixture². The TIO-540 series Lycoming operators manual³ included data for operation up to 46 inches of manifold pressure when the engine is operated at 2575 RPM. The chart indicated that at 2575 RPM, 46 inches of manifold pressure is equivalent to 375 brake horsepower. Analysis of recorded air traffic control audio data indicates that prior to top of descent, one or both engines of MZK were operating at 2400 RPM. Sheet 2 of the chart included data for operation up to 40 inches of manifold pressure when the engine is operated at 2400 RPM. There was no data in the operator's manual regarding horsepower at manifold pressure settings greater than 40 inches at an RPM of 2400. The chart suggests that Lycoming does not recommend operations at manifold pressures greater than 40 inches at 2400 RPM. However, that does not mean that the engine cannot operate at greater than 40 inches manifold pressure at that RPM. Indeed, operation of the engine under those conditions was demonstrated at a US engine test facility and the operating parameters recorded. In one demonstration, the engine was operated at 2397 RPM, 45.8 inches manifold pressure, and produced 359 brake horsepower. (See Attachment D for screenshots of parameters for engine operating at 2400 RPM and manifold pressures greater than 40 inches and Attachment F for a more detailed explanation of the maximum single-engine speed achievable by VH-MZK.)

- It is important to emphasise that there is no information available regarding the pilot's actions around time 1847:15. The recorded propeller RPM values reflected engine RPM at specific times. They do not indicate what the RPM might have been at any other time. Therefore, and as stated in ATSB Report 200002157, p 114:

Additional information regarding such issues as:

- the maximum power that was set on the right engine and timeframe over which that applied,
 - whether the power increase was made incrementally or as a single step, and
 - the operating temperatures reached and their rate of increase, would have enabled a better understanding of the pilot actions and responses regarding the right engine operation. The [right engine] open cowl flaps may indicate an attempt by the pilot to respond to the right engine overheating and malfunction.
- The nature of the damage to the right engine indicated that once the No. 6 piston was holed, the engine was still capable of operating, but at reduced power.
 - From the top of descent to time 1858, the aircraft maintained a rate of descent of about 400 feet per minute. This was consistent with a normal descent for the aircraft to arrive at Whyalla Airport at circuit height. At 1858, the rate of descent increased to 650 feet per minute. It remained around that rate until the aircraft disappeared from radar coverage two minutes later: 650 feet per minute was not a normal rate of descent and could not have been intended because, if maintained, the aircraft would have reached circuit height well short of Whyalla. The aircraft could not have maintained 650 feet per minute rate of descent without some power being available from one or both engines. The propeller on the left engine was in the feathered position at impact while the propeller from the right engine was in a normal

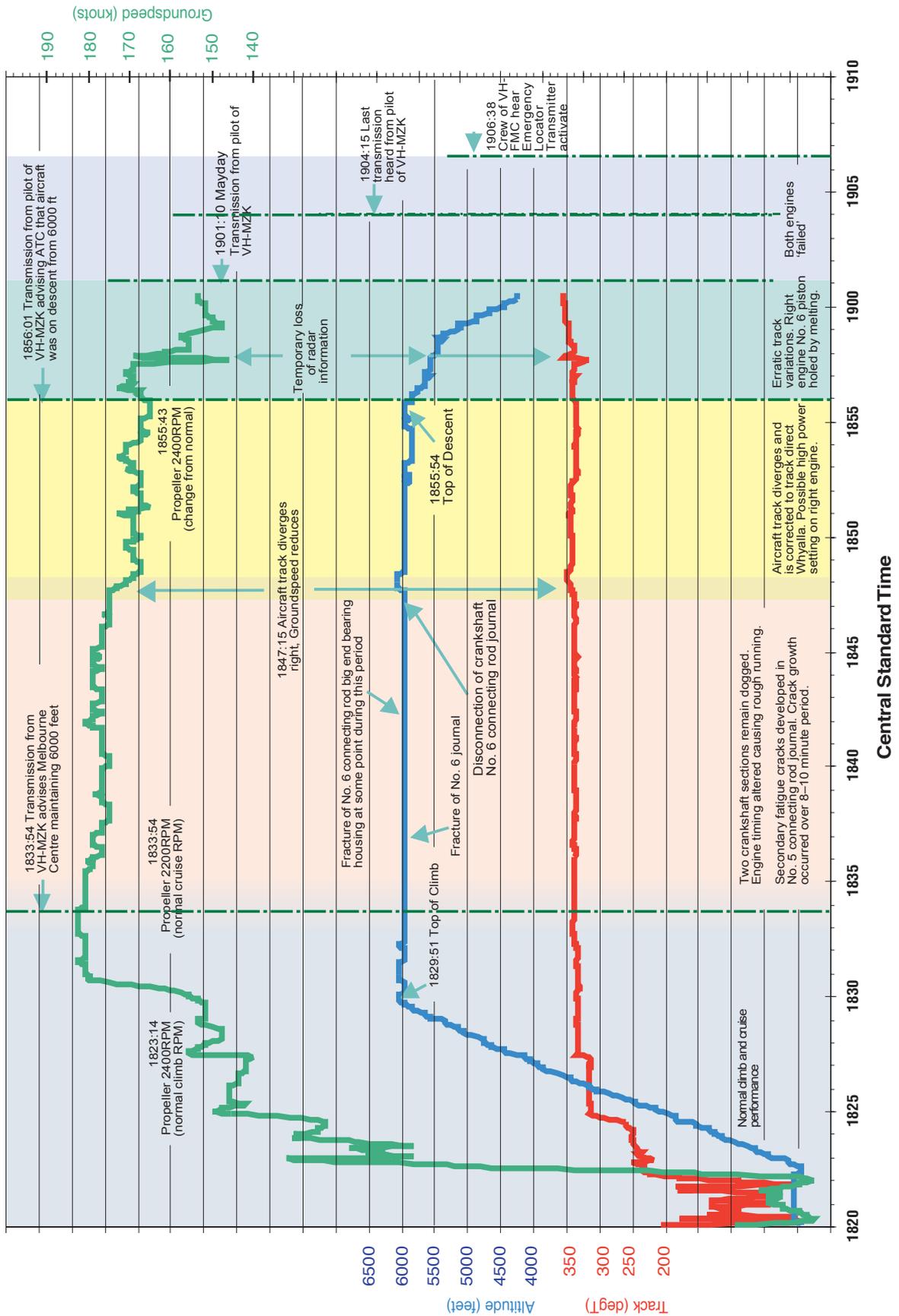
² Engine test stand data recorded in the US in November 2002 included the example of a TIO-540 engine producing 365 brake horse power (104 per cent of rated power) at 43.3 inches manifold pressure, and 2588 RPM at full rich mixture setting. The test facility operator did not indicate that the engine was being over-stressed when operating under these conditions. Leaning to best power (maximum EGT), while increasing the power output from the engine beyond 365 brake horse power, would likely have led to engine damage. (See Attachment D)

³ See Figure 3-36 Sea Level and Altitude Performance -TIO 540-J,-N series - Sheet 1 of 3 chart.

operating pitch range and rotating at impact. That information suggests that the right engine continued to operate at reduced power until the aircraft struck the water.

- As indicated in ATSB Report 200002157 (pp 114 to 116), very little was known regarding the precise nature of the information the pilot had concerning the engines, the behaviour of the passengers in response to the developing situation, and the pilot's response to the increasingly serious and very stressful situation that required him to fly the aircraft, manage the developing engine malfunction situation, and manage the passengers. There are many possible scenarios and explanations about what the pilot could and should have done. However, because the information available was so limited, no conclusions regarding the pilot's actions could be drawn with any certainty. The ATSB remains strongly of the view that the pilot should not be 'blamed', as was emphasised when ATSB Report 200002157 was released on 19 December 2001.

Figure 1:
VH-MZK sequence of events based on recorded radar and audio data and engine failure analysis



Copy of Fig. 53 from ATSB Report 200002157 amended to correct minor typographical errors.

Note: The actual groundspeed did not vary significantly between 1847:15 and top of descent. The graphical information above was derived from a combination of radar data from two sensors. One of the radar sensors provided intermittent data during this period and consequently shows fluctuations in groundspeed. (see pp 62 and 169).

Because the aircraft was not equipped with a Flight Data Recorder or a Cockpit Voice Recorder, the amount of factual information regarding the sequence of events was limited and some aspects regarding the accident will never be known conclusively. Scenarios examined by the ATSB during the course of the ATSB investigation, and during the coronial inquest included:

- **The engines were damaged during the flight departing Whyalla at 1700 to Adelaide earlier in the evening before the accident flight.** There was no metallurgical evidence that supports giving any weight to this scenario. It is also most unlikely that the pilot would have continued with the next flight without taking any action if he had experienced symptoms of engine problems during the previous flight and another aircraft was available in Adelaide. The left engine fatigue crack had commenced many flights before and would not have been apparent. Had the right engine been holed before the accident flight, this would have been evident.
- **The No. 6 piston right engine was damaged during the accident flight climb.** The performance of the aircraft recorded on radar shows a normal rate of climb indicative of normal two-engine operation and no abnormalities prior to 1837:41 (8 minutes after the top of climb by which time engine power settings are normally reduced). While it is possible for mild detonation to occur at the climb power settings used by the operator, the damage sustained to the right engine could not have happened as a result of mild detonation. Evidence against this notion is also the absence of a history of melted pistons of the operator's engines, and the lack of damage evident during borescope inspections of the pistons of the other Piper Chieftain aircraft in the operator's fleet following the accident. Evidence given during the coronial inquest that MZK's fuel flow gauges were under-reading would make MZK less likely to experience detonation in the climb than other Chieftains in the fleet.
- **Detonation occurred during the climb and the piston was holed shortly after top of climb.** The evidence relied on to support this notion is the track deviation to the right at 1847:15 and the assertion that the aircraft could not maintain the groundspeed seen after 1848:15 on one engine. It is argued that the groundspeed after 1848:15 must have been achieved using high power from the left engine supplemented by moderate power from the right engine. It is also suggested that the track deviation to the right at 1847:15 was the result of the pilot reducing power on the right engine at that time. It is then argued that the fluctuation and reduction in groundspeed between 1837:41 and 1847:15 is consistent with an unspecified problem with the right engine.

Against this, there is no evidence to identify or explain why the No. 6 piston in the right engine was holed, with heat damage via detonation to other cylinders. The evidence does not implicate the spark plugs, magneto-to-engine timing, the operator's climb power setting, a blocked fuel injector, cross-tracking magnetos, overhanging helicoil tang or contaminated fuel.

A variation of this scenario is the development of a small hole in the No.6 piston early in the flight which then grew to a larger hole later. However, it would be impossible to reheat the piston to its melting point because of the leakage of combustion chamber gases through the hole.

If the No. 6 piston hole was formed about 1837:41, it is not explained why the engine was this hot 8 minutes into the cruise, well after power was reduced from climb power. A hole at this stage (about 27 minutes before impact) would have led to oil venting and likely engine seizure well prior to impact even if power was reduced in the interim.

For this scenario to be correct, it is necessary to find that the pilot either did not identify a prolonged excessive right engine cylinder head temperature during a relatively routine, low-workload phase of the flight, or failed to take sufficient corrective action to rectify the over-temperature condition, that would have been very apparent given that the instrumentation is sourced from the No. 6 cylinder.

- **Right engine failed late in cruise but before the left engine failed.** For this scenario to be correct, again it is necessary to find that the pilot either did not identify a prolonged excessive right engine cylinder head temperature during a relatively routine, low-workload phase of the flight, or failed to take sufficient corrective action to rectify the over-temperature condition. This scenario also does not explain the speed and track variations earlier in the flight.

Moreover, the statistical remoteness of two independent and unrelated engine failures during a single flight argues compellingly against any right engine failure first scenarios.

Importantly, the detonation damage and overheating evident in the right engine was most unlikely to occur at cruise power settings.

- **Sudden left engine crankshaft fracture at 1847:15.** For the left engine to have suddenly failed at 1847:15, the groundspeed variations between 1837:41 and 1847:15 must be explained. As stated in Section 3 above, information from the BoM, along with recorded radar data from flights before and after the accident flight indicated that stable atmospheric conditions existed and that aircraft operating normally maintained steady cruise speeds. Therefore, the only explanation for the groundspeed fluctuations between 1837:41 and 1847:15 is that the aircraft was not performing normally during that time, arguing against the crankshaft fracturing suddenly at 1847:15. The metallurgical evidence from the crankshaft, (the other main bearing fatigue crack striations, and bluing of the metal in the vicinity of the fracture) and the symptoms reported by the crew of VH-JCH provide a good explanation of the groundspeed fluctuations between 1837:41 and 1847:15.
- **The left engine timing was not adjusted properly when the engine was fitted to the aircraft in February 2000 and the crankshaft damage occurred as a result.** This theory does not involve a manufacturing defect, but rather links initiation of the fatigue crack to abnormal combustion loads. While the physical evidence supports the contention that the left engine had experienced abnormal combustion loads, there is incontrovertible evidence that the fatigue crack progressed over a period of about 50 engine start/stop cycles (flights), placing crack initiation in early May 2000. If the crack had initiated in February 2000, many more start/stop cycles would have been involved. (See A2 pp 40 and 84).

ATSB Report 200002157 included detailed evaluation and analysis regarding the behaviour of the left engine No. 6 connecting rod big end bearing. The report also included several new safety recommendations, including one regarding the use of anti-galling compounds on the backs of connecting rod bearing inserts and one regarding conditions under which combustion chamber deposits that may cause preignition are formed.

ATSB Report 200002157 described the mode of bearing 'failure' that was apparent to the ATSB from the bearing examination. In its use of the term 'failure', the report was not implying that the bearing was 'destroyed' or that it 'broke down' in the conventional sense around 50 flights before the accident, but rather that it failed to operate as designed (the potential for misinterpretation of technical descriptors such as the term 'failure' was cautioned in Section 1.17, p 35 of ATSB Report 200002157). Of course, any bearing destruction or liberation of most of the bearing material 50 flights before the crankshaft failed or in the period from then to the maintenance conducted on 30 May 2000, the day before the accident, would cause some instances of oil pressure fluctuations and bearing fragments in the oil filter. These were not reported in company trend monitoring or maintenance documentation. The ATSB conclusion was that some combination of reduced retention forces due to the use of anti-galling compound and increased operational loads brought about through deposit induced preignition, damaged the bearing to the extent that it allowed forward movement by as little as 0.5 mm to bring the bearing edge into contact with the rotating crankshaft journal transition to the fillet radius, and caused abnormal thermal stress at the location where the fatigue crack originated. Further justification for the bearing having failed in this manner is included in the report at Attachment C.

During the inquest there was considerable discussion about the operation of the density controller and regarding the term 'overboost'. It became clear to the ATSB that there was a general lack of understanding of these issues, not only by those involved in the inquest, but by the broader aviation community. In particular, a number of myths were perpetuated throughout the inquest, specifically that:

- the density controller would not allow the engine to generate more than the rated horsepower of the engine (in this case 350 bhp), and
- the density controller would not allow an engine overboost situation to occur.

To assist the Coroner in understanding that over 350 bhp could be generated, the ATSB prepared and submitted an explanation of engine overboost and operation of the turbocharger control system. The document has been independently reviewed by the US National Transportation Safety Board (NTSB). A copy of that explanation is at Attachment E.

8 MAXIMUM SINGLE ENGINE SPEED ACHIEVABLE

Another issue that was examined at length during the inquest was the maximum single engine speed achievable by the aircraft. The ATSB position regarding the maximum power output the engine could provide was based on performance data provided by the aircraft and engine manufacturers, supported by propeller efficiency data and explanations of turbocharger operation (see Section 7 above) and radar data interpretation. A detailed explanation of the ATSB position regarding the maximum single engine speed achievable is at Attachment F.

9.1 Crankshafts

In December 2002, CASA issued Airworthiness Directives AD/LYC/107 Amdt 2, Crankshaft Replacement, and AD/LYC/108, Crankshaft Material Inspection that required compliance with the Mandatory Service Bulletins issued by Textron Lycoming with respect to crankshafts in six-cylinder turbocharged engines (Service Bulletins 550, 552, and 553). In view of that action, the ATSB does not consider that there is any further safety action warranted concerning those matters at the time of the release of this supplementary report.

9.2 Engine bearings

CASA has advised that it is continuing its investigation concerning possible problems with bearings installed in Textron Lycoming piston engines. The investigation is not limited to high-powered piston engines, but involves lower powered engines as well. CASA has advised the Federal Aviation Administration (FAA) of its ongoing investigations and concerns in this area and sought the ongoing cooperation of the FAA (as the aircraft certifying authority), the engine and aircraft manufacturers. The ATSB strongly supports this safety action by CASA. In addition, in response to ATSB Recommendation R20010255, the FAA advised in August 2002 that it will:

...review the effect of anti-galling compound relative to connecting rod bearing insert retention and rotation on Lycoming engines. The counter rotation capacity derived from the 'crush fit' forces and the tang/slot arrangement will be assessed, and if found to be inadequate, the appropriate changes to the Textron Lycoming design and Service Instructions will be issued'

The ATSB has classified the recommendation as 'Monitor' and has sought an update from the FAA.

9.3 Combustion chamber deposits

The ATSB had already recommended (R20010254) that the FAA (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. The need for such a recommendation was reinforced by the evidence of the chemical engineer retained by the Coroner. The Coroner's expert agreed that lead oxybromide deposits were present in the left engine, but did not believe that what he observed from the accident aircraft was sufficient to cause preignition. The quantity present after the accident is not relevant, as the ATSB had suggested that lead oxybromide-induced preignition occurred around 50 flights earlier. The Coroner's expert also opined that the subject of combustion is complex and investigation into the nature and affects of combustion chamber deposits requires a more scientific and thorough approach than that employed by the ATSB. The ATSB fully agrees that such an approach to this matter is required. The ATSB does not have the resources to carry out a scientific analysis of deposit formation, and therefore it issued Recommendation R20010254. In response to the recommendation, the FAA advised in August 2002 that it was:

...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.

The ATSB has classified the recommendation as 'Monitor' and has sought an update from the FAA.

9.4 Aircraft system monitoring equipment

In July 2002, the ATSB issued a further safety recommendation, R20020149, to recommend that CASA examine whether the potential safety benefits from devices such as those that monitor and record aircraft fuel and engine system operation are sufficient to warrant them being required in general aviation aircraft used in air transport operations. After subsequent exchanges in correspondence between the ATSB and CASA, the ATSB received a final response on this matter from CASA on 16 April 2003 which, in conclusion, stated that:

CASA does not consider the potential safety benefits of fitting devices that monitor and record aircraft fuel and engine system operation are sufficient to warrant their fitment being made mandatory. This construct does not imply any concerns with operators/owners voluntarily fitting this equipment.

The ATSB is monitoring the uptake on voluntary fitment of such equipment and is also monitoring other occurrences that may have been averted through the use of such equipment. As such, the ATSB has classified the CASA response to this recommendation as 'Monitor'.

The ATSB has noted the comments by the Coroner with regard to multi-probe engine monitoring systems that he 'cannot to be satisfied that the use of a multi-probe gauge or knock sensor would have prevented this accident'. Multi-probe engine monitoring systems are one of a number of systems that fall within the description of 'devices that monitor and record aircraft fuel and engine system operation'. Multi-probe engine monitoring systems can provide very comprehensive information on engine operation compared to the standard instrumentation fit in most piston engine aircraft. However, the value of such systems was of value only if the operator (pilot) accurately interpreted the information presented. During the inquest, there were examples quoted where multi-probe systems had likely prevented serious engine damage or failure. It was also apparent, however, that without proper training in interpreting the information such systems provide, there was real potential for inappropriate response action by the operator. The ATSB believed that extensive additional training in piston engine theory and operation would be required if multi-probe systems became a requirement. Further, a multi-probe gauge would increase crew workload, particularly in single-pilot operations. On the other hand, the standard engine instrument fit of cylinder head and exhaust gas temperature gauges provide a high level of engine reliability provided engine operation is in accordance with clear procedures specified by aircraft manufacturers. On balance, the ATSB does not consider that there is sufficient justification at this time to issue a safety recommendation regarding the fitment of multi-probe engine monitoring systems.

9.5 Engine operating procedures

The ATSB notes the CASA advice in its submission to the Coroner regarding the need for the review of the engine operating procedures set out in the various versions of the pilot operating handbooks (POH) and flight manuals for Piper Chieftain aircraft. The ATSB

report highlighted differences between the Piper Chieftain POH and the Textron Lycoming IO/TIO-540 operator's manual. Engine test stand data recorded in the US at the request of the ATSB indicated that mild detonation was likely to occur when less than full rich fuel flow is used in the climb. Consequently, the ATSB believes that possible safety issues with operating Piper Chieftains below full rich in climb and above 40 inches of manifold pressure at lower engine speeds (eg 2400 and 2200 RPM) require particular attention. In October 2000, the ATSB had recommended (R20000250) that CASA 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.

On 14 February 2003, the ATSB wrote to CASA noting the comments in its submission and seeking its confirmation that the matter of the differences between manuals was being raised with the FAA and was being dealt with appropriately to ensure that clear and unambiguous engine operating procedures are promulgated. On 19 March 2003, the ATSB received a response from CASA, advising that the Authority had raised the concerns with the FAA but the FAA did not see any reason to suspect that the Piper approved lean of peak operating procedure resulted in detonation damage in the Whyalla Airlines accident aircraft engines. Of course, ATSB Report 200002157 pointed to preignition in the left engine not detonation, with detonation in the right engine the result of the response to a failure of the left engine.

Further correspondence regarding engine operating procedures was sent to CASA on 9 October 2003 (see Section 10).

9.6 Provision of guidance on ditching to pilots of smaller aircraft

The ATSB had recommended (R20010258) that CASA educate industry on procedures and techniques that may maximise the chances of survival of a ditching event. Part of the education program should include the development of formal guidance material of the type contained in the UK CAA General Aviation Safety senses leaflet 21A 'Ditching'. In April 2003, CASA issued Civil Aviation Advisory Publication (CAAP) 253-1(0) – Ditching.

The ATSB has classified the recommendation as 'Closed – Accepted'.

10 SAFETY ACTION IN RESPONSE TO RECOMMENDATIONS MADE BY THE CORONER

As part of his findings, the Coroner made five recommendations. Those recommendations, and the ATSB response to each, are as follows.

- 15.62. *Engine operating procedures set out in the various versions of the Pilot Operating Handbooks and Flight Manuals for Piper Chieftain Aircraft be reviewed with the object of ensuring: (a) accuracy of the detonation limiting conditions; and (b) clarity of all engine operating procedures.*

ATSB comment

Section 9, above, of this report included the advice the ATSB had received from CASA following its approach to the FAA regarding flight manual differences. The FAA response did not appear to address specifically the two components of the Coroner's recommendation.

In this regard, the ATSB wrote to CASA on 9 October 2003 in support of the Coroner's recommendation and requesting that CASA:

- a. Seek further clarification from the FAA regarding detonation limiting conditions, particularly with respect to the engine climb power settings contained in the various versions of the PA-31 Pilot's Operating Handbook, and
- b. Examine what steps can be taken to ensure that the operating procedures used by operators of fleets including more than one model of a particular aircraft type take account of different versions of operating manuals and handbooks that might apply to those models, specifically with regard to engine operating procedures.

- 15.63. *CASA and the ATSB consider how lines of communication could be improved so that communication continues to flow even in circumstances where litigation might be threatened.*

ATSB comment

Under Part 2A of the Air Navigation Act, courts could gain access to sensitive ATSB investigation information through a subpoena. Under the Transport Safety Investigation (TSI) Act, introduced on 1 July 2003, the Executive Director of the ATSB must sign a certificate for any restricted information to be released to courts. Such a release can only be made if the disclosure is not likely to interfere with any investigation. Therefore, overseas bodies can have confidence that sensitive information will be protected and as such they may be more willing to provide information to the ATSB. In addition, the TSI Act prevents the use of ATSB reports in criminal or civil proceedings (except a coronial inquiry) in Australia.

The ATSB enjoys a very good relationship with its counterparts in other countries, and is regularly engaged in air safety and accident/incident related activities with overseas investigation bodies, regulators, and manufacturers. While the level of cooperation from these bodies is normally very high, there have been a few instances when that has not been the case. One such example is when litigation is threatened or in progress, as was evident during the Coroner's inquest.

The ATSB agrees that in some instances the interests of safety could be improved with a better flow of information, but recognises that there may be practical limitations that exist in other countries or in multilateral bodies, and over which the ATSB has no control. Nevertheless, the ATSB will raise this issue with its counterparts as part of the ongoing close working relationships that presently exist.

- 15.64. *CASA consider how the development of On-Board Recorders suitable for use in light commercial aircraft might be facilitated. Should fitment of On-Board Recorders in these aircraft become feasible, I further recommend that their use be mandatory in the carriage of passengers for payment, or at least in RPT operations.*

ATSB comment

ATSB recommendation R20020149 discussed in Section 7 above addressed on-board system monitoring and recording devices for aircraft engaged in air transport (fare paying passenger) operations. (See also ATSB comments regarding the Coroner's paragraphs 15.27 to 15.32 at Attachment A, page 104.)

- 15.65. *The ATSB and CASA undertake a research program to ascertain whether it is feasible to fit a self-deploying ELT system to all aircraft engaged in carriage of fare-paying passengers, whether by RPT or charter operations, over water. If it is feasible, the use of such instruments in those circumstances should be mandatory.*

ATSB comment

R20000249 stated that:

The ATSB recommends that the Civil Aviation Safety Authority ensure that Civil Aviation Orders provide for adequate emergency and life saving equipment for the protection of fare-paying passengers during over-water flights where an aircraft is operating beyond the distance from which it could reach the shore with all engines inoperative.

The ATSB considers that self-deploying ELTs are a component of 'emergency and life saving equipment' and that CASA, AusSAR (AMSA) and Defence are best placed to progress this issue.

CASA advised that it 'is sympathetic to recommendation R20000249 but wishes to consult more widely with the aviation community and other stakeholders including ATSB before taking further action'.

- 15.66. *CASA amend the Civil Aviation Orders to make it mandatory that aircraft should carry lifejackets and/or a life-raft for the protection of fare-paying passengers whenever the aircraft is operating beyond the distance from which it could reach the shore with all engines inoperative.*

ATSB comment

Section 4.4 of ATSB Report 200002157 detailed safety recommendations (R20000248 and R20000249) issued by the ATSB on 30 October 2000 concerning the carriage of life jackets and emergency and life saving equipment.

Recommendation R20000248 was accepted by CASA and had the effect of amending Civil Aviation Order 20.11 to require all aircraft on over-water flights engaged in passenger carrying operations to carry life jackets.

Recommendation 2000049 dealt with 'emergency and life saving equipment'. The following information was received from CASA on 10 February 2003:

In its response of 1 March 2002, the Authority advised that, on 21 December 2001, it had released a Discussion paper concerning the Carriage of Life Jackets and Other Issues Related to the Operation of Twin Engine Aeroplanes.

After consideration of the responses to that Discussion Paper, the Authority has decided not to amend the Civil Aviation Orders.

However, a number of issues were raised in the responses which the Authority has considered in the context of proposed CASR Part 121B. CASR Part 121B relates to Air Transport Operations – Small Aeroplanes. The draft regulations included in a Notice of Proposed Rule Making (NPRM) released by CASA in July 2003 for this Part includes various requirements for emergency cabin lighting and carriage of items such as of life jackets and other flotation devices, life rafts, ELTs (Emergency Locator Transmitters) or EPIRBs (Electronic Position Indicating Radio Beacons) and other survival equipment, including provisions.

ATTACHMENTS

Attachment A: ATSB response to the SA Coroner's findings of 24 July 2003

A1. Overview

The South Australian State Coroner's findings on the inquest into the fatal accident involving Whyalla Airlines Piper Chieftain VH-MZK were delivered on 24 July 2003, 18 months after the ATSB released its final investigation report and more than 3 years after the accident. Millions of dollars were spent on the inquest process and a significant focus of the Coroner's conclusions was a critique of the ATSB report and the proposal of an alternate accident scenario. Scant acknowledgment was given to the complexity of the initial investigation and dearth of data including no survivors, no aircraft data recorders, a heavily damaged aircraft that had been corroded by a week on the seabed, limited information from the engine manufacturer and other parties in the US, and the fact that the engine manufacturer only listed the MZK left crankshaft among those potentially affected by a manufacturing defect on 16 September 2002, 9 months after ATSB Report 200002157 was released.

When the ATSB was able, in March 2003, to destructively test both sides of the fatigue crack in MZK's left crankshaft, no evidence was found of a material defect that under normal engine operating conditions could have initiated the crack. Surprisingly, the Coroner concluded that that the ATSB's 50 page documented test report (Attachment C) 'takes the matter no further'. Documents obtained by the ATSB subsequent to the inquest indicate that this conclusion was not based on any specialist review or advice (see A3 p 93 for further explanation). It is therefore apparent that the Coroner relied on earlier opinion, including from the US firm acting for the parties to US civil damages litigation, that there may have been a significant non-metallic 'inclusion' in the steel that had 'dropped out', concluding that 'such an inclusion was not found at the origin of the fracture site but this does not exclude the possibility that it was lost during the fracture process'. The Coroner also relied upon the circumstantial evidence of service bulletins issued in 2002 indicating a potential manufacturing defect (a so called 'honeycomb feature') without acknowledging that a substantial majority of potentially affected crankshafts tested were not defective. The types of suggested defect in the steel – seams of massive high temperature oxide inclusions; one significant non-metallic inclusion that had dropped out; and a honeycomb feature; were all quite different and yet are each given weight in the Coroner's findings despite the ATSB testing results.

In contrast to the ATSB's accident scenario of the left crankshaft failing due to the fatigue crack and then the right engine being damaged through detonation and overheating in response, the Coroner believes the right engine was damaged first as a result of detonation in the aircraft's climb phase and that the damage to the two engines was independent of each other. While the Coroner states that 'it is difficult to form definite conclusions on this issue' [of the right engine No. 6 piston holing and the heat damage to other pistons], he finds that signs of the detonation damage arose 8 minutes into the cruise phase and that 10 minutes later the pilot reduced power on the right engine causing a 'yaw' to the right. This scenario requires the pilot to have ignored an extended over-temperature condition in the No. 6 cylinder (on which the temperature probe is located) during a non-stressful part of the flight to enable a hole to become apparent well after climb power was reduced, and then allow the aircraft track to diverge 19 degrees to the right when he intentionally reduced power to that engine.

The main evidence cited by the Coroner as a mechanism for the early right engine damage is: the relatively mild detonation shown in a test engine in the US by Mr Braly, based on Whyalla Airlines' fuel and power settings that would not be sufficient to melt a piston; Mr Braly's example of a melted piston where a spark plug had prior damage (the Coroner, like the ATSB, finds MZK's spark plugs were not damaged before the accident), and a 2002 case of a melted No. 3 piston in Chieftain VH-LTW early in the climb that was not similar to the broader detonation damage seen in VH-MZK.

It is also most unlikely that a pilot deliberately reducing power to an engine would not be prepared to counter any yaw towards that engine. In the ATSB's view, the Coroner's alternate scenario has not been proven and given this, and the errors and omissions in his own findings (see below) despite the benefit of an extra 18 months and new evidence, the strident criticism of the ATSB and its scenario is regrettable.

The ATSB's 'no blame' focus has always been on future safety and on encouraging safety action and making recommendations to prevent accidents in the future. Based on the ATSB's professional judgement, having regard to experience with a number of failed engines in 2000 and 2001, the ATSB made recommendations concerning the need for further research and conservatism with regard to fuel leaning, engine deposits and anti-galling compounds ahead of scientific or legal 'proof' that these factors directly 'caused' the VH-MZK accident. Parties to the inquest seeking civil damages from the engine manufacturer in the US had a different agenda.

In the ATSB's assessment, among the errors and omissions in the Coroner's findings are the following (all paragraph numbers refer to the Coroner's findings, unless stated otherwise):

- (paragraph 1.1) the claim in the opening paragraph of the findings that the VH-MZK pilot's mayday call time was incorrectly recorded in the ATSB report as 1901:10 rather than 1901:14 (an immaterial difference of 4 seconds) is both petty and wrong. The time cited by the Coroner was that provided by Airservices Australia derived from a copy made of the original tape without time injection, whereas the time used by the ATSB was based on multiple replays and checking of the original air traffic control tape (with time injection) by ATSB specialist investigators;
- (paras 5.9, 5.40, 9.21 & 12.40) the assertion that the ATSB had postulated that the left crankshaft bearing had been in a process of decomposition and progressive failure over at least the last 50 flights whereas the ATSB had emphasised that the bearing movement around 50 flights before the accident, when the fatigue crack initiated, was not the result of such 'destruction' but failure to operate as designed by an edge touching the crankshaft surface. This interference would not lead to an expectation of obvious metal particles in engine oil before the accident flight on 31 May 2000 when destruction of the bearing is likely to have occurred;
- (paras 9.39, 9.56, 13.14 & 14.100) suggesting there is an inconsistency with the ATSB's view that detonation occurred in the right engine and the carbonaceous deposits found that were indicative of a rich fuel setting. A fuel setting can be rich (more fuel than the stoichiometric mixture) but not full rich. Detonation can also occur with a full rich fuel setting;
- (paras 9.50, 9.53, 14.51 & 14.53) there is no acknowledgment of the ATSB's submission that a density controller operates at full power (at 2575 RPM) and can be properly set to up to 46.5 inches manifold pressure (MP) at ground level. At a lower RPM such as 2400, particularly if not full rich, and at altitude, high manifold pressures could provide engine power above the rated 350 brake horsepower without

the density controller malfunctioning. The Coroner observed first hand an engine operating on a test stand at 2400 RPM and 45.8 inches MP delivering 359 brake horsepower (see Attachment D fig. 4). This is in stark contrast to the Coroner's apparent acceptance of other evidence from the test stand operator that the engine could only deliver about 340 brake horsepower at 2400 RPM. It is also noteworthy that the density controller does not prevent engine detonation;

- (para 10.40) no mention is made that of crankshafts listed in the service bulletin and tested for a possible material problem, almost 70 per cent were found to be unaffected;
- (para 11.66) the criticism that the similarities between the crankshaft fractures of VH-JCH and VH-MZK should have been clearly apparent to the ATSB is unwarranted because JCH was examined by the ATSB (after the MZK report was released) and the ATSB highlighted the similarities to those assisting the Coroner;
- (paras 14.21 to 14.24, 14.74 & 14.105) in dismissing the ATSB's conclusion that the VH-MZK crankshaft remained dogged for some time after its complete fracture in favour of an immediate cessation of the left engine, the Coroner omits incontrovertible metallurgical evidence relating to cracks in other journals and the significance of about 20,000 'striations' in secondary fatigue cracks (see ATSB Report 200002157 p 60) and metal 'bluing' and does not give due weight to the evidence of other dogged crankshafts such as VH-JCH, VH-SJQ and VH-LAN (see A2 p 41);
- (para 12.21) a key omission here is acknowledgement of the ATSB's contention that the quantity of lead oxybromide potentially relevant to the initiation of the left crankshaft fatigue crack through some combination of preignition and bearing slippage was the quantity about 50 flights before the accident not the quantity after the engine had been partially destroyed in the accident and had been on the seabed for over a week before being stripped down (cf paras 13.9 & 13.10);
- (para 12.62) omitting to note that thermally-induced cracking can occur radially as subsequently conceded by the Coroner's expert Mr McLean (transcript of evidence T4572 and T4574). There are many examples of such radial cracking that can be demonstrated;
- (paras 12.79, 12.97 & 12.103) omitting to note that the ATSB does not assert that deposit-formation on any pistons led to detonation or that lead oxybromide deposits were significant in causing the right engine damage. Mr Braly's statement that the debate about deposits causing detonation was a 'red herring' (which is adopted by the Coroner at para 14.95) is therefore not relevant. The ATSB reference to lead oxybromide was in the context of preignition in the left engine;
- (para 12.85) erroneously stating that the ATSB did not examine the fuel and engine settings used by Whyalla Airlines during climb (cf para 9.27 and page 75 of the Coroner's report where it is accepted that the ATSB did examine these);
- (para 12.119) omitting to note that the ATSB's destructive testing in March 2003 did look at both sides of the fracture and found no material defect that could have initiated the fatigue crack under normal operating conditions;
- (paras 12.122 & 13.15-13.18) omitting to mention that the 'tiresome' circumstances of the US testing being halted led to the ATSB requesting the engines back to test and that a section 19CC legal mechanism was first discussed (positively) with the Coroner's Counsel Assisting to this end. Despite these discussions, the Coroner authorised the US testing to be resumed without independent witnesses and with no

advice to the ATSB, in contrast to the Coroner's formal order of 3 January 2003 that the ATSB was 'entitled to attend any testing which takes place on 13 January 2003 or thereafter'. The ATSB offered to provide sworn evidence on these issues after an invitation from the Coroner's solicitor to do so but the Coroner himself wrote a letter on 14 March 2003 stating that this would not be required as the ATSB's 'grievances do not touch upon the issue before me'. Nevertheless, the Coroner's findings do address the matters raised by the ATSB;

- (para 13.5) omitting to mention that the draft ATSB report had a very different failure sequence involving independent engine failures which was discarded when further evidence became available and additional analysis was undertaken. This shows that the ATSB had not set out to prove a single hypothesis (and, of course, in contrast to the Coroner's suggestion, utilising statistical analysis is a well-established tool in a scientific approach);
- (para 13.21) the harsh criticism of the ATSB for not destructively testing the left crankshaft fracture in 2000 and 2001 should be seen in the context of service bulletins indicating a possible manufacturing defect relevant to Australian registered Piper Chieftain aircraft being progressively issued in 2002 (ie after the December 2001 release of ATSB Report 200002157). The Coroner had control of the crankshaft in Adelaide from late March 2002 until early August 2002 and did not suggest or require such testing. Indeed, his Counsel Assisting advised the Coroner during inquest hearings on 2 August 2002 that:

I have made enquiry from engineers at the Adelaide University that we have commissioned, and they say that they do not need further access to any of these parts in order to complete their reports which they are in the process of doing.

On this basis, the Coroner allowed the engines to go to the US for further testing on behalf of parties to litigation there. In October 2002, after the 16 September 2002 service bulletin that first listed the MZK left crankshaft among those possibly affected by a manufacturing defect, the Coroner authorised destructive testing. Despite the ATSB's representations, this was not commenced until January 2003 and not concluded until the ATSB insisted on getting the crankshaft back and did its own (independently witnessed) further testing in March 2003;

- (para 13.25) as previously noted, the assertion that the ATSB's March 2003 destructive testing and April report 'takes the matter no further' is incorrect given that the ATSB report found no manufacturing defect in the left crankshaft steel that could have caused the fatigue fracture under normal operating conditions. The ATSB has been advised by the Coroner's Solicitor that the Coroner reached this finding without receiving expert advice on the ATSB's 50 page test report.

In summary, the ATSB believes that there are significant inconsistencies in the Coroner's findings. Many of the more technical and complex issues appear to have been not fully understood, and factual information in some critical areas was ignored. The ATSB scenario is significantly more likely than the Coroner's (which itself is similar to a scenario the ATSB suggested in a draft report and discarded after further evidence and analysis). Some aspects of the accident will never be known with certainty because of the dearth of evidence. This suggests that the strident criticism of the ATSB by the South Australian Coroner is inappropriate and lacks expertise and objectivity.

A2. Comments relating to the Coroner's Executive Summary

ATSB comments on the Coroner's Executive Summary refer to specific text from the executive summary (in italics).

Page vii: The failure of the right engine was caused by a holed No. 6 piston due to melting of the piston material. The ATSB postulated that when the left engine stopped at 1847:15, Mr Mackiewicz increased the engine power settings on the right engine to an inappropriate extent ('overboosting the engine') until, at about 1858 to 1900, detonation holed the piston and the right engine also failed. To that extent, the ATSB argued that the two engine failures were 'dependent' in the sense that the failure of the left engine was causally linked to the failure of the right engine.

ATSB comment

The ATSB report concluded that the pilot increased the power on the right engine in response to the failure of the left engine, and that at that increased power setting, severe detonation occurred. There is no information available regarding the actual engine power settings that were applied. However, the nature of the damage evident in the right engine could only have occurred while the engine was operating beyond the normal limits at greater than normal cruise power settings. The ATSB did not argue that the failure of the left engine was causally linked to the failure of the right engine but rather the reverse.

Page vii: Evidence of material defects in crankshafts in Textron Lycoming engines, the type fitted to MZK, did not begin emerging until a Special Advisory Bulletin was issued on 9 November 2000, although similar failures had been noted in Teledyne Continental engines, the brand fitted to Cessna aircraft among others, as early as April 2000.

ATSB comment

The 9 November 2000 bulletin issued by Textron Lycoming was addressed to individual customers who were known to have engines with particular serial numbers. Textron Lycoming advised CASA that no engines in Australian registered aircraft were affected.

The FAA did not issue any Special Airworthiness Information Bulletin or other document addressing Textron Lycoming crankshaft material during 2000.

Against that background, there were no grounds for the ATSB to consider that there may have been an emerging issue relating to a manufacturing defect in the crankshaft of the left engine of MZK before the release of ATSB Report 200002157 on 19 December 2001.

Page viii: The Civil Aviation Safety Authority (CASA) was advised that no Australian aircraft were affected by the 9 November 2000 Special Advisory Bulletin. On 1 February 2002, Textron Lycoming recalled about 400 engines, including one fitted to an identical aircraft to MZK, at around the same time the left engine was fitted to MZK. More extensive recalls were made on 16 August 2002 and 16 September 2002. Included among the approximately 3,000 engines on the 16 September 2002 list was the left engine in MZK. Each of these recalls was accompanied by a Mandatory Service Bulletin issued by Textron Lycoming which stated that the cause of the crankshaft failures was 'material related'.

ATSB comment

The ATSB took immediate action to obtain further information about each of these service bulletins as they were released. Textron Lycoming did not respond to the ATSB's requests for further information and the response from the FAA did not provide any clear indication as to the nature or characterisation of the 'defect'. Service Bulletin 553 only identified the left crankshaft of MZK as having a potential defect. It has been reported that of the

crankshafts that were subject to that service bulletin, about 70 per cent were not defective and were permitted to continue in service after testing. The results of testing by the Coroner's experts, the US firm acting for plaintiffs in civil litigation and the ATSB strongly indicates that the left crankshaft of MZK was part of the 70 per cent that were not defective.

Page viii: On 14 December 2001, only five days before the ATSB final report was published, the right engine in an aircraft identical to MZK failed. Upon inspection of the engine, it was established that the crankshaft had fractured, and the appearance of the fracture was strikingly similar to that of MZK's left engine crankshaft. The ATSB did not examine the fracture in detail, so the aircraft owner commissioned an examination by an engineer who concluded that the failure was caused by a material flaw, and not by thermal cracking.

ATSB comment

The ATSB did examine the failed engine and crankshaft from VH-JCH, and noted striking similarities between that failure and the MZK left engine crankshaft failure. The similarities, including the presence of lead oxybromide and the fact that the engine had continued to operate after the crankshaft had failed but remained 'dogged', were specifically pointed out to the Coroner's Counsel and Solicitor during an invited visit to the ATSB on 1 March 2002. The reason the ATSB did not conduct a detailed examination of the crankshaft was because the similarities were fully recognised and such an examination was not the most effective use of investigation resources.

The 'conclusion' by the automotive engineer commissioned by the owner that the failure was caused by a material flaw was his expressed opinion rather than a 'conclusion' based on demonstrated scientific fact.

Page viii: Professor King concluded that there was considerable doubt about the ATSB conclusion that lead oxybromides were present in sufficient quantity to be a significant factor in the failure of the left engine;

ATSB comment

The ATSB forwarded samples of deposits from piston crowns from the MZK left engine and four other engines that had experienced mechanical failure, including components other than crankshafts, to the Research School of Chemistry at the Australian National University (ANU). The ANU was asked to identify the composition of the deposits. Using a variety of techniques including x-ray powder diffraction, Raman spectroscopy and quantitative chemical analysis, lead oxybromide (Pb₃O₂Br₂) emerged as 'ubiquitous and abundant in the tan deposits', according to the ANU.

Professor King confirmed the presence of lead oxybromide in one of six samples taken from the left engine No. 6 piston crown. The Coroner acknowledged that the testing method used by Professor King to determine the nature of the compound was inferior to that used by the ANU. It is impossible for either Professor King or the ATSB to determine the quantity of lead oxybromides present in the combustion chamber at the time the fatigue crack initiated, 50 or so flights before the accident.

During the inquest, Professor King agreed with ATSB recommendation (R20010254) that further research was required into the significance of lead oxybromide deposits in piston engine operation.

Page viii: *Dr Zockel concluded that the damage to the left crankshaft was not caused during the combustion stroke of the engine and so abnormal combustion was irrelevant anyway;*

ATSB comment

Dr Zockel's conclusion that fatigue cracking in the No. 6 connecting rod journal could not have been caused by combustion gas loads is based on his proposition that only the journal deflects elastically in response to gas loads. His assumption is that this form of elastic response creates a compressive stress in the section of the journal fillet between the crankarms when gas loads are applied to the connecting rod journal. He advances his proposal further by claiming that fatigue crack growth cannot occur as a result of compressive stress.

The proposal is not backed by any substantive evidence or argument. It ignores the extensive references in the literature to combustion gas loads being a critical design parameter for crankshaft and engine design. In particular, the design of fatigue resistant crankshafts is based on the maximum gas load created during the operation of the engine. For example, Gassner and Schultz state that 'The assessment of crankshaft suitability as regards fatigue strength should therefore be based primarily on the maximum firing pressure.' Gas loads are primarily responsible for crankshaft bending. The report of Gassner and Schutz is based on extensive testing on strain gauged crankshafts in static engine loading tests and in operating engines. These tests were conducted at the Motor Industry Research Association in England and The Fatigue Strength Laboratory, Darmsadt.

The proposal ignores the flexure of crankshaft crankarms or webs during engine operation. The geometry of a Lycoming TIO-540 engine is different to the example shown by Dr Zockel when he gave his evidence. The lack of a main bearing between each connecting rod journal and the lack of journal overlap between connecting rod journals 5 and 6 will increase the severity of crankarm bending in the arm between con rod journals 5 and 6.

The proposal also ignores the fact that the initial plane of fatigue crack growth occurred at an angle of approximately 15 degrees to the short axis of the crankarm. That angle is consistent with the maximum bending load being applied after top centre (a condition that is consistent with combustion pressures and inconsistent with inertia loads).

The evidence of Mr Murphy who cited material from a Caterpillar publication, also contradicted Dr Zockel's evidence on this matter.

Page viii: *Dr Zockel also concluded that the failure of the left crankshaft was not caused by bearing failure or thermal cracking as suggested by the ATSB;*

ATSB comment

That conclusion went against the notion of lead oxybromide deposits, anti-galling compound and crankshaft metallurgy issues that formed the basis for the left engine failure sequence in the ATSB accident report, and which were developed by an ATSB investigator who is an expert in metallurgy and failure analysis with over 20 years practical experience in material failure analysis.

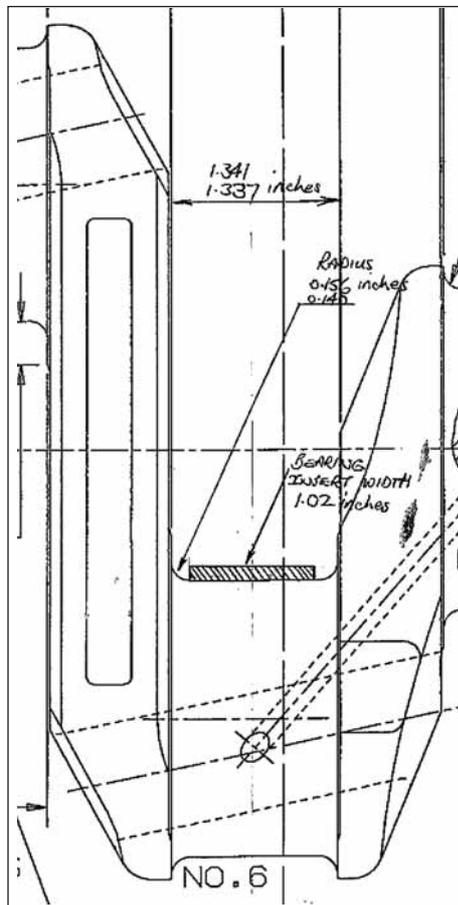
The ATSB identified two issues with respect to the bearing movement – combustion chamber pressures and the presence of an anti-galling compound. As indicated in ATSB Report 200002157, the ATSB was unable to determine the relative contribution of these issues. They formed the basis for safety recommendations R20010254 and R20010255 that further research into combustion chamber deposits and the use of anti-galling compounds was required. Those recommendations were accepted by the US FAA.

The axial location of bearing inserts in the big end housings of connecting rods may change during engine operation if the primary insert retention force (friction force created between the back of the insert and the bore of the housing by a designed interference fit) is reduced. The incorporation of materials such as anti-galling lubricants/compounds between the insert and housing will reduce the coefficient of friction between the insert back and therefore the friction force created by the interference fit. (Note: the bearing manufacturers state in technical publications that the locating tang/lug at the end of a bearing insert is provided to position the insert accurately within the housing. The tang/lug is not intended to prevent bearing insert rotation under the forces imposed on the bearing during engine operation.)

While the tang/lug is not designed to prevent bearing rotation over the operational life of the engine, it can resist some degree of bearing rotation force for limited engine operation. However, continued engine operation with the tang/lug providing the primary resistance to bearing insert rotation eventually results in the loss of the ability of the tang/lug to retain the bearing inserts in the centre of the big end housing. The potential range of bearing insert axial movement before contact between the connecting rod bolt guide section and the bolt clearance cut out following tang/lug failure, will result in contact between the edge of the insert and journal fillet radius.

Figure 1 below is included to clarify the clearance between the bearing insert and the transition of the journal surface to the fillet radius. The distance between the surfaces of the crank arms is 1.341-1.337 inches, the fillet radius is 0.156-0.140 inches, and the width of a bearing insert (p/n 74309) was measured and found to be 1.02 inches. The clearance between the insert edge and journal transition to the fillet radius is of the order of 0.022 inches (0.56 mm).

Figure 2:
Clearance between the bearing insert and the transition of the journal surface to the fillet radius



Contact between the bearing insert and the journal surface can create localised thermal strains in the journal surface causing short, axially oriented, cracks in the hardened surface of the journal.

The ATSB position, as stated in ATSB Report 200002157, is that lead oxybromide-induced preignition occurred in the left engine about 50 flights before the accident. The resulting excessive combustion loads triggered a failure of the bearing to operate as designed as detailed above i.e. movement of the bearing insert caused contact between the edge of the bearing insert and the transition of the journal surface to the fillet radius, causing localised heating which resulted in a thermal crack in the surface hardened zone. This, in turn, produced a stress concentration point for the initiation of the fatigue crack just below the nitrided case.

The nature and extent of the combustion chamber deposits varies continuously as engine operating conditions change, and from engine to engine. For example, the heavy detonation that occurred in the right engine during the accident flight was very likely to have removed any evidence of lead oxybromide deposits that may have been in the combustion chamber at the commencement of that flight. Thus, it would be unrealistic to expect the combustion chamber deposits at the time of the accident to reflect those that were present 50 flights before the accident. Further, the left engine No. 6 piston was slammed against the cylinder head during the engine failure sequence and the engine was submerged in sea water for 10 days before it was recovered and disassembled. Any or all of those factors could have contributed to a loss of deposit material from the piston crown.

The characteristics and behaviour of piston engine deposits such as lead oxybromide are very complex. Research in this area is beyond the resources of the ATSB, but goes to the heart of the ATSB recommendation to the FAA with respect to engine deposits. In accepting the recommendation, the FAA advised the ATSB that it was '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.'

Further information regarding bearing failure and thermal cracking is included at Attachment C.

Page viii:

Dr Powell and Mr McLean, both experts in metallurgy, found iron oxide inclusions at the nearby No. 5 journal of the left crankshaft of sufficient size to constitute a material defect capable of affecting the tensile and torsional strength of the crankshaft. Although similar inclusions were not found at the fracture site, they could have been lost during the fracture process;

ATSB comment

The sample from the left engine crankshaft No. 5 journal that was examined by Dr Powell and Mr McLean in August 2002 was the same sample that was taken from the crankshaft and examined by the ATSB in mid-2000 shortly after the accident and stored in a plastic bag in the intervening period. Initial testing of the sample by Dr Powell and Mr Hood revealed what they referred to as 'massive high-temperature oxide inclusions'. However, the 'inclusions' were subsequently removed after light grinding and polishing removed about 55 microns from the sample surface.

The ATSB believes very strongly that the 'massive high-temperature oxide inclusions' were oxidation products that had formed from exposure to the atmosphere during the period between the ATSB examination of the sample and that conducted by Dr Powell

and Mr McLean. Dr Powell and Mr McLean did not cut a fresh sample from the crankshaft. The specimen examined was that same one cut by the ATSB some 22 months previously and which had been stored in a plastic bag. This old specimen was initially examined by Dr Powell on 26 April 2002 and there was no report or record of 'massive iron oxide inclusions'. The specimen was examined by Dr Powell again on 30 May 2002 and there was no report or record of 'massive iron oxide inclusions'. Some 3 months later, after the sample was reground with 1200 grit and repolished, the sample was visually examined by Dr Powell and Mr Mclean on 27 August 2002 using a reflected light microscope and 'massive' grey coloured 'inclusions' were reported. Interestingly, during the inquest, Dr Powell gave evidence that the 'inclusions' were of such a size (about 1 mm) as to be visible to the naked eye. It is not clear why these 'inclusions' were not observed during Dr Powell's examination of the specimen in April and May 2002. Furthermore, if such artefacts had been present when the ATSB metallurgists examined the specimen in August 2000, there is absolutely no question that they would have been 'identified' as a major material defect at that time. It is also likely that the crankshaft would have failed much earlier than it did if such massive 'inclusions' existed.

It is beyond comprehension that the self-evident conclusion that the artefacts arose during storage was not recognised or accepted by the Coroner. It is also difficult to comprehend why such reliance was placed on this small and old specimen, when Dr Powell could have taken any number of fresh samples from the crankshaft while it was in his possession.

Destructive testing of the failed No. 6 journal in the US by Mr Hood, of McSwain Engineering on 13–16 January 2003 did not reveal any evidence of massive high-temperature oxide inclusions at, or in the vicinity of, the fatigue fracture location. Later testing of a 'freshly-cut' sample from the crankshaft was normal, and did not reveal any 'massive high-temperature oxide inclusions'.

Page ix: Mr Braly, an aeronautical engineer, aviator and manufacturer of aircraft components, also disputed that lead oxybromides were relevant to the failure of MZK's left engine, that the crankshaft could have remained 'dogged' as the ATSB suggested, that the aircraft could have maintained 167 knots groundspeed on one engine after 1847:15, and hence that the left engine failed first. He argued that the right engine suffered a partial loss of power at 1847:15, and that it was not until after 1858 or so that the left engine failed;

ATSB comment

The ATSB conclusions regarding lead oxybromides were based on the careful examination and consideration of the deposit and metallurgy information from the left engine of MZK, as well as 11 other engines that had suffered mechanical damage. The damage included failures to engine components other than crankshafts (eg. connecting rod big end and little end bearing housings, and main bearing fatigue cracking) that were typical indicators of high combustion gas loads and high piston temperatures. The common feature in these engines was the presence of tan coloured lead oxybromide deposits in the combustion chambers. (ATSB report 200002157, p84). Testing by the ATSB revealed that the deposits did not vaporise at low temperatures but melted and became incandescent when heated by a propane flame, thus possibly becoming a source of ignition within the combustion chamber and causing abnormal combustion.

The alternative theory put by Mr Braly was that the left engine timing was not adjusted properly when the engine was fitted to the aircraft in February 2000 and that crankshaft damage occurred as a result. However, as indicated previously, the crack grew over about 50 engine start/stop cycles (flights), placing crack initiation in early May 2000. If the crack had initiated in February 2000, as suggested by Mr Braly, many more start stop cycles would have been involved. The fracture surface features did not exhibit that evidence.

The recorded radar data (notably fluctuating groundspeed data) indicated that an abnormal engine operating condition existed between 1837:41 and 1847:15. The fluctuations in groundspeed alone do not 'prove' the left engine crankshaft had fractured and was dogged, but that event has occurred in other cases (eg VH-LAN, VH-SJQ, and VH-JCH, – see Note 1).

The absence of significant variations in altitude and track supports the assertion that the pilot had engaged the autopilot during this period. The steady altitude does not 'prove' that there was no mechanical failure in the left engine at this time. The fluctuations in groundspeed are not explained by the damage to the right engine, whereas the crew of VH-JCH reported surging of the aircraft in response to RPM fluctuations, and which would explain the fluctuating groundspeed data.

Maintenance documentation entries of possible significance to the operation of the left engine were made on 9 and 10 May 2000, between 46 and 49 hours (59 and 63 flights) before the accident. Pilot references to possible magneto problems and the engine 'missing' may indicate the presence of an underlying anomaly in the combustion conditions in the left engine at that time, particularly as no defect with the magnetos was identified during maintenance checks in response to those entries. The apparent resolution of the problem (there were no subsequent pilot reports on the matter) without any recorded corrective maintenance action is consistent with the transitory nature of engine deposit formation referred to above.

The ATSB is not arguing that the bearing had experienced failure in the sense of 'destruction' 50 to 60 flights before the accident or at any time before the accident flight. Rather, that the bearing failed to operate as designed in that the bearing retention force was insufficient to retain the bearing in the correct position in the big-end connecting rod housing and prevent bearing contact with the crankshaft journal fillet radius. The bearing retention force was insufficient due to some combination of engine combustion pressures and the effect of the anti-galling compound. The inference should not be drawn that the bearing continued to 'ride' on the fillet radius following initial contact.

As detailed in ATSB Report 200002157 and further explained to the Coroner during the inquest, fatigue cracking striations which resulted from the abnormal alternating loads being imposed on the adjacent journals could be resolved under a microscopic examination of the crack surfaces. The uniform spacing of the striations indicated that a constant amplitude loading had been applied to the journals. If crack growth occurred as a result of loads applied with every rotation of the crankshaft and the engine was operating at the normal cruise speed setting of 2200 RPM, then the number of striations indicates that crack growth (the period that the crankshaft remained dogged) would have occurred over a period of 8–10 minutes.

The issue of the speed achievable on one engine is addressed at Attachment F.

Note 1: The ATSB has records of a number of instances where crankshafts have fractured but remained 'dogged' and the engine has continued to operate. Those include:

1. Cessna U206G, VH-LAN, 20 August 2001. A major defect report was submitted to CASA, to the effect that, during an engine run, the propeller would not cycle [i.e. the pitch would not vary]. Subsequent investigation revealed that the crankshaft had fractured at the No. 4 main journal. Clearly the engine was running and the propeller was turning, but the crankshaft was fractured but had remained dogged. It is most likely that the engine had been operating in that condition for at least the final part of the aircraft's previous flight.
2. Cessna 210L, VH-SJQ, 6 May 1999. The pilot reported that the engine was running roughly and diverted to Albury. The aircraft landed safely at Albury

12 minutes later. Investigation revealed that the engine crankshaft had broken behind the front cylinder. The engine had continued to operate at reduced power although the crankshaft was broken.

3. Piper PA31-350, VH-JCH, 14 December 2001. During cruise at 8,000 ft, the propellers lost synchronisation. The right engine RPM then began fluctuating. The crew shut down the engine, feathered the propeller and conducted a single engine landing. Disassembly of the engine revealed that the crankshaft had fractured at the No. 6 connecting rod journal in a manner that was very similar to the failure of the crankshaft in the left engine of MZK. Analysis of the fracture revealed that fatigue cracking had initiated below the surface of the journal and was associated with a discontinuity in the nitrided surface zone at the transition from the journal to the forward fillet radius. The No. 6 connecting rod bearing inserts were destroyed. Fatigue crack growth had commenced at the centre of the connecting rod cap, most probably after the bearing inserts had failed. There were tan deposits on the piston crowns, with characteristics similar to the lead oxybromide deposits on the pistons of the left engine of MZK.

Page ix: Mr Braly also said that the mixture settings adopted by Whyalla Airlines for the climb phase of flight were too lean, and these settings may have caused or exacerbated the damage to the right engine;

ATSB Comment

The Whyalla Airlines operations manual stipulated the climb power settings for company Piper Chieftain aircraft as follows:

Initial climb speed 110 kts until 500–800 feet

Initial climb power 38–40 inches MP [manifold pressure], 2400 RPM, 30 GPH

Cruise climb speed 130 kts

Cruise climb power 36–38 inches MP, 2400 RPM, 27 GPH or max 1,500°F EGT [exhaust gas temperature].

The Manager of Whyalla Airlines was asked to describe the Piper Chieftain engine handling and fuel leaning practices taught by him and used by company pilots. He indicated that he expected all pilots to use the following aircraft speeds, and engine power and mixture settings:

- Climb. Accelerate initially to 110 kts, reduce power to 36 inches MP, 2400 RPM (38 inches initially if heavy), fuel flow adjusted to 27–30 GPH by leaning the mixtures. EGT to not exceed 1,500°F (if necessary, fuel flow would be increased to avoid exceeding 1,500°F).

Section 4 of the Piper Chieftain Pilot's Operating Handbook (POH) included amplified normal procedures to provide detailed information and explanations of the normal procedures necessary for operation of the aircraft.

Paragraph 4.24 (Climb) of the POH version REPORT: 2046, issued 1 November 1976 and the version in use by Whyalla Airlines, included the following information regarding power settings and engine operating limitations during climb:

38 inches MP

2400 RPM

27 USG/hr minimum fuel flow

1,500°F EGT maximum

475°F CHT [cylinder head temperature] maximum

Paragraph 4.24 (Climb) of the POH version REPORT: LK-1208, issued 14 September 1979 and the version applicable to MZK, included the following information regarding power settings and engine operating limitations during climb:

40 inches manifold pressure

2400 RPM

30 GPH minimum fuel flow

1,500°F EGT maximum

475°F CHT maximum

Engine test runs by Mr Braly using the Whyalla Airlines climb engine settings indicated that the peak cylinder pressures at a climb power setting of 38 inches MP, 2400 RPM, 27 GPH fuel flow and EGT of 1450°F degrees were slightly less than peak cylinder pressures at full power, 2575 RPM and full rich mixture (maximum continuous power, normally only used for takeoff). It should be noted that testing conducted at the request of the ATSB by Mr Braly using his engine test facility showed that at both 38 inches MP, 27 GPH and 2400 RPM, and 40 inches MP, 30 GPH and 2400 RPM, the EGT was identical at 1,450 degrees and the peak cylinder pressure was identical at 900 psi.

Mr Braly noted that 'the magnitude of the peak cylinder combustion pressure events and their proper location after TDC [top dead centre] are critical parameters that dominate most other engine management considerations in predicting engine durability'. He also commented that increasing the EGT setting to 1,500°F, the EGT climb limit specified by Whyalla Airlines, would have increased the peak cylinder pressures well above those occurring at full power. (It should also be noted that a reduction in manifold pressure to 36 inches, the lower limit specified by the manager, and increasing the fuel flow to 30 GPH, the upper limit, would reduce the peak cylinder pressures and therefore reduce the likelihood of engine damage.)

The takeoff and climb performance of the aircraft recorded on radar was indicative of normal two-engine operation and no abnormalities in aircraft performance were evident prior to 1837:41 (eight minutes after the top of climb).

Whyalla Airlines had operated up to four Piper Chieftain aircraft for more than 10 years. However, there was no pattern of ongoing maintenance problems such as dished piston heads, collapsed valve heads, tuliped intake valves or burnt pistons etc indicating abnormal combustion. This suggested the company's climb power settings were not responsible for melting the No. 6 piston in MZK's right engine. In addition, no piston damage was evident during borescope inspections required by CASA of the pistons of the other Piper Chieftain aircraft in the Whyalla Airlines' fleet following the accident. Evidence was tendered at the inquest which indicated that MZK's fuel flow gauges were under-reading, which would reduce the likelihood of the engines of MZK detonating in the climb. If the piston had been holed early in the flight, it would likely have resulted in oil venting and engine seizure well before impact.

There was one instance of overheating damage in a Whyalla Airlines Chieftain engine that was accompanied by noticeable vibration from the engine. The engine problem became evident early in the flight, but the pilot was apparently not sufficiently concerned to report the problem to air traffic controllers, and continued the flight from Whyalla to Adelaide. Textron Lycoming advised that the damage in that case was the result of a damaged spark plug.

The pilot of JCH when it sustained a broken crankshaft very similar to MZK's left engine, reported that his aircraft 'surged' in response to changes in RPM. Such surges would be consistent with the observed fluctuations in groundspeed between 1837:41 and 1847:15.

If the right engine of MZK had overheated during the climb, it would be reasonable to expect the pilot to have observed the excessive temperature on the CHT gauge during what was a normal, stress-free segment of the flight and, at that early stage of the flight, returned to Adelaide.

Page ix: *Mr Hood, a metallurgist with McSwain Engineering Inc. in the United States of America also confirmed that the left engine crankshaft in MZK did not fail due to thermal cracking initiated fatigue fracture, that bearing failure was not relevant, and that the crankshaft failure was due to a 'manufacturing-related material condition'. Like Dr Powell and Mr McLean, they were unable to identify an inclusion in the metal at the fracture site, but he found a 'pocket' there, from where an inclusion may have fallen during the fracture process.*

ATSB comment

It is potentially misleading for the Coroner to state that Mr Hood 'confirmed that the left engine crankshaft in MZK did not fail due to thermal cracking initiated fatigue fracture, that bearing failure was not relevant, and that the crankshaft failure was due to a 'manufacturing related material condition''. That was Mr Hood's opinion rather than 'confirmation' by way of scientific fact.

Mr Hood identified a pocket area at the fatigue crack origin that he said showed no indication of an inclusion, but he concluded 'any inclusion that may have been present could have been lost during the fracture process'. He also impact-fractured a section from the crankshaft and concluded that the fracture appearance was atypical. He stated that a similarly produced fracture from an older vintage Lycoming 540 crankshaft exhibited different features and that the subject crankshaft did not exhibit typical overload fracture features.

The Coroner omits to acknowledge the flaws in the argument presented by McSwain on this matter. Ductile fractures in quenched and tempered low alloy steels (for example the type used in the manufacture of the crankshaft) created by overload or impact at room temperature involve the process of microvoid coalescence. The nature of non-metallic inclusions, in particular their size, shape and distribution, plays a dominant role in development of fracture surface features, eg dimple size and shape. A comparison of fracture surface features between two steel alloys must be made on the basis of the knowledge of the non-metallic inclusion shape, size and distribution. It should be noted that 'older vintage Lycoming 540 crankshafts' were manufactured from air melted steel. The inclusion size, shape and distribution of non-metallic inclusions in air melted crankshaft steel is very different from that in vacuum remelted, calcium and magnesium treated crankshaft steel. The differences in ductile fracture surface features reported in the McSwain report can be explained by the effect of differences in steel production.

It should also be noted that a degree of confusion is created in the comparison of fracture features from crankshaft s/n V537912936 and an 'older vintage Lycoming 540 crankshaft' by the publication of scanning electron micrographs at different magnification – the magnification of one of the micrographs in the McSwain report was 2,500 times, while the magnification of the micrograph with which it is compared is 1,000 times.

Subsequent impact testing and examination of fracture surfaces conducted by the ATSB, and in the presence of a number of observers, including from Whyalla Airlines, CASA, and the engine manufacturer, did not reveal any evidence of atypical fracture features.

Mr Hood concluded that the crankshaft failure was due to a manufacturing related material condition that resulted in sub-surface fatigue crack initiation, noting that the crankshaft was identified 'as having a material related issue that could result in failure by Textron Lycoming Mandatory Service Bulletin Number 553, dated September 16, 2002'. (See Attachment B for a more detailed ATSB response to the results of the McSwain testing).

In March 2003, after the left engine crankshaft was returned to Australia, testing of the crankshaft and the fatigue crack initiation site commenced at the ATSB technical analysis laboratory. The tests were conducted in the presence of observers independent of the ATSB (the Coroner was invited to send an observer(s), but chose not to). The results of those tests are included in the comprehensive report at Attachment C.

In short, no irregularity or defect in the crankshaft was identified that could have initiated the fatigue fracture under normal engine operating conditions. No 'massive high temperature oxide inclusions' were identified, either in the crankshaft material generally, or in the vicinity of the fatigue crack initiation area. Coincidentally, independent testing by a commercial laboratory in Australia at the request of the ATSB did not reveal the presence of an atypical fracture surface as reported by Mr Hood. A similar test by the ATSB confirmed those results.

Avflash bulletin, 3 April 2003, reported that of 601 TIO-540 engines that had been tested in accordance with Service Bulletin No. 553, 184 crankshafts were removed from service with the remaining 417 being permitted to continue in service. That statistic indicates that the likelihood of there being a manufacturing defect in the left engine crankshaft of MZK was about 30 per cent and implies that any conclusion based on circumstantial evidence regarding a material defect would need robust supporting evidence to be credible. The Coroner has not provided such evidence.

To suggest that an inclusion might have been present but 'could have been lost during the fracture process' when no other similar defect (excluding the erroneous observations regarding corrosion by Dr Powell and Mr McLean referred to earlier) was noted at any stage during a number of examinations of the crankshaft material by totally independent organisations, is highly speculative. In the absence of any concrete evidence of a material defect, and in light of the supporting detail in Attachment C, the ATSB position that the crankshaft failure originated from a thermal crack remains as the most likely explanation.

Page ix: On the basis of the evidence presented at the inquest, I reached the following conclusions about how this tragedy occurred:

- *Page ix: It is possible (but not capable of proof) that the No. 6 piston in the right engine of MZK was damaged during the takeoff and climb of Flight 904. It is very unlikely that damage occurred during the cruise phase;*

ATSB comment

While the possibility exists that the No. 6 piston was damaged during the takeoff and climb, there was no factual evidence to support that notion. The following points argue against such an event:

- Analysis of the recorded radar data for the climb did not reveal any loss or change in aircraft performance,
- There was no indication from the pilot that the flight was operating other than normally during the takeoff and climb,
- The mild detonation demonstrated by Mr Braly at the climb power setting used by Whyalla Airlines would not have been sufficient to cause the damage observed,
- There was no pattern of similar failures in other Whyalla Airlines Chieftain aircraft during more than 10 years the company had been operating Piper Chieftain aircraft and using the same engine operating procedures as the pilot of MZK was using,

- Borescope inspections of the engines of the remaining Whyalla Airlines Chieftain aircraft after the accident did not show any indication of heat damage to combustion chamber components as might have been expected if the company's engine climb settings were problematic.

The ATSB agrees that it is very unlikely that the damage to the right engine occurred during NORMAL cruise engine operating conditions.

The Coroner's preferred scenario of the pilot allowing the right engine to overheat holing a piston in the cylinder on which the temperature gauge is located without the explanation of the prior loss of the left engine is suggestive of pilot culpability.

(See also p 42–44)

Page ix: *The right engine began running roughly and showing signs of end gas detonation damage at around 1837:41. Mr Mackiewicz reduced power on that engine at 1847:15 to protect it, causing a yaw to the right and reduction in groundspeed to 167 knots. He increased the RPM on the left engine to 2,400 to compensate. This was not 'overboosting' the engine;*

ATSB comment

The ATSB scenario is that the left engine experienced problems and then failed before the right experienced detonation damage. The ATSB has never argued that the left engine was overboosted. Moreover, as noted elsewhere in relation to the right engine it is possible to overboost an engine at 2400 RPM (see Attachment E).

The term 'yaw' (or skid) relates to the orientation of the aircraft with respect to the relative airflow, not relative to its track over the ground (ie the radar track). An aircraft can maintain a constant track while 'yawed to the right or left'. The radar cannot determine which way the aircraft is oriented in space, but can only 'see' the position of the aircraft relative to the radar antenna and calculate a track from the previous positions of the aircraft. The radar data showed that the aircraft track diverged right. There was no way of determining from the radar data whether the aircraft yawed, or if it did yaw, in which direction.

Fundamentally, the ATSB considered that the track deviation recorded on the radar data did not, of its own, provide any confirmation as to which, if any, engine malfunctioned at that time. The ATSB view is that the radar analysis indicates that there was a problem with an engine at 1847:15 but that the radar evidence alone is not sufficient to determine which engine was involved. There is no dispute that the track of a twin engine aircraft 'will diverge towards the dead or malfunctioning engine' if autopilot or pilot input does not counter that tendency. But it is entirely possible that some combination of the initial response of the autopilot and pilot reaction to a left engine failure explains the radar evidence. On balance, the ATSB suggests that the track divergence right is not persuasive of either a right first or left first engine failure scenario.

The coincident sudden and significant speed reduction at 1847:15 is strongly suggestive of an engine problem at that time so the other factual evidence must then be evaluated in conjunction with the radar data to see if there is any indication of which engine was involved.

Any analysis of the likely response of an aircraft, autopilot and pilot following an engine failure is difficult as there are numerous possibilities, including the nature of the engine failure itself. However, a brief discussion of some of the possibilities follows.

Following an engine failure in a twin engine aircraft such as the Piper Chieftain, the aircraft will initially yaw, and then roll in the direction of the failed engine. These initial movements should be arrested virtually immediately by the pilot or autopilot manipulating the rudder, aileron and elevator. The autopilot may react more rapidly than the pilot if the

pilot is completely unaware of the impending failure. If, as the evidence suggests (the fluctuations and reduction in groundspeed between 1837:41 and 1847:15), the pilot of MZK was aware there was something wrong with the left engine, he would likely have been alert to a possible failure of that engine and been able to arrest the initial yaw towards the left almost immediately and certainly within 3.7 seconds (the period between successive radar sweeps).

Pilot reaction within 3.7 seconds is entirely possible. Research in car driver reaction time⁴ has demonstrated that a driver's mean steering response time to an unexpected event on the side of the road ahead was 1 to 1.5 seconds. In this case, the unexpected event was the opening of a door of a car parked on one side of the road ahead. If the event to which the driver was responding was expected, it is reasonable to believe that the response time would be reduced. Research evaluating the time required for surprised drivers to move their foot from an accelerator to the brake found this time to be 0.6 to 0.8 seconds .

Based on the above, it is reasonable to expect that the pilot would have reacted to the engine failure, in terms of initially responding to a sudden change in pitch or yaw, in less than 3.7 seconds.

Any change in aircraft attitude does not immediately result in a deviation in track. The aircraft may skid for a short period of time in the direction it was previously moving before it responds to the control deflection/attitude adjustment/engine failure. Even a moderately alert pilot should have been able to apply some yaw-counteracting rudder within a few seconds and largely maintain the track direction as previously recorded. (The Chief Pilot of Whyalla Airlines gave evidence at the inquest that he expected, and trained, his pilots to react immediately to an engine failure. Another experienced pilot expressed a similar opinion.) If there is no input from the pilot or the autopilot in response to an engine failure or power reduction on one side, the aircraft will enter a spiral dive. Therefore, the sustained track deviation to the right over about 1 minute was probably autopilot and/or pilot induced.

The aircraft was equipped with a two-axis autopilot and a yaw damper. It is likely that the autopilot was on during the initial stages of the cruise. If the autopilot remained engaged in heading hold mode after the engine failed, it would have manipulated the ailerons to roll the aircraft to the right to counteract the effect of the engine failure to the yaw of the aircraft to the left. In this situation the aircraft would be in unbalanced flight and although it would be oriented or aligned in the direction it was previously flying, the unbalanced condition would cause the aircraft to skid to the right, producing a track deviation to the right consistent with what is seen between 1847:15 and 1848:15 on the radar record.

However, it would be unusual for a pilot not to disconnect an autopilot in the event of an engine failure and therefore any control surface reaction to the engine failure was most likely pilot induced. That scenario and others were raised with various witnesses to demonstrate to the Coroner that there are logical ways to explain a right track deviation following a left engine failure. An expert witness with experience as a test pilot for Piper Aircraft Corporation told the Coroner that if the left engine catastrophically failed 'it doesn't surprise me to see a change in course in the opposite direction. If the pilot is aware and he's flying the aircraft and he's picking up the wing like I said, then over-correcting would not be something that would be unusual'.

The most likely explanation for the sustained track deviation to the right following the left engine failure is simply that the pilot began hand-flying the aircraft and that he did not maintain the aircraft's heading because he was occupied with other tasks such as completing engine failure drills, troubleshooting the failed engine and communicating with his passengers.

⁴ H. Summala, Driver/vehicle steering response latencies, *Human Factors*, vol. 23, 1981, pp 683–692.

In his findings, the Coroner gave no consideration of the influence passenger behaviour may have had on the sequence of events. Irrespective of the sequence in which the engine failures occurred, it is inconceivable for the passengers not to have been aware of the deteriorating situation. Passenger reaction probably varied among individuals, and could have ranged from denial/inaction to panic/hysteria. It is realistic to believe that the pilot would have had to devote some of his attention to communicating with and/or controlling the passengers. As highlighted in ATSB Report 200002157 (p 116), passenger management would have added to the already very high workload situation facing the pilot. In such an environment, it is entirely conceivable that the pilot's control of aircraft heading deteriorated for a period, particularly if he had turned his head away from the flight instruments to address the passengers.

The physical evidence from the left engine crankshaft indicates that the engine continued operating for 8–10 minutes after the crankshaft initially fractured. Information regarding the VH-JCH incident (see p 42) indicates that during that time, symptoms of engine ill health would have been evident to the pilot, and therefore he would have been alert to a possible failure of the engine.

Page ix: The crankshaft in the left engine failed at 1858:30 causing immediate cessation of function;

ATSB comment

There was compelling metallurgical evidence, including fatigue cracking in other main bearing journals and bluing of the crankshaft fracture surfaces (see ATSB Report 200002157, pp 59 and 60) that the crankshaft remained dogged and that the engine continued to operate for a further 8–10 minutes. That metallurgical evidence was consistent with evidence obtained from ATC audio and radar data. On that basis, the left engine could not have suddenly failed at 1858:30.

Page x: The cause of the fracture of the left crankshaft was a fatigue crack, initiated from a sub-surface defect in the steel as a result of a flaw in the manufacturing process, which created a point of weakness from which fatigue cracking radiated outwards over the ensuing 50 to 70 flights until it finally fractured through at around 1858:30 on 31 May 2000 causing immediate cessation of functioning;

ATSB comment

As explained in Attachments B and C of this report, metallurgical examination of the crankshaft by independent experts in Australia and the US, as well as the ATSB, did not reveal any evidence of a manufacturing or material defect in the crankshaft. The evidence of bluing and the secondary fatigue cracks referenced above and in ATSB Report 200002157 pp 59 and 60, indicate that the engine could not have failed immediately at 1858:30.

Page x: The cause of the failure of the right engine was end gas detonation damage to the No. 6 piston, not due to 'overboosting' but possibly due to detonation during the 'climb' phase of Flight 904 when the mixture settings (specified in the Whyalla Airlines Operations Manual) were unduly lean and were likely to create unduly high peak cylinder pressures.

ATSB comment

The physical evidence of the engine and the radar information do not support the assertion that the No. 6 right piston was 'compromised' on an earlier flight or during climb on the accident flight (see pp 42–44). In addition, the mild detonation demonstrated by Mr Braly using the climb power settings used by Whyalla Airlines is not likely to have caused the damage evident on the No. 6 piston. Furthermore, the long standing use of that climb power setting by Whyalla Airlines over almost 10 years without a history of maintenance

problems associated with detonation does not provide support for the notion that the piston was compromised during the climb phase of the flight.

Page x: *In forming those conclusions, a number of issues were identified at the inquest and considered. They assisted me to reach these conclusions in the following way:*

- *It is very unlikely that MZK would have been capable of maintaining a groundspeed of 167 knots in those conditions after 1847:15 if, as the ATSB argued, one engine was completely inoperative;*

ATSB comment

During the inquest into the MZK accident, significant attention was focussed on the ATSB position that a Piper Chieftain aircraft could maintain the observed 167 kts average groundspeed between 1847 and top of descent on one engine. Aircraft groundspeed is based on numerous factors. A full explanation of the ATSB position regarding the maximum single engine speed achievable is at Attachment F.

No firm conclusion is possible regarding the precise top speed achievable by MZK because no data is available regarding operations outside the limits stipulated by the engine and airframe manufacturers' data. Nonetheless, based on all the factual information available, the ATSB is confident that the observed speed is possible on one engine, and that the sequence of events contained in the ATSB final report remains the most likely explanation of the accident sequence.

During the inquest, the Coroner observed a TIO-540-J series engine in an engine test facility producing 357 brake horsepower (104 per cent rated power based on a gross corrected horsepower of 365 at 43.3 inches manifold pressure and 2588 RPM and full rich mixture (see Attachment D fig 2). There was no indication from the test facility operator, Mr Braly, that the engine was being overstressed when operated in this configuration and power setting. Clearly, an engine can output greater than rated power. Further increase is possible if the mixture is adjusted from full rich to the 'best power' position. However, setting the mixture at the best power position while the engine is operating at maximum manifold pressure and RPM will establish the conditions for detonation and result in significant damage to the engine, including heat damage/melted components such as was evident in the right engine of MZK.

The Coroner also observed the engine producing 359 brake horsepower (106 per cent rated power based on a gross corrected horsepower of 373) at 2397 RPM, 45.8 inches manifold pressure and full rich mixture (see Attachment D, fig 4). A less rich mixture and/or higher manifold pressure could produce more power while increasing the risk of detonation.

- *Even if the aircraft was so capable, to achieve that groundspeed in those conditions, would have required absolutely maximum power on one engine, which was completely unnecessary since the aircraft was quite capable of maintaining altitude at a lower groundspeed on one engine at lower power settings, without putting the engine at risk;*

ATSB comment

The ATSB agrees that the aircraft was capable of maintaining level flight on one engine operating at less than maximum power and that the use of maximum power would, in that context, not have been necessary. However, that fact provides no additional information about how the pilot operated the engine.

The pilot's initial reaction and response to the left engine failure would very possibly have been influenced by the previous engine failure he experienced (also in VH-MZK) where, because of engine cowl damage, he was unable to maintain altitude and was forced to land at Maitland, SA. Complete engine failures are rare, but can be psychologically

significant events, particularly if the circumstances include being unable to maintain altitude and require an emergency landing.

Any consideration of the pilot's actions must also take account of the environment existing at the time (dark moonless night, over water, seven passengers who were probably reacting to the stress of the developing situation, and previous engine failure where he was unable to maintain altitude on one engine). As well, consideration should also be made for the amount and type of information available to the pilot regarding the operation of the engines. In addition, as detailed in Attachment C to ATSB Report 200002157, there are a number of cases recorded where Piper Chieftain aircraft could not maintain altitude on one engine and had to ditch (mostly in daylight). Against that background, it seems reasonable that as part of the initial reaction to the left engine failure, maintenance of altitude might have been a primary concern for the pilot.

The human response to highly stressful situations can be unpredictable, even in well trained, skilled and experienced people. As described in background information provided to the Coroner by the ATSB (exhibit C234), stress (or pressure or high workload) increases the likelihood that a person will make an error. The higher the stress level (above a normal level), the higher the error probability. The nuclear power industry has estimated that the human error rate in very high stress situations is about 30 per cent. In extreme stress situations, as the time available to respond decreases, the error rate approaches 100 per cent. There are not grounds to 'blame' the pilot.

The ATSB has not been critical of the pilot and has not blamed him for the accident. Indeed, ATSB Report 20002157 (p 116) commends the actions of the pilot in ditching the aircraft to provide as good a chance of survival for the passengers as was possible. At the time of the release of the report, the ATSB highlighted that it was not blaming the pilot or Whyalla Airlines. However, to ignore the multitude of factors that may have influenced the pilot's actions and decision making on the night of the accident and to infer that the pilot's actions would have been perfect in all respects is naïve at best, and ignores the wealth of examples from aircraft accidents (and other transport and industrial accidents) worldwide where human performance under stress has deteriorated.

The ATSB made it clear that it will never be known exactly what actions the pilot took on the night, particularly with respect to engine management. However, the irrefutable metallurgical evidence is that the right engine was operated beyond normal limits at some stage during the flight. If this occurred when the pilot was not under stress or distracted by other events (such as during the climb, as the Coroner has found was the most likely scenario), it is much more difficult to explain why he did not take corrective action to a rising and/or high right engine engine operating temperature (CHT) than if it occurred when stress levels were higher (such as following the failure of the left engine).

- *If Mr Mackiewicz had overboosted the engine, it is more likely that it would have been operating at 2,575 RPM (maximum) rather than 2,400 RPM detected by the ATSB;*

ATSB comment

As indicated in ATSB Report 200002157, 2400 RPM was an instantaneous snapshot from a radio transmission shortly before top of descent. There was no other information available regarding the power settings at other stages of the cruise between 1833:54 (2200 RPM) and 1855:37 (2400 RPM). The pilot could have initially increased the engine RPM to 2575 RPM and later reduced it to 2400 RPM, or only increased from 2200 to 2400 RPM. The main inference to be drawn from the 2400 RPM indication is that the aircraft was not operating at normal cruise power when the transmission was made, and that the pilot probably had adjusted one engine to a power setting greater than normal cruise power.

As indicated at p 49, an engine operated at 2575 RPM and full throttle at any mixture setting less than full rich would constitute 'overboosting' the engine. Similarly, at 2400 RPM any manifold pressure over 40 inches would constitute 'overboosting'. (See also Attachment E).

- *It is very unlikely that Mr Mackiewicz would have commenced his descent into Whyalla at 1855:54, and advised Adelaide Flight Information Service that he was expecting to arrive on time, if he was operating on only one engine at absolutely maximum power and was worried about maintaining altitude;*

ATSB comment

The Chieftain aircraft is normally capable of operating satisfactorily on one engine operated within normal operating parameters. Therefore, under normal circumstances there was no reason for the pilot to be concerned about maintaining altitude. The dark conditions on the night of the accident would have limited the ability of the pilot to determine if there had been any disruption of engine cowlings such as he experienced following a catastrophic failure of the left engine on 7 January 2000 near Maitland, SA. On that occasion, the pilot had been unable to maintain altitude on one engine. It is likely that the Maitland experience influenced the pilot's reaction and decision making in response to the left engine failure on the night of the accident (the damage to the right engine indicated that the engine had been operated beyond normal operating limits). It is not surprising that the aircraft could maintain altitude on one engine in such circumstances and once this became apparent to the pilot (soon after 1847:15) he may have held much less concern than in the situation where the aircraft could not maintain altitude no matter what the power setting on the remaining engine. As such, it is quite possible that the pilot had no concern about reaching Whyalla on one engine at that stage.

- *Mr Mackiewicz made a number of radio transmissions after 1847:15, and as late as 1856:03 he was reporting his position without apparent concern. It is almost inconceivable that he would not have issued a Pan (distress) call at that point if he had completely lost one engine and was worried about maintaining altitude;*

ATSB comment

The absence of a Pan call does not prove that the left engine did or did not fail at 1847:15. There are many recorded examples where pilots in 'emergency situations' have not declared emergencies.

The accident pilot was reported to have experienced engine vibration and misfire during climb or early in the cruise during a Piper Chieftain flight from Whyalla to Adelaide in 1999. Maintenance examination found erosion damage to a cylinder head of the affected engine. The pilot did not return the aircraft to Whyalla after the engine problem became apparent, and did not notify the air traffic controller of the situation.

The failure of the left engine on the accident flight did not result in any deformation of the engine cowling, and the aircraft should have been able to comfortably maintain altitude on a normally-functioning right engine.

In any investigation, all the available facts must be evaluated. Speculation regarding what a prudent or competent pilot would or should have done in ideal circumstances fails to acknowledge the realities of human performance. The radar, statistical and physical (mainly metallurgical) evidence support the ATSB position that the left engine failed first, and the right engine was operated beyond normal limits and malfunctioned as the result of severe detonation. The absence of a Pan call does not have any bearing on the factual metallurgical, radar, and audio information.

- *It is highly unlikely that the bearings in the left engine failed long before 31 May 2000, to the extent that they could cause thermal cracks in the crankshaft and initiate the fatigue fracture 50 to 70 flights before Flight 904, and yet no sign of bearing damage, particularly metal particles in the oil, was noted in any of the services performed on the engine in the meantime;*

ATSB comment

As indicated in ATSB Report 200002157, the ATSB does not postulate that the left crankshaft No. 6 bearing 'failed' and had been in the process of significant decomposition or destruction over at least the last 50 flights before the accident flight. Rather, the ATSB believes that the bearing had failed to operate as designed and had moved sufficiently to interfere with the surface of the crankshaft and initiate a thermal crack about 50 flights before the accident. (See also p 17 of this report and A2 pp 37–39.)

Page xi:

I have been informed that there have been a total of more than fifteen crankshaft failures in Textron Lycoming engines since this incident. Information about many of them is meagre, but a material defect has been confirmed by the United States authorities in seven cases, and suspected as the cause in the rest. This is the only case in which a different explanation for the crankshaft failure has been offered.

ATSB comment

The schematic attached to the FAA document detailing the failures of Lycoming crankshafts shows fatigue crack growth extending through the crankarm between the No. 5 and No. 6 connecting rod journals. The nature of fatigue crack propagation in the case of the Whyalla Airlines crankshaft failure is different, in that cracking extended through the journal.

While the cause of the failures was attributed to a random metallurgical flaw, the nature of the flaw is ill defined and has been named 'honeycomb'. Honeycomb defects have not been documented in the literature on high strength ultra clean steels. The honeycomb features have been observed only on impact test fracture surfaces. The defects reported by others (Powell, Hood, Murphy) to be responsible for fatigue crack initiation differ from the reported nature of the honeycomb defect. Testing of crankshaft material by independent US laboratories has not identified any fatigue strength reduction in material that displays a honeycomb feature. Testing and examination of the crankshaft from the left engine MZK by the ATSB in March 2003 did not reveal any evidence of a 'honeycomb' feature (see Attachment C).

There are many ways a crankshaft can fail during engine operation. These are listed in FAA Advisory Circular 20-103, 3/7/78. These include, material defects, manufacturing defects, overheating, overstress. Bearing spin is an identified factor that may cause failure through overheating or damage through fillet ride. Overstress is identified with operating conditions resulting in overboost or abnormal combustion. It is noted that engines designed with higher cylinder pressures for increased efficiency and horsepower require greater accuracy in ignition timing (they are more susceptible deviations in time of peak pressure development).

A3. Comments relating to chapters 1 to 13 of the Coroner's findings

1.1 *At 1901:14 (7:01:14pm) Central Standard Time, (incorrectly recorded in the ATSB report, Exhibit C97, as 1901:10) on Wednesday 31 May 2000, a radio message was received at the Adelaide Flight Information Service ('FIS')*

ATSB comment

The claim in the opening paragraph of the Coroner's findings that the VH-MZK pilot's mayday call time was incorrectly recorded in the ATSB report as 1901:10 rather than 1901:14 (a difference of 4 seconds) is both petty and wrong. It provides a good illustration of what is to follow. The time cited by the Coroner was that based on a copy of the tape reviewed by Airservices Australia without the benefit of the original time injected tape, whereas the time used by the ATSB was based on multiple replays and checking of the original air traffic control tape (with time injection) by ATSB specialist investigators.

2.41 *The wreckage was identified and mapped over the ensuing days until, on 9 June 2000, the wreckage was lifted onto the salvage vessel 'Andrew Wilson'. The remains of the aircraft were then handed over to the ATSB for scientific analysis.*

ATSB comment

The ATSB paid for the salvage operation and under the Air Navigation Act the wreckage of VH-MZK was under the control of the ATSB.

4.30 *On that basis, I agree with the author of Exhibit C97 when he comments:*

'The information available does not indicate that the pilot was affected by fatigue at the time of the accident.' (Exhibit C97, p7)

ATSB comment

Suggesting that there was one male author of ATSB Report 200002157 with whom the Coroner agrees is incorrect. Report 200002157 was produced by a team of male and female ATSB investigators prior to management review and release.

5.9 *Mr Jelinek told me that if, as has been postulated by the ATSB in its report (Exhibit C97), the No. 6 main bearing of the left crankshaft had been in the process of decomposition over at least the last 50 flights (which according to the Trend Monitoring Data, Exhibit C151, was between approximately 28 April and 5 May 2000), then he and his engineers would have found signs of this in the form of metal particles in the oil filters (T802).*

5.16 *Dr Romeyn, ATSB's Chief Metallurgist, explained that since there were no particles found during those service inspections, either the particles given off as a result of the failing bearings were too small to be caught by the filters and were suspended in the oil, or the damage occurred after the last inspection (T4314) For reasons I will discuss later, this explanation seems unlikely to be correct.*

5.40 *It is not possible to conclude that spectrographic oil analysis would inevitably have detected incipient bearing failure, although there is a high likelihood that it would have done so had the bearings of MZK been progressively failing over 50 to 70 flights, as the ATSB has suggested.*

9.21 *Textron Lycoming pointed out, and I accept the force of this argument, that on this hypothesis, the bearings would have been failing for some time, and the debris from the progressive bearing failure should have been detected at the last 100 hourly inspection, culminating on 30 May 2000, the day*

before the accident. During that service the oil filters were cut open and inspected, and the suction screens were taken out and inspected (see the evidence of Mr Jones T908 and Mr Parker T939). No such debris was found.

12.40 From all of the above, it can be concluded from Dr Zockel's evidence as follows:

- The fracture of the crankshaft was not due to bearing failure or thermal cracking at the No. 6 journal in the left engine;
- The fatigue cracking in the crankshaft led to failure of the bearings rather than the other way round;

ATSB comment

The ATSB agrees that the destruction of the No. 6 bearing most likely occurred during the accident flight on 31 May 2000 and hence no large metal particles from the bearings were to be expected in oil filters before the accident. This lies behind the explanation at paragraph 5.16. It is also important to note that the ATSB position is that the term failure as used with respect to 50 flights prior to the accident is a failure of the bearing to operate as designed. (See also p 17 of this report and A2 pp 37–39).

5.23 Dr Zockel tested the twelve spark plugs from the right engine of MZK in December 2002. The No. 1 spark plug was coated with aluminium from the No. 6 piston and had shorted out. It had been dismantled and the ceramic insulator was broken, but after it was cleaned and 'refurbished', a regular spark was obtained. Several of the plugs malfunctioned as a result of an excessive gap between the electrodes, indeed Dr Zockel observed that 'all but two plugs have gaps more than 20 per cent greater than the specified value' (Exhibit C233, page 3).

5.24 Dr Zockel's conclusions, expressed as 'tentative', were as follows:

'The following tentative conclusions may be drawn:

- 1 The cylinder with number 3 and 4 spark plugs may have experienced some intermittent operation since both spark plugs failed to provide regular sparks at 125psi.
- 2 No. 6 cylinder with No. 1 and 2 spark plugs may also have had weak or intermittent sparks. The problem would have been exacerbated after No. 1 spark plug was shorted by the metallic deposits.
- 3 All other cylinders had at least one spark plug which fired regularly under the test pressure. In the operating engine the pressures are somewhat higher than the test pressures but so are the temperatures which makes it easier for the spark to discharge. Consequently the test pressure is a reasonable representation of the in cylinder conditions.

Overall I do not consider the spark plugs on the right hand engine to have contributed significantly to the crash.' (Exhibit C233, page 4)

5.42 There is no evidence before me that anything happened on 30 May 2000 which damaged or rendered less efficient any of the spark plugs in either engines of MZK.

10.10 Surprisingly, the spark plugs were not tested by the ATSB to examine Mr McHardy's theory.

ATSB comment

The ATSB agrees with the Coroner's conclusion that there was no significant problem with spark plugs on the accident flight prior to the damage caused by the right engine detonation and overheating.

It is not correct that the ATSB did not test the spark plugs. The spark plugs were removed and inspected for obvious damage. The gaps were checked using a wire feeler gauge and recorded by two ATSB LAME investigators. The gaps were all around 0.018 inch with a few plus 0.001 inch or 0.002 inch (set about mid range which is a normal practice) except for the number six cylinder plugs which were heavily contaminated and blocked with debris as a result of the overheating during the accident flight. This put all the recordings within the manufacturer's recommendations. The remaining plugs were also examined for debris or lead fouling and found to be clear and, apart from corrosion (following over a week on the seabed), exhibited fairly clean burning characteristics with little to no build up of deposits around the centre electrode. No cracking of the ceramics could be discerned on any of the remaining plugs. Electrode wear patterns appeared normal. Several of the plugs were found to be oil contaminated, but the opposite plug in the cylinder pairing was found clean. Washing out the oil showed similarly clean burn characteristics to these plugs. The deduction from this was that all plugs were capable of operating and that the oil contamination of some of the plugs was from post accident leakage.

5.32 *In my opinion, although Mr Braly's observations are supported by the Trend Monitoring Data to some extent, the changes are not so obvious that a definite conclusion can be reached that the timing on the left engine was so badly awry that it contributed to the failure on 31 May 2000.*

5.44 *When the left engine of MZK was replaced in February 2000, it had new magnetos fitted. The settings would have been checked after installation, and after every 100 hour inspection thereafter. Such an inspection occurred on 30 May 2000 and no adjustment was necessary. I accept the evidence of Mr Jelinek that these checks were appropriate.*

9.17 *In a letter dated 23 April 2001, Textron Lycoming responded to the findings of the draft ATSB report. The letter forms part of Exhibit C213. While Textron Lycoming accepted that 'abnormal combustion' was involved in both engine failures, they questioned whether incandescence from combustion chamber deposits was the cause of that. They offered a number of other possible explanations:*

- *improper spark timing – there was no suggestion that the magnetos had been checked to investigate that possibility;*

12.35 *Dr Zockel said that end gas detonation can be caused or exacerbated by a number of things:*

- *If the spark timing is inappropriate, particularly if it is too far advanced.*

It is an unfortunate aspect of the ATSB investigation that the spark timing was not examined on either of these engines.

ATSB comment

It is incorrect to assert that the ATSB investigation did not examine spark timing on either engine. Details regarding the ATSB examination of engine timing are as follows:

Magnetos Right Engine:

Due to the inability to rotate the engines, the in situ magneto to engine timing could not be verified in the normal fashion (ie connect timing light to magnetos, engine to TDC No. 1 cylinder, rotate engine back to 20 degree timing mark and watch for timing lights) so an alternate method had to be devised. The magnetos did not appear to have moved in their mount clamps so therefore appeared to be 'as set' by the maintenance shop.

The ATSB marked the magneto positions by alignment marks on the magneto body and adjacent accessory case. After disassembly of the engine timing cover from the engine,

the magneto drive pads were examined and their engagement in the gear drive train was verified. The timing of the accessory gear drive train was verified by alignment of all the master markings on the gears. With the drive train verified, the ATSB needed to verify the magneto was correctly timed to the engine at 20 degrees BTDC (before top dead centre). Unfortunately the magnetos would not rotate due to salt-water immersion, so rotating to the magneto internal timing mark (red line on gear viewed through vent plug) was not possible. The ATSB believed that the next best option was to examine the distributor gear and check the position of the finger (that passes the distributor and fires the spark down each lead in turn) and check that the cylinder on the end of that lead was on compression stroke. That cylinder did appear to be on compression stroke. The magnetos were then reassembled and aligned to the markings on the accessory cover and the clock angles were noted. Using a small bubble protractor the ATSB later compared the magneto positions relative to the accessory cover to the clock angle position of the magneto bodies on the accessory cases of another aircraft and found them consistent.

With the magneto caps removed, the magnetos were examined internally for carbon tracking, broken gear teeth, loose points screws etc. Nothing was apparent. There was however, a large amount of fungal growth and whitish grey greasy type emulsion. This emulsion was thought to be a wash through mixture of water and grease from the magneto bearings. Significant corrosion was also apparent. The points were found to exhibit normal type wear patterns from sparking. No heavy pitting was evident. It was not possible to accurately check the gaps as they would not rotate.

Magnetos Left engine:

The same methodology was used on the left engine but because of the disconnection between the cylinders and the accessory drivetrain due to the broken crankshaft, it could not be completed to the same extent. The magneto drive pads were properly engaged in the gear train and the gear train was properly timed to the crankshaft. Because of the broken crankshaft, verifying which cylinder was firing was a moot point and was not pursued.

The clock angles for the left and right magnetos were similar between the ATSB recordings and those on other installed engines. As far as was possible, the magneto timing was found to be as close to correct as could be measured under the circumstances. The ATSB did examine the magneto-to-engine timing of both the left and right engines to the extent possible and advised the Coroner of the results of that examination. Any competent aircraft mechanical engineer knows that timing is a crucial parameter for effective engine operation, and as such, it was vital for the ATSB to establish the timing of the engines as far as possible. In addition, the timing was reportedly checked during the 100 hourly maintenance activity completed the day before the accident flight.

In compiling its investigation reports, the ATSB is required to balance the need to publish a readable document against the requirement to properly explain the circumstances of the accident. In this case, once the ATSB established that the timing was unlikely to be a contributing factor to the accident, it was considered unnecessary to include that finding in the final report, along with many other findings regarding possible contributing factors that had been considered and subsequently disregarded on the basis of the evidence.

6.18 *There was no evidence before me that Mr Mackiewicz found the incident in January 2000, when he completed a forced landing on one engine at Maitland, South Australia, particularly stressful. The only evidence of distress Mr Mackiewicz may have suffered as a result of that incident was in relation to Mr Kym Brougham's reaction to the incident afterwards. The calmness and professionalism evident in Mr Mackiewicz's voice during radio transmissions on 31 May 2000 suggest that he was still in control and had not panicked or otherwise acted inappropriately.*

- 6.19 *Mr Cavenagh, the Senior Transport Investigator in charge of the ATSB investigation, argued that Mr Mackiewicz may have mismanaged the right engine as a result of the ‘terrifying’ situation he found himself in. He said:*
- ‘Then its in our view that it is entirely reasonable to understand the pilot as soon as the left engine failed, to firewalling the other engine to ensure that he maximises his survivability chances. It’s bad enough with something like this happening during the day, but for it to happen at night would be pretty terrifying.’ (T3544)*
- 6.20 *The ATSB commissioned an analysis of these radio transmissions by Dr Maurice Nevile of the Research School of Social Sciences at the Australian National University. Dr Nevile’s report is part of Mr Cavenagh’s evidence, Exhibit C213. Dr Nevile is described as an applied linguist and interaction analyst, whose PhD research involved language and interaction in airline cockpits.*
- 6.21 *Dr Nevile found nothing unusual or significant in the Mayday transmission or subsequent transmissions (p14). He had been asked by the ATSB ‘whether there is anything that could be considered consistent with a change in workload, attentional focus, stress, anxiety or similar mental state’. He found no such evidence.*
- 6.22 *The radio transmissions were also analysed by Ms Jennifer Elliott who is described as a Consultant in Forensic Speech Analysis. Ms Elliott concluded that she found no sign of ‘change of workload, attentional focus, stress, anxiety or similar mental state’ until the transmission immediately before the Mayday call, after which she found ‘intermittent’ signs of those conditions which, she said, ‘one would expect after finding oneself in the situation that the pilot communicated to ATC in his Mayday call’ (p14).*
- 6.23 *On the basis of this evidence, there is nothing to justify the ATSB conclusion that MZK had suffered a catastrophic failure of the left engine at 1847:15, about 14 minutes earlier, and that, as a result of such a ‘change of workload, attentional focus, stress’ etc, Mr Mackiewicz inadvertently overboosted the right engine thereby damaging it.*

ATSB comment

Overboosting is one of only a few likely explanations for the nature and extent of damage to the right engine. The ATSB strongly believes that, on any reasonable consideration of the very limited factual information regarding the operation of the right engine during the flight, ‘overboosting’ must remain as the most probable explanation for the right engine malfunction.

The ATSB commissioned additional MZK pilot voice analysis in the context of a suggestion in the inquest that the pilot answering air traffic control with a ‘goodday’ at 1855 indicated there was no serious problem with the aircraft at that time. Both voice analysts found that the use of ‘goodday’ was standard reciprocal language commonly used in aviation and of no significance either way. The Coroner has suggested that the voice analysis does nothing to justify the ATSB’s scenario of the left engine failing at 1847 and subsequent pilot overboosting of the right engine possibly being related to an error under stress. However, the Coroner’s scenario of the pilot allowing detonation and overheating of the right engine during and after the climb phase suggests a mistake or lapse unrelated to any stress. The voice analysis shows little pilot stress reaction even after the 1901 mayday call when there is general agreement that both the left engine had failed completely and the right was damaged. As this must have been a high stress situation, a sounder conclusion to be drawn is that the voice analysis does not assist in determining the engine failure sequence. The Coroner’s use of it to cast doubt on the ATSB scenario appears to lack objectivity.

7.16 *Dr Brian Parkinson is a radiologist who regularly travelled to Whyalla and other places in aircraft similar to MZK. Dr Parkinson said that soon after takeoff he could smell an ‘electrical burning smell’ in the cabin. He became so concerned that he looked under the seat for a lifejacket (T1911), but of course the aircraft was not equipped with them. Dr Parkinson also noticed that the engines were ‘surging’ a lot during the latter third of the flight. This also made Dr Parkinson ‘quite anxious’ (T1912). He accepted that this noise might have been due to the engines not being completely synchronised.*

7.24 *It is not possible to form a conclusion that either of the engines in MZK were malfunctioning during Flight 903. The fact that Dr Parkinson noticed that the engines were surging more than usual (he was an experienced passenger) suggests that one of the engines may have lost power, but this was not evident during takeoff and climb during Flight 904. The ‘burning smell’ is also a mystery, and none of the experts who gave evidence suggested a cause for it.*

ATSB comment

It is difficult to reconcile the Coroner’s comment that Dr Parkinson’s observation (as an experienced passenger) of the engines surging more than normal suggests that one of the engines may have lost power, when the pilot, who had over 2,000 hours experience, made no mention of any problem to the Chief Pilot after arrival in Adelaide, particularly in light of the fact that there was a spare Whyalla Airlines Chieftain aircraft on the ground at Adelaide at the time. It is almost inconceivable that the pilot would have departed on another flight if he had been aware of any problem with the aircraft engines.

The Coroner states that an electrical burning smell on the previous flight WW903 was a ‘mystery’ since none of the experts who gave evidence about it suggested a cause. There was evidence given by Dr Parkinson (T1910) that ATSB investigators had advised him that it was likely to have been from a new cabin heater that had been installed during the recent 100 hourly maintenance (such odours are common from newly installed heater units).

9.10 *The draft report acknowledges that Whyalla Airlines’ Operations Manual (Exhibit C73h) refers to Report 2046, issued by Piper Aircraft Corporation for ‘Aircraft Technical Data’ (p38). Report 2046 was one of three such reports produced by Piper for Navajo Chieftain aircraft, i.e. numbers 1750, 2046 and 1208. In fact, 1208 was the correct report for MZK but nothing turns on that - the directions for fuel leaning are the same in both versions.*

9.13 *The Pilot Operating Handbook also sets out the procedure for takeoff and initial climb as follows:*

4.23 TAKEOFF

Normal

While holding the brakes with the mixture and propeller levers full forward, advance the throttles slowly to a manifold pressure of 30 inches of mercury; then continue to advance the throttles at a normal rate and release brakes, but do not allow manifold pressure to exceed 49 inches. Use smooth, steady throttle movements, and avoid rapid opening and closing. Propeller speed for takeoff should be 2575 RPM.

The engines are adjusted to provide 43 inches Hg. manifold pressure at full throttle in standard temperature at sea level. Depending upon an altitude and temperature it is possible to reach higher (up to 49 inches) or lower manifold pressures.

Each engine density controller is set to produce rated takeoff power for the engine. The takeoff power manifold pressure for each engine will not necessarily be the same. However, if the spread in manifold pressure exceeds three inches during a full throttle climb, the density controller settings should be checked and serviced.

At 85 KIAS, rotate to a 10° pitch attitude and allow the aircraft to fly off. Maintain a pitch attitude which will result in acceleration of the aircraft to 95 KIAS at 50 feet. Before airspeed reaches 128 KIAS, retract the landing gear. Continue acceleration to the desired climb airspeed.

4.24 CLIMB

When clearance above obstacles and terrain permits, reduce to Maximum Normal Operating Power by setting the throttles to 40 inches Hg. manifold pressure and the propellers to 2400 RPM. Turn air conditioner on as desired. Lean the mixture to a minimum fuel flow of 30 gallons per hour at a maximum exhaust gas temperature of 1500°F and maximum cylinder head temperature of 475°F. Adjust cowl flaps and mixture as necessary to maintain engine temperatures within limits.

Turn the emergency fuel pumps OFF one at a time, and check fuel gauges and warning lights. At power settings above 75 per cent, maintain the mixture controls in the full RICH position except with Maximum Normal Operating Power setting when the mixture may be leaned as stated in the preceding paragraph.

Although the maximum approved operating altitude for this airplane is 24,000 feet, under standard atmospheric conditions and at maximum gross weight the multi-engine service ceiling and absolute ceiling are 27,200 feet and 28,300 feet, respectively.

(Exhibit C170g, sections 4.23 and 4.24)

It can be seen from the above that the Whyalla Airlines Operations Manual specification for climb of 30 usg/hr is the minimum specified in the Pilot Operating Handbook, and the cruise climb specification of 27 usg/hr is below the minimum specified. There is the protective caveat that the EGT should not exceed 1500°F, which is consistent with the specifications quoted above, although, as I will discuss later, Mr Braly said that this was too high, and that detonation was possible within those limits. There is no injunction against operating the engine at mixtures lean of peak.

ATSB comment

The Coroner states that the directions for fuel leaning in climb are the same in Piper Pilot Operating Handbook (POH) reports 2046 and 1208. In fact there is a difference in manifold pressure and minimum fuel flow in cruise climb between the two versions (see A2 pp 42–43).

The four Whyalla Airlines Chieftains were fitted with vortex generator kits, which according to the associated flight manual supplement, reinforced the climb power leaning procedure in POH 1208 (2400 RPM, 40 inches MP, and fuel leaned to not less than 30 usg/hr or maximum 1,500°F EGT. The actual settings specified in the company's operations manual for cruise climb were 2400 RPM, 36-38 inches MP and 27 usg/hr or max 1,500°F EGT. The Coroner commented that the Whyalla Airlines' cruise climb fuel flow setting was below the minimum specified. However, the minimum referred to is stipulated in Piper Chieftain POH version LK-1208 that also required the use of 40 inches of manifold pressure (cf the operator's lower 36–38 inches). The climb power settings, including fuel flow, were within the limits stipulated in Piper Chieftain POH 2046. The differing POH versions and the company setting appear to be similar in that each may lead to mild detonation (and in the ATSB's view possible formation of engine lead oxybromide deposits plus excess bromine that could cause other damage).

Mr Braly demonstrated that the peak cylinder pressures and temperatures at 38 inches MP and 27 usg/hr, and at 40 inches MP, 30 usg/hr, were identical. As the ATSB recommended in October 2000, conservatism is required in cruise climb settings with full rich to be preferred pending further research in the US. Greater clarity is also required in POH versions concerning the likelihood of serious detonation with engine settings such as 2400 RPM and manifold pressures above 40 inches even when fuel settings are relatively (or full) rich.

9.17 *In a letter dated 23 April 2001, Textron Lycoming responded to the findings of the draft ATSB report. The letter forms part of Exhibit C213. While Textron Lycoming accepted that ‘abnormal combustion’ was involved in both engine failures, they questioned whether incandescence from combustion chamber deposits was the cause of that. They offered a number of other possible explanations:*

- *excessive manifold pressure can be caused by improperly set density control valves on the turbochargers – there was no mention of this being examined either.*

9.50 *Mr Fearon acknowledged that if the density controller on the turbocharger was correctly adjusted, the engine on MZK should not have been producing more than 350 horsepower, whereas he was required to acknowledge that in order to achieve 147 knots TAS, the engine must have been able to produce more than 370 horsepower at 2,400 RPM between 1847:15 and 1855:54 (T4370).*

9.53 *Indeed, Mr Fearon acknowledged that if the density controller on the turbocharger was effectively limiting the power output to 350 horsepower, then the documentation from Piper Aircraft Corporation and Textron Lycoming does not support the assertion that the aircraft could obtain 147 knots true airspeed, let alone 153 knots or 158 knots.*

ATSB comment

The left engine density controller had its housing bolts sheared by a blow sustained during the aircraft impact and subsequent break up sequence. The upper housing had separated from the lower housing mount flange. The sensing bellows were exposed and subjected to bending pressure away from the lower housing. This was applied by forces associated with the attachment plumbing and relative movement of surrounding damaged structure. Some debris contamination of the bellows was evident. Discussion with overhaul personnel suggested that this disruption would render test figures unreliable for this unit when reassembled.

The right density controller did not exhibit any obvious external impact damage. It was examined and found appropriately locked and safety wired. In compliance with a recurring AD, the calibration of the density controllers was checked and found compliant only a few days prior to the accident. Because this is a repetitive requirement done using calibrated test equipment, the ATSB did not have any immediate concern regarding the density controllers’ settings.

As previously indicated, normal rated power for the TIO-540-J2B engine is 350 horsepower at 43.0 inches manifold pressure and 2575 RPM. Slight and permissible increases in maximum manifold pressure setting and maximum RPM setting will increase the maximum engine power output above 350 brake horsepower. In addition, any leaning of the mixture from full rich will increase the engine horsepower output until the fuel/air ratio is equivalent to best power, about 125°F rich of peak EGT. (Any leaning of the mixture at maximum manifold pressure and maximum RPM will increase power but is not approved by the aircraft or engine manufacturer and is likely to result in engine damage.) Similarly, as indicated at Attachment D, figs 1–4, the engine power output may exceed 350 bhp depending on the RPM, manifold pressure, and fuel flow settings selected.

The Coroner's comments regarding Mr Fearon's evidence are misleading. Mr Fearon gave evidence that 'if there was some means whereby the engine had a brake horsepower sensor, output sensor and that sensor limited the output horsepower to 350 horsepower, then the documentation from Piper and Textron do not support the assertion that the aircraft could attain 147 knots true airspeed'. Mr Fearon gave evidence (T4532) that the density controller 'doesn't know what the horsepower output of the engine is', and that other factors influence horsepower output, such as RPM and fuel mixture. As explained in Attachment E, the density controller only operates at full throttle and then, in simplistic terms, only limits the manifold pressure as adjusted during maintenance (between 41.5 inches and 46.5 inches) to achieve 350 horsepower at 2575 RPM, full rich. Clearly the density controller does not detect engine RPM or fuel flow and as such, cannot limit the engine power output to 350 horsepower under all circumstances. The demonstrations provided for the Coroner by Mr Braly clearly show the engine producing in excess of 350 horsepower under a variety of operating parameters at 2575 and 2400 RPM (see Attachment D, figs 1-4).

9.32 *Mr Kell told me that he calculated that MZK would have had a 20 knot tailwind during Flight 904, on the basis that MZK's groundspeed during Flight 903 was only 154 knots, and he would have expected the aircraft to fly at 174 knots during Flight 904 at 62 per cent power. He used this information to calculate that the difference, 20 knots, was the headwind component for Flight 903 (T3755-6). This seems a rather arbitrary and unsatisfactory method of calculating a wind component*

ATSB comment

The Bureau of Meteorology (BoM) provided the investigation with the 20 knot wind speed estimate. The investigator explained during the inquest (T3755 and T3787) that his wind analysis was only for the purposes of validation. Subsequently, during the inquest, the BoM provided the ATSB with a more conservative estimate of wind speed of 15 to 20 knots from 170 to 150 degrees true. See Attachment F.

9.39 *However, Textron Lycoming in a commentary on the ATSB final report which is also part of Exhibit C213, said that in order to achieve sufficient horsepower to achieve that speed on one engine, the mixture would need to be leaned to a 'best power' setting (T3540). As I have already observed, this seems inconsistent with the metallurgical analysis which suggested that the carbonaceous deposits on the No. 6 piston were consistent with the engine operating with a rich, not lean fuel/air mixture.*

9.56 *By the time Mr Fearon was being cross-examined by Mr Eriksen, the inconsistency between the allegation that Mr Mackiewicz had 'firewalled' the throttle on MZK without making a corresponding adjustment to the fuel mixture, thereby creating an unduly lean fuel/air mixture, on the one hand, and the evidence of Dr Romeyn that the carbonaceous deposits on the No. 6 piston from the right engine indicated that it had been operated at a rich mixture setting, on the other, had become apparent.*

13.14 *It is at this point that I found Dr Romeyn's evidence confusing and somewhat contradictory to the ATSB position. The theory advanced by Mr Cavenagh and his assistant Mr Fearon was that the left engine failed first at 1847, and that as a result the pilot 'firewalled' the throttle of the right engine in order to obtain maximum power, which thereby enabled the aircraft to fly at 147 knots true airspeed. In doing so, the theory suggested that the pilot, in the agony of the moment, neglected to firewall the mixture control as well, thereby creating abnormally lean mixture conditions at a high power setting, thereby leading to end gas detonation and damage to the No. 6 piston of the right engine leading to its failure. This theory is quite inconsistent with Dr Romeyn's theory about the presence of carbonaceous deposits on the No. 6 piston, due, as he asserts in the final ATSB report:*

'The characteristics of the piston crown deposits remaining on the pistons of MZK's right engine indicate that detonation is likely to have occurred under rich mixture

conditions. That is, the detonation free operating limits were exceeded at a high engine power setting.’(Exhibit C97, p52)

14.100 *I have already mentioned the apparent contradiction, between Mr Cavenagh’s theory that Mr Mackiewicz advanced the throttle on the right engine to maintain altitude without moving the mixture level to full rich, thereby causing abnormal combustion and the holing of the No. 6 piston in the right engine, and the evidence of Dr Romeyn that the presence of the carbonaceous deposits on the No. 6 piston in the right engine suggested that detonation is likely to have occurred under rich rather than lean mixture conditions. In other words, the Cavenagh theory is that Mr Mackiewicz unduly leaned the engine, whereas Dr Romeyn’s evidence suggests that the damage occurred when the engine was at a richer than usual power setting.*

9.14 *On the other hand, Textron Lycoming’s Operators Manual (Exhibit C172f) advises that their engines should ‘always be operated on the rich side of peak’ (Section 3, p6). In a later Service Instruction 1094D (Exhibit C73o), the following message appears:*

‘Textron Lycoming does not recommend operating on the lean side of peak EGT.’

ATSB comment

There is no inconsistency in the ATSB’s view that detonation occurred in the right engine and that the carbonaceous deposits found were indicative of a rich fuel setting. Although the expression ‘leaned to a ‘best power’ setting’ might suggest a lean mixture, a mixture set to the best power setting is approximately 125°F rich of a stoichiometric mixture, and therefore quite consistent with the deposits indicative of a rich mixture in the right engine No. 6 piston. A fuel setting can be rich (more fuel than the stoichiometric mixture) but not full rich. Detonation can also occur with a full rich fuel setting. Errors in advancing levers are not uncommon among experienced pilots (eg see ATSB Report 199904538, QF1 pp 44–45) and in this case the fuel lever may have inadvertently not been advanced to a full rich position.

9.52 *For example, I put to Mr Fearon that it was all very well referring to an average groundspeed of 167 knots, as calculated by Mr Kell from the radar data, but a reference to that same data suggests that the groundspeed varied up and down by a factor of five to six knots (T4371). If one accepts that the groundspeed dropped as low as 163 knots on occasion, one must also accept that it increased to 173 knots on other occasions in order to maintain the average of 167 knots. In order to achieve those peaks of 173 knots, and allowing for a tailwind component of 20 knots, this would have required the aircraft to achieve a true airspeed of 153 knots, and allowing for a 15 knot tailwind component, this would have required a true airspeed of 158 knots. Mr Fearon’s response was that the radar data has its limitations (see the discussion at T4370-73).*

ATSB comment

The actual groundspeed of the aircraft did not vary significantly from 167 kts between 1847:15 and top of descent. The graphical information included in the ATSB final report is a combination of radar data from two radar sensors. One of the radar sensors provided intermittent data during this period, and consequently the combined data shows fluctuations in groundspeed. Good data from the other radar sensor showed the groundspeed to have been quite steady at around 167 knots. It is difficult to understand why the Coroner has not referred to evidence provided by the ATSB during the inquest that included a large-scale graphical printout of the radar data showing the separate data from the two radar sensors and the correlation between the spikes in groundspeed and the intermittent data reception from one of the sensors.

9.54 *Mr Fearon was happy to use Mr Braly's findings, but when it became clear that the demonstration conducted by Mr Braly in America, which was demonstrated by him in a CD rom video (Exhibit C196m), was in an aircraft which, as I have already mentioned, was 350 pounds lighter, was fitted with winglets which reduced the drag of the aircraft, and was fitted with an intercooler, (which will allow the engine to produce more horsepower than a non-intercooled engine for the same manifold pressure) (T4524). Mr Fearon was unable to suggest what the difference in performance would have been having regard to these variations in specification of the aircraft (T4526-27).*

ATSB comment

As was explained to the Coroner during the inquest (T4525), in assessing Mr Braly's test flight, the ATSB had allowed for an 8 knot reduction in speed to allow for the weight difference between Mr Braly's aircraft and the accident aircraft. Only after Mr Fearon gave evidence that the test flight data provided support for the ATSB position, was he advised while under cross-examination that the provider of the test flight data had subsequently advised that his aircraft was fitted with performance enhancing modifications. The opinion of Mr Braly was that the combined effect of the weight difference and the performance enhancements would amount to between 5 and 7 knots speed improvement over VH-MZK. The ATSB does not have any data to challenge or question the reported value of the speed improvement. Therefore, accepting this advice, the 8 knot allowance for the weight difference applied by the ATSB was more than adequate to account for any difference in performance between the aircraft. Indeed, this further strengthened the ATSB view that Mr Braly's test flight supported the ATSB position.

9.55 *Beyond that discussion, Mr Fearon's evidence became unhelpfully speculative. For example, it was his suggestion that the pilot, Mr Mackiewicz may well have pushed the right engine up to a full power setting after the left engine failed, because it was his experience from the Maitland incident that the aircraft could not maintain altitude on one engine (T4547). However, in the Maitland incident there was extensive damage to the engine cowling which created significant drag, to the extent that the aircraft was unable to maintain altitude. See the photographs which appear at page 99. In this case there was no such damage to the cowling, yet Mr Fearon argued that Mr Mackiewicz might have jumped to the conclusion that MZK might behave in the same way in the absence of any decrease in the engine performance (T4548).*

ATSB comment

The Coroner has not acknowledged that in the dark unlit conditions and the high workload environment, the pilot would not have been readily able to view the left engine cowling to determine whether there was any damage.

The issue is the pilot's initial reaction to the left engine failure, and his response to that may well have been influenced by the Maitland incident, simply because genuine engine failures are rare, but also psychologically significant events, particularly when altitude cannot be maintained and an emergency landing is necessary (see also A2 p 51). As noted, it is possible that having increased the power on the right engine following the failure of the left, the pilot later assessed that maximum power (or more) was not required on the remaining engine and selected a lower power setting at some stage.

9.57 *Mr Fearon said that it was a possibility that Mr Mackiewicz did make the appropriate adjustment to the mixture, pushing it to full rich, but neglected to open the cowl flap, thereby allowing the engine cylinder head temperature to increase (T4549). It seems difficult to accept that failure to open the cowl flap would have been responsible for the engine overheating to the extent that aluminium would melt. It would seem extraordinary that Mr Mackiewicz would not notice a significant increase in cylinder head temperature if this had occurred. Mr Fearon's theory also overlooks the fact that the cowl flaps*

were open when the aircraft hit the water, on the evidence of the wreckage examined after it was recovered (see Exhibit C97).

ATSB comment

The Coroner's opinion that closed cowl flaps would be insufficient to cause overheating of the engine to the extent that aluminium would melt demonstrates a lack of understanding of the operation of high-powered aircraft engines and goes against the very reason for which cowl flaps are fitted. Operation of a high-powered piston engine at high power settings with the cowl flaps closed could induce excessive engine temperatures. The temperature of the engine is dependent on the rate of heat input from the combustion cycle less the cooling effect of the oil and airflow over the engine. Closing the cowl flaps significantly disrupts the airflow over the engine, restricting the ability of the engine to dissipate heat through airflow. If the rate of heat gain is greater than heat loss, the temperature of the engine will continue to rise till it reaches an equilibrium position where rate of gain is equal to rate of loss. This equilibrium temperature could be above the incipient melting temperature of aluminium piston material especially if there was single engine high power operation.

Regardless of how 'extraordinary' it might be to consider that the pilot would not notice a significant increase in cylinder head temperature, the damage sustained by the right engine could only have occurred if the cylinder head temperature was above the maximum limit. The cylinder head temperature sensor was fitted to the melted piston and cylinder assembly. Therefore, regardless of when the right engine overheated, and assuming the CHT indicating system was functioning correctly (and there is no evidence to the contrary), the pilot either did not identify a prolonged excessive right engine cylinder head temperature, or failed to take sufficient corrective action to rectify the over-temperature condition. The cowl flap actuators were in the open position when the aircraft was recovered from the water but this fact provides no conclusive information regarding the position of the cowl flaps at any stage of the accident flight, other than at the instant that the aircraft hit the water.

The Coroner sees a failure by the pilot to notice a significant increase in CHT during a phase of the flight associated with high workload and high stress as something 'extraordinary'. That raises the question of how he would describe the failure of the pilot to notice a significant increase in CHT during the climb and first 8 minutes of the cruise, an apparently benign and stress-free phase of the flight which is the period preferred by the Coroner for when the right engine damage occurred.

10.14

On 29 September 2000, Mr Lyons emailed the FAA, seeking similar information. He did not receive a response from the FAA until 23 February 2001 and this reply did not address the issues he had raised (Exhibit C222b, LL-7). This does not represent a good example of the much-vaunted international cooperation which is supposed to be a feature of aviation regulation based upon the Chicago Convention on International Civil Aviation.

ATSB comment

The ATSB investigation was hindered by less than full international cooperation, particularly in the context of US civil damages litigation. The implied criticism of the Chicago Convention and its Annex 13 covering accident investigation is unrealistic. There will always be shortcomings perceived in international multi-lateral agreements and in the amount of cooperation independent nation-states can obtain from companies and bodies in other nation-states. An adversarial legal process in Australia, including an inquest, may well gain even less cooperation than through the Annex 13 mechanism agreed by most countries in the world including Australia.

10.24 *The paper outlined that on 22 and 23 January 2002, Textron Lycoming were visited by a team from the FAA and advised that they were still trying to identify the problem and to determine a method of testing for the problem. It is to be noted that the FAA and Textron Lycoming had taken on board the ATSB conclusion that the Australian failure was caused by engine detonation due to leaning procedures, rather than by a defect in the crankshaft itself (see underlined sentence in the passage quoted above).*

ATSB comment

The Coroner incorrectly suggests that the FAA and Textron Lycoming had taken on board an ATSB conclusion that the left MZK crankshaft had failed due to detonation as a result of fuel leaning practices. ATSB Report 200002157 clearly attributes the left engine crankshaft fatigue crack initiation to a combination of preignition (not detonation) and bearing slippage. The ATSB concluded that detonation occurred in the right engine.

10.40 *The Mandatory Service Bulletin (MSB) No. 553 issued by Textron Lycoming on 16 September 2002 includes the crankshaft serial number V537912936, the crankshaft in the left engine in MZK, as one of about 3,000 crankshafts which are said to be affected by the MSB which states 'metallurgical testing indicates that the cause is material related'.*

ATSB comment

The Coroner's summary of the service bulletin does not make it clear that about 3,000 crankshafts were stated to be potentially affected by a material defect. The Coroner omits to mention the advice submitted regarding the testing of potentially affected crankshafts which indicates that about 30 per cent were affected and 70 per cent were not.

10.45 *It is clear that the ATSB conclusion that the failure of the left engine crankshaft in MZK on 31 May 2000 was initiated by thermal cracking as a result of bearing failure, rather than from a material defect in the crankshaft, affected the investigation in the USA. As a result, the MZK failure was put in the unconfirmed category. The briefing in February 2002 by the FAA states:*

'Eight fatalities are reported in one of the unconfirmed failures. This failure occurred in Australia and the Australian National Safety Board (sic) has attributed this failure to engine detonation due to the engine leaning procedure used by several Australian operators.'

(Exhibit C219d)

To that extent, the ATSB conclusion led the US Authorities to believe that the failure of the left engine crankshaft in MZK on 31 May 2000 was not relevant to their investigations, despite the highly suggestive circumstantial evidence outlined above.

ATSB comment

As noted re para 10.24 above, the ATSB at no time proposed that detonation from fuel leaning caused the left engine failure as suggested by the FAA.

11.24 *In light of all this evidence, and in particular the outcome of the Maitland incident on 7 January 2000, I am not persuaded that Mr Mackiewicz would have been influenced in any way by what happened in these incidents. In particular, the Maitland incident was unique in that the damage to the cowling of the left engine was so extensive, and created so much drag, that the aircraft would not have maintained altitude even if the other engine was functioning perfectly. The damage would have been apparent to him at the time. I am confident that Mr Mackiewicz would have assessed the ability of MZK to fly on one engine by reference to the performance of the aircraft on the day, rather than what happened in January 2000.*

ATSB comment

The Coroner has reached a conclusion concerning the response of the pilot that, in the ATSB's view does not take account of well established and recognised aspects of human performance that lead to a conclusion that the pilot's initial response to the left engine failure may well have been influenced by the Maitland incident. At the very least, the ATSB believes that there is no definitive proof that the pilot would not have been influenced by that event.

It is likely that, in the dark conditions during the accident flight, the pilot would not have been able to determine whether there was any cowling damage following the left engine failure. That would have added to the stress and uncertainty of the situation.

11.61 *The incident involving VH-BYG on 9 September 1999 illustrates that the vibration in the left engine and, inferentially, the damage which was noted later, occurred at the end of the climb and the beginning of the cruise phase of flight. This is consistent with Mr Braly's thesis that the leaning practices of Whyalla Airlines during the climb phase of flight, may have led to detonation and consequential heat damage to the piston. The incidents on 8 February 2000 and 20 May 2000 occurred while the aircrafts were in the cruise phase, while the engine was on a relatively low power setting. This does not assist in the analysis of whether high power settings may lead to such damage. The incident in April 2002 involving VH-LTW occurred while the aircraft was in the climb phase of flight, when vibrations in the engine commenced. Once again this incident illustrates the fact that heat damage to the piston can occur during a high power setting phase of flight.*

ATSB comment

The incidents referred to above can be distinguished from MZK by way of the stage of flight at which they became apparent and the nature of the damage. In the case of BYG on 9 September 1999, the damage was clearly limited to one piston and was reported to have been caused by a cracked spark plug ceramic. The 8 February 2000 incident occurred about 1 hour into the cruise phase of the flight and the 20 May 2000 incident more than 2 hours into the cruise phase of the flight. The LTW incident in April 2000 involved a melted piston that occurred very early in the initial climb phase of the flight that became immediately apparent to the crew and the aircraft was returned for a landing.

The Coroner fails to acknowledge that for such heat damage to occur, the cylinder head temperature gauge in the cockpit must show an elevated, above normal limits, indication, for at least a number of minutes. He has provided no explanation for why the pilot would not have observed the high temperature. There is certainly no indication that the pilot was under any abnormal stress during the climb phase of the flight. (See also ATSB comment re 9.57 at p 64 above).

11.36 *Mr Sharp said that the engine was impounded by the ATSB on 17 December 2001. He said that Dr Romeyn told him that the damage was similar to that of MZK, that it looked as if it was caused by leaning, and that there was some evidence of lead oxybromides in the cylinder. Mr Sharp said that his company used conservative leaning techniques, after which Dr Romeyn did not pursue the subject (Exhibit C179, p4)*

11.41 *Dr Romeyn acknowledged that Sharp Aviation did not lean their engine to the same extent as Whyalla Airlines did, although he was unable to assess the significance of that difference (T4063).*

ATSB comment

The ATSB does not believe that this hearsay evidence about what Mr Sharp said that Dr Romeyn said is accurate. Dr Romeyn at no time advised Mr Sharp that leaning caused the failure of the VH-JCH engine. The damage to the crankshaft of JCH was remarkably

similar to that of MZK. There was also evidence of lead oxybromides on the piston crowns of the JCH engine. Dr Romeyn pointed out the similarities with the MZK failure and explained the ATSB position in relation to the factors relating to that failure.

Before the crankshaft failure in JCH, the procedures of the operator of that aircraft involved leaning from full rich during climb. After the occurrence, the operator changed to using full rich fuel mixture settings during climb.

11.37 *Mr Sharp said that by March 2002 the ATSB indicated that they did not propose to carry out a detailed analysis of his broken crankshaft, even after the recall of similar units by the Lycoming factory on 1 February 2002. Mr Sharp said he found this confusing in light of the similarities with the MZK crankshaft (Exhibit C179, p4).*

ATSB comment

The ATSB did not say that no detailed analysis was going to be undertaken, rather that the detail would be for its high-powered engine study report involving more than 12 engine failures, rather than directing limited resources at an individual occurrence report.

11.43 *Mr Murphy is a qualified Mechanical Engineer who has specialised in Automotive Engineering for more than 30 years. This was the first time he had worked on an aircraft engine (T2143). For the purposes of this inquiry, I will work on the basis that the principles involved are the same. No party has suggested to the contrary.*

ATSB comment

While some principles are the same, most aircraft have much higher powered engines and tighter tolerances and are designed and operate with much greater precision. The stresses/loads and pressures on turbo charged aircraft engines are significantly more critical than those in most automotive applications.

11.44 *Mr Murphy's findings were as follows:*

- *He detailed the damage noted to the bearings, connecting rods, pistons and crankshaft due to the flailing of the connecting rod after the end cap of the big end came away;*
- *There was a substantial drop in the crown hardness of all the pistons noted, especially numbers 2, 4 and 6. He said:*

'The under crowns of these pistons are also showing signs of piston crown over heating. The crankshaft failure has taken place through the number six big end journal. From the beach marks on the fractured surface it is clear that this failure has been caused by a fatigue crack. It is also clear that this fatigue crack has started near the fillet radius, at the edge of the journal and at the lowest point of this journal, when it is in its TDC position. Microscopic examination of this fractured surface reveals that this fatigue crack actually started at a very small void (flaw) in the journal surface, approximately 0.8 mm below the surface of the fillet radius. This fatigue crack appears to have initially developed relatively slowly. However, after extending out radially some 2.5 mm, its progression has then accelerated, covering at least 60 per cent of the fractured surface before the crankshaft finally broke.' (Exhibit C177)

11.52 *Mr Murphy said that he saw no thermal crack from the surface of the journal down to the fatigue crack initiation point, as suggested by Mr McIlwaine SC, counsel for the ATSB. He would have expected to see one under the microscope if there had been one there (T2167, T2175).*

ATSB comment

The examination of the fatigue fracture features of the crankshaft from VH-JCH (Sharp Aviation) by Mr Murphy is based on stereo light microscopy. Only one side of the fracture surface was documented.

In light microscopy, images are formed as a result of the scattering of light. Contrast between features is created by differing orientations to the incident light, different reflective properties or shadowing by oblique illumination.

The claim that the dark area in the general proximity of the fatigue origin is a void created by a non-metallic inclusion has not been verified by the examination of the mating side of the fracture or the use of alternate means of lighting, such as, coaxial incident lighting.

Close examination of the initiation site has revealed that the shadow feature is located off centre from the fatigue progression marks. Under oblique illumination the dark feature may be created by the shadow from a step feature.

There has been no acknowledgment of the effects of fracture surface secondary damage on the microscopic features of the fatigue initiation site.

The proposal that a spherical inclusion acted as the fatigue initiator is at odds with the oxide filled seam defect proposed by Dr Powell.

The proposal that the inclusion had fallen out is speculation. No physical evidence is provided regarding the nature of the proposed inclusions and no reference is made to the mating side of the fracture. It is unlikely that an inclusion could fall out cleanly from both fracture surfaces.

The features of the failure of crankshafts from MZK and JCH were similar. In addition to the location and nature of fatigue crack growth, the nature of No. 6 connecting rod journal bearing destruction was similar. Both bearings had been installed with a copper-based anti-galling compound between the bearing back and journal housing. High melting point lead compounds (lead oxy-bromide) were present on all combustion chamber surfaces.

A very significant difference between the engine failures of MZK and JCH was the time in service since factory overhaul. The engine from MZK failed after 262.1 hours in operation while the engine from JCH failed after 1054.9 hours in operation. If the defect responsible for the initiation of fatigue cracking is of similar severity the large difference in failure time indicates that the defect was not created by crankshaft manufacture. If the very significant defects, located in the same highly stressed region of the crankshaft, were present from the time of manufacture failure would be expected after a short time in service, not after approximately half of the engine life as was the case for the JCH engine.

11.50 *Mr Murphy did not agree with the ATSB report into the JCH failure (Exhibit C177d). In particular, he did not agree that the fatigue crack initiation was 'associated with a discontinuity of the nitrided surface zone' (T2156).*

ATSB comment

Mr Murphy was unclear as to the extent of the nitrided zone. In evidence, he claimed it was very shallow. He subsequently corrected that view in a letter to the Coroner.

11.51 *Mr Murphy also disagreed that it was possible to see fatigue cracking in the centre of the connecting rod cap at all. He said that the failure of the big end bearing and, consequently, the end cap, was due to the progressive failure of the crankshaft, and was not a separate example of fatigue failure (T2157-58).*

ATSB comment

The separation of the connecting rod cap from the connecting rod occurred after a nut was lost from one big end assembly bolt. The cap was intact following engine stoppage.

Fatigue cracking was evident in the cap during examination by the ATSB. The cap was bent to open the fatigue crack surfaces for inspection.

No evidence has been presented to support views that the connecting rod big end bearing was damaged and destroyed by the action of the opening of the fatigue crack in the journal. Evidence of bearing material adhering to the fatigue fracture surfaces and fracture surface edges would be expected if this mode of bearing destruction had occurred.

11.54 *The features of the failure of the JCH crankshaft are identical, in almost every respect, with that of the left crankshaft of MZK. The failure happened only five days before the release of the ATSB final report (Exhibit C97), and more than a year after Mr McHardy notified Mr Lyons of CASA that a metallurgical problem had been identified in Textron Lycoming crankshafts in the USA, and a year after an Emergency Airworthiness Directive had been issued in relation to Teledyne Continental crankshafts. Yet the occurrence warranted no more than a 1½ page report, without detailed metallurgical analysis, by the ATSB, and an indication that it would be included in a larger study, which is still yet to occur.*

ATSB comment

In March 2002, the ATSB emphasised the similarities between the failures of MZK left and JCH crankshafts to those assisting the Coroner. The Coroner omits to mention that the ATSB could not reasonably have had regard to problems with a different engine manufacturer's crankshafts and to problems in the US said to not affect Australian aircraft as the Coroner finds elsewhere (paras 10.4, 10.17 & 10.36). The resource demands of the MZK inquest were principally responsible for the delay in the larger study report.

11.56 *VH-JCH suffered a virtually identical crankshaft failure where engine leaning procedures could not be blamed (and there was no talk of lead oxybromide deposits), and yet the ATSB did not re-evaluate their conclusions.*

11.65 *To what extent do the events of 14 December 2001 suggest that the left engine of MZK failed in similar circumstances. In particular:*

- *The fact that lead oxybromides were not implicated in the failure;*
- *The operator's leaning techniques were described as conservative;*
- *The similarity of the apparent cause of the fracture of the crankshaft*

ATSB comment

The assertion that there were no lead oxybromide deposits or engine leaning issues with VH-JCH contradicts the evidence supplied by the ATSB and accepted in the Coroner's own paragraph 11.36.

11.66 *The features in the fractured crankshaft in VH-JCH on 14 December 2001 (the Sharp Aviation incident), are strikingly similar to the fracture of the crankshaft in the left engine of MZK on 31 May 2000. Dr Arjen Romeyn, the ATSB metallurgist who had been heavily involved with MZK, agreed that the features in the JCH crankshaft were very similar. I find it surprising that Dr Romeyn did not subject the JCH crankshaft to a detailed examination having regard to these similarities. The investigations by Mr Murphy reveal the striking similarity between the features in MZK and those in JCH, including the fact that the fracture had occurred at precisely the same location. The beach marks were very similar. The fatigue crack initiation point was almost identical. These similarities should have been clearly apparent to the ATSB.*

ATSB comment

The Coroner does not mention that, at a briefing specially conducted by the ATSB on 1 March 2002 for Counsel Assisting, Solicitor Assisting, and the investigating police officer, the significance of the JCH incident was highlighted. This included showing those persons the disassembled engine that displayed the fractured crankshaft and noting striking similarities between that failure and the MZK left engine crankshaft failure. It was suggested by the ATSB that the Coroner might be interested in taking possession of the JCH crankshaft for its potential relevance to the inquest. No action in that regard was taken by the Coroner or his team.

The JCH crankshaft was subject to detailed examination by the ATSB to the extent that the similarities between it and MZK left were 'clearly apparent' to the ATSB. However, the owner of the aircraft was in a hurry to regain possession of the crankshaft for warranty claim purposes. Analysis of deposits on the piston crowns of the JCH engine identified the presence of lead oxybromides. The Coroner found it 'surprising' that the ATSB 'did not subject the JCH crankshaft to a detailed examination having regard to these similarities'. Those similarities were the very reason why the ATSB brought the incident to the attention of the Coroner. It is not clear what benefits the Coroner anticipated that a more detailed examination of the JCH failure would bring beyond the 'striking similarities' that were brought to his attention by the ATSB. The ATSB emphasised that further analysis of the similarities was to occur in a larger multi-engine study.

- 12.6 *The ATSB did not attribute the failure of the right engine of MZK to lead oxybromide deposits. Indeed, the ATSB concluded that the 'carbonaceous nature of the residual deposits on the piston crowns (of the right engine) indicated that detonation had occurred under a rich fuel-air mixture setting. Rich mixture settings are used with high engine power settings' (Exhibit C97, p vii). This is to be contrasted with their assertion that lead oxybromide deposits, which were more likely to be the consequence of operating the aircraft with an excessively lean fuel-air mixture, contributed to the left engine failure.*

ATSB comment

Because the failure mode for the left and right engine was different, it is hardly surprising that different issues (including deposits) would be identified as contributing to the failures. (See also ATSB comments re the Coroner's 9.14 at p 62 above).

Deposits characteristic of rich-mixture operation may be laid down over a short period of engine operation. Therefore, rich mixture deposits evident in the right engine of MZK are likely the result of the operation of the engine during the period that severe detonation was occurring, that is during the latter stages of the accident flight. The ATSB believes that the fuel setting was rich of stoichiometric but it probably was not full rich. However, detonation can occur even at full rich fuel settings. With the left engine, the ATSB recommended further research concerning the formation of lead oxybromide deposits but did not assert that they formed lean of the stoichiometric mixture.

- 12.7 *Dr King said that the damage to the No. 6 piston in the right engine was due to end gas detonation, which is a function of increasing temperature and pressure, and does not require an ignition source as preignition does (T3454). Lead oxybromides were therefore irrelevant to the failure of the right engine.*

ATSB comment

This misleadingly reads as if Professor King was disagreeing with the ATSB whereas the reverse is the case and the above statement by Professor King is consistent with ATSB Report 200002157. The ATSB has never suggested that lead oxybromide played any part in the failure of the right engine.

12.20 Professor King made a number of other criticisms of the scientific methods adopted by the ATSB technicians in reaching their thesis, but for the purposes of these findings, it is not necessary to discuss them here.

ATSB comment

The assertion that the ATSB investigator with a Ph.D and twenty years experience in failure analysis whose experience led him to suggest the lead oxybromide 'thesis' was a 'technician' in contrast to 'scientists' or 'experts' assisting the Coroner is gratuitous. In addition, the Coroner notes at paragraph 12.12 that the ATSB analysis identifying lead oxybromide was carried out by a group of five appropriately qualified independent scientists. (See also A2 p 36 and A3 p 88).

12.21 As to the conclusion of the ATSB that one of the factors leading to the failure of the left engine was 'the accumulation of lead oxybromide compounds on the crowns of pistons and cylinder head surfaces':

- Professor King said that there is no evidence whatsoever that there were lead oxybromides on any of the cylinder head surfaces of VH-MZK (Exhibit C208a, p12);
- If there were lead oxybromides present they were confined to one small area on the piston crown of the No. 6 piston, left engine, which coincidentally was the spot where the ANU took one of two samples, leaving nothing on the rest of the piston crown and nothing on any of the other pistons tested in either engine (Exhibit C208a, p13);
- The tan coloured deposits referred to in Figure 47 of the ATSB final report (Exhibit C97) were not found in VH-MZK's engines and it is not possible to compare them with MZK's piston crowns as the magnification in the photographs in Figure 47 is not stated (Exhibit C208a, p12);
- Even if lead oxybromides had been present on the piston crowns in the left engine, there is still not enough material from which it could be concluded that they are relevant to the issue of preignition. Professor King said:

'It is not just the temperature of the deposit that's important, it's also the mixture composition so what one needs to reach what is called the minimum ignition energy which depends on the pressure, it depends on mixture composition, it depends on temperature, how many different deposits you might have; it's a very complex issue and one could not say simply because you have one deposit of lead oxybromides that it will cause pre-ignition'(T3451-52).
- Professor King concluded:

'This evaluation, combined with the results of the SEM analyses presented in Section 3 above must cast considerable doubt on the ATSB conclusions that lead oxybromide compounds were present in sufficient quantity to play a significant role in the failure of the left hand engine of VH-MZK.' (Exhibit C208a, p13)

ATSB comment

The statement by Professor King that there is no evidence whatsoever that there were lead oxybromides on any of the cylinder head surfaces of VH-MZK is wrong and ignores the evidence of Dr Romeyn and the Australian National University and University of Canberra scientists. The Coroner's apparent acceptance of Professor King's opinion, by use of the word 'if', that lead oxybromide may not have been present in the samples taken by the ANU and University of Canberra scientists is offensive and unwarranted. Further, the Coroner omits to cite here the ATSB contention that the quantity of lead oxybromide potentially relevant to the initiation of the left crankshaft fatigue crack through some combination of preignition and bearing slippage was the quantity about 50 flights before the accident not the quantity after the engine had been partially destroyed in the accident and had been on the seabed for over a week before being stripped down (cf paras 13.9 & 13.10).

12.27 *Dr Zockel explained that the manner in which the fatigue crack propagated through the journal to approximately half way, and at an angle of about 15° to the webs on each side, indicates that the forces acting upon the journal were not simply bending, but also had a torsional shear component (T2050). This is demonstrated in the ATSB report Exhibit C97, figure 31, page 57.*

ATSB Comment

See A2 p 37 of this report.

12.29 *As to the failure sequence of the left engine, Dr Zockel contended that it is not possible to determine whether the journal completely failed first, or whether it remained 'keyed together' by the end cap of the connecting rod remaining intact, and the final failure did not occur until the end cap failed as a result of the bearings being 'machined out' by the steadily failing crankshaft within, eventually producing the same result. He said:*

'They are both possible but for the bearing failure to occur at the same time and the same place as the fatigue (crack), the probabilities are very much less, and so I would say on the basis of probability that the crack in the journal resulted in the failure of the bearing. But in the end it was the bearing had to let go completely - the big end had to basically be destroyed for the crankshaft to actually come apart.' (T2063)

ATSB comment

Dr Zockel has provided no substantive arguments or evidence to support his conclusions. With regard to bearing failure there a number of ways a bearing can fail. The loss of sections of bearing alloy from a multi layer bearing is one mode. Equally as important is the failure to continue to retain the bearing in its correct location. It is acknowledged in the literature on journal bearings that the loss of location of bearing inserts can have life-limiting effects on crankshafts. (See also A2 pp 37–39).

12.32 *Dr Zockel said that he did not believe that the bearings would have been damaged or destroyed as a result of preignition. He said:*

'We see on the right-hand engine that where there was undoubtedly detonation, whether it was pre-ignition or otherwise, the bearings were fine. There was no damage to the big-end bearings or the crankshaft, so detonation doesn't necessarily mean a damaged bearing.' (T2079-80)

ATSB comment

The ATSB agrees with this citation from Dr Zockel regarding the right engine bearings.

The fact is that in the left engine the bearings were not 'fine' and the ATSB has an explanation for that whereas others don't. The evidence of bearing slippage, excess bromine and presence of some quantity of lead oxybromide deposits is incontrovertible and should not occur in a properly functioning engine. There are significant safety implications regarding these issues that the Coroner dismisses (paras 15.15, 15.16).

The bearing inserts from both MZK engines did not show bearing alloy delamination. However, an examination of the bearing surfaces indicated that high combustion pressures had affected the bearing surfaces. Mr Murphy also made this observation.

12.33 *Dr Zockel said that it is clear from an examination of pistons No. 5 and No. 6 in the right engine, and in particular the melted piston edges, that the right engine had experienced detonation. He said that the rough appearance of the melted parts indicated that the detonation was in the form of end gas detonation rather than preignition.*

12.34 Dr Zockel explained that because the sandblasted appearance of the No. 5 and No. 6 cylinders in the right engine was due to end gas detonation, which does not require an external ignition source, he was able to dismiss the theory that the detonation process was due to deposits on the pistons (T2088). He said:

'Combustion knock (end gas detonation) is facilitated by mixtures that ignite easily, such as those close to stoichiometric, or those having low octane number fuels.'

(Exhibit C176, p7)

ATSB comment

It is not made clear by the Coroner that Dr Zockel is agreeing with the ATSB's conclusion here regarding the right engine.

12.39 As to the mechanism of engine failure from there, Dr Zockel's opinion is as follows:

'Once the piston was sufficiently damaged to allow the charge to enter the crankcase the compression in this cylinder would have been significantly reduced and the engine power would have dropped. The gas flow through the crankcase would have carried out oil mist through the breather pipe until the oil level fell below the oil pump intake pipe. The lack of oil pressure would then also feather the propeller and so effectively become an engine failure although the engine would have been capable of delivering power until the engine seized due to lack of oil. There is no evidence of any seized components.'

(Exhibit C176, p8)

ATSB comment

In contrast to the Coroner's conclusion at para 12.40 about the right engine damage probably arising from detonation in the climb phase, Dr Zockel emphasises that a hole would have led over time to loss of oil and propeller feathering and engine seizure and notes that this did not occur. This is strong support for the scenario proposed in ATSB Report 200002157 that the hole in the No. 6 piston, right engine, developed later in the flight (after the left engine failure).

12.40 From all of the above, it can be concluded from Dr Zockel's evidence as follows

- *The fatigue crack which caused the failure of the crankshaft in the left engine was not initiated during the combustion stroke of the engine, and hence any suggestion that abnormal combustion was occurring in that cylinder is irrelevant;*
- *The fracture of the crankshaft was not due to bearing failure or thermal cracking at the No. 6 journal in the left engine;*
- *The fatigue cracking in the crankshaft led to failure of the bearings rather than the other way round;*
- *The appearance of the No. 6 piston in the right engine suggests that it was damaged as a result of end gas detonation;*
- *End gas detonation does not require an external ignition source, so any discussion of lead oxybromides in relation to the right engine is irrelevant;*
- *End gas detonation was more likely to occur during operation of the engine at settings approaching the detonation limits for the engine, which most probably occurred during the climb phase of the flight.*

12.68 *Mr McLean produced a PowerPoint demonstration which illustrated the angles at which cracks could be expected to be found as a result of varying causes. The diagrams (Exhibit C221) demonstrate that the actual angle at which the fatigue crack propagated is at about 75° to the angle at which thermal cracks or cracking from piston loads might be expected (see Exhibit C221 and T4384).*

12.70 *Mr McLean did not accept the ATSB's theory that abnormal bearing loads caused bearing failure resulting in the bearing rubbing on the fillet radius and causing a thermal crack, for several reasons:*

- *In his view the evidence suggested that the cracking occurred under reasonably low stress conditions and not in conditions where abnormal loads were being created;*
- *The alignment, as I have already discussed, is not consistent with a thermal crack;*
- *He found it difficult to believe that the bearing, having failed to the extent that it was rubbing on the fillet radius and causing a thermal crack, would then survive for between 50 and 70 flights, as the number of beach marks evident in the fracture surface demonstrate (T4386-87).*

ATSB comment

See A2 pp 37–39 of this report.

12.44 *The steel used in aircraft crankshafts is commonly designated 4340 which is an American specification. Dr Powell said that the Metals Handbook, 8th Edition, Volume 1 entitled, 'Properties and Selections of Metals', published by the American Society of Metals in 1961, at page 224, specifies that the maximum permissible size for oxide inclusions in 4340 steel is 8 microns, and that once this level is exceeded, the fatigue strength of the metal decreases significantly (T3381).*

ATSB comment

The reference in Metals Handbook 8th Edition Vol 1 page 224 does not specify the maximum inclusion size permissible in 4340 steel. The data presented shows the effect of inclusion size on fatigue strength for 4340 heat-treated to a particular strength (the ultimate tensile strength is not reported). The dependency of fatigue strength on non-metallic inclusion size is well established.

The claim that the maximum permissible size for oxide inclusions in 4340 steel is 8 micron is made without any basis and no reference to any manufacturing process specification. It is made without an understanding of the component design process.

The maximum allowable design stress is established on the basis of applying factors to the strength of the material to allow for geometric details (such as the stress concentrating effect of fillets) and the scatter in the material strength from lot to lot and surface finish. Material data is grouped by manufacturing process, surface finish and method of loading (eg rotating bending or alternating tension etc). Fatigue testing of material establishes strength levels that include the effects of non-metallic inclusions typically formed by the specified manufacturing process.

Crankshafts have been manufactured from steels produced by melting while exposed to air. This method of production results in oxide and sulphide inclusions of larger size and greater volume fraction than steels produced by the vacuum arc remelting process. The data contained in the metals handbook shows that the fatigue strength of air melted 4340 is significantly less than that of vacuum arc remelted 4340. Crankshafts manufactured from air melted 4340 steel are still used in high power Lycoming engines and are not subjected to any recall.

Fatigue failure is a function of the applied stress level and the component strength. The applied stress level is controlled by the detail design of the crankshaft (web, journal sizes, fillet dimensions) and the effect of the compressive residual stress state created by the

nitriding process. The relationship between applied stress levels and material fatigue strength is based on the application of factors of safety. Design to prevent fatigue failure is not simply and solely based on published values for fatigue strength.

12.47 *In summary then, the ATSB investigators accepted Dr Kim's assertion to that effect at face value and incorporated it within their report.*

ATSB comment

The Coroner's assertion that information was accepted from Textron Lycoming's metallurgist on face value and incorporated in the report is wrong and does not reflect the evidence given by the ATSB during the inquest.

12.49 *Dr Powell and Mr Alasdair McLean, a doctoral student who was assisting him, ground and polished the sample again, since it was in an etched condition when received from the ATSB. After grinding and polishing, they examined the samples under the reflected light microscope, and found 'grey particles' approximately 4 millimetres below the nitrided surface and at the nitrided surface of the sample. These particles were particularly concentrated in two groups approximately 7 mms apart. He said that the clusters were slightly larger than 1 mm across and individual particles were approaching 100 microns. Taking a cluster of up to 1 mm across, which is 1,000 microns, this massively exceeds the 8 micron limit described above (T3386).*

12.50 *Dr Powell said that even one of those particles of 100 microns would have been enough to substantially reduce the fatigue strength of the crankshaft and a cluster of such particles would have an even greater effect (T3387).*

12.58 *Following this further testing, Dr Romeyn changed his position somewhat, and withdrew the suggestion that this corrosion was due to hydrochloric acid as part of Marble's reagent. A further statement from Dr Romeyn submitted through Mr McIlwaine SC (Exhibit C219e) states:*

'10.1 Following open candid discussions, review of test results and methods it was agreed that the presence of the grey iron oxides in the specimen may be related to one of two mechanisms, oxidation at high temperature or corrosion:

10.1.1 Dr Powell still holds the opinion that the large grey coloured abnormalities are iron oxides created during crankshaft high temperature manufacturing processes.

10.1.2 Dr Romeyn is of the opinion that the grey coloured anomalies which he has viewed under the light optical microscope on two occasions at the Adelaide University engineering department are iron oxides as a result of localised corrosion created by the action of water vapour (humidity) on the specimen surface.

10.1.3 Dr Romeyn is of the opinion that the grey abnormalities are iron oxides caused as a result of corrosion as referred to above. However, he agrees that the corrosion is unlikely to be caused by the Marble's reagent infiltration of the crack between the specimen and the Bakelite sample or that this has as a result of capillary action gravitated to the sides and surface of the specimen causing the corrosion.

10.2 The detected presence of Chlorine in some 'inclusions' is most probably (greater than 75 per cent) related to the presence of residual chemical species from the Marble's macro-etchant.

10.3 With regard to the cluster of smaller oxide 'inclusions' observed approximately 4 mm below from the surface of the journal radius and away from the other oxide 'inclusions':

10.3.1 Dr Powell considers that these oxides have formed as a result of processing at high temperatures.

10.3.2 *Dr Romeyn considers that it is possible that these oxides had been formed as a result of localised corrosion.*

(Exhibit C219e, p7-8)

ATSB comment

The ATSB is firmly of the opinion that the 'massive' grey particles in the old sample were the result of surface corrosion and that the observed smaller oxide inclusions were normal. (See pp 4–5, A2 pp 39–40 and Attachments B and C of this report).

12.59

Dr Powell explained that the relevance of the presence of oxide inclusions in the bakelite sample which is taken from the No. 5 fillet radius is that when the crankshaft is being manufactured, a crack can form during the casting process at elevated temperature, and the surfaces of the crack can become oxidised rendering the steel prone to flaking or 'cold cracking'. If such a cold crack runs to the surface, any subsequent reheating of the forging will oxidise the surface of the crack again, so that any subsequent deformation through rolling or forging will produce a seam with oxide inclusions spread out along the seam (T3401).

ATSB comment

The claim that the oxide inclusions present on the surface of a section prepared from the No. 5 main bearing journal two years prior to examination by Dr Powell were high temperature iron oxide inclusions is made with no supporting evidence. Attempts by Dr Powell to establish the crystallographic structure of the oxides were unsuccessful. After light grinding and repolishing by Dr Powell and his assistant removed about 55 microns from the specimen surface, no features were evident. The ATSB has concluded that it is most likely that what was observed was surface corrosion that had occurred during storage.

The claim that the presence of iron oxide, in the form of thin discs, was evidence of a seam defect in the steel forging is tenuous. No other sectioning by Dr Powell revealed any evidence of a seam. The proposal that a seam may be formed during the reduction in cross-section of a large bloom or billet of steel is made with no reference to the process of vacuum arc remelting and the scale of forging stock produced by this process. The claim that a seam defect created by hot working stock material was present at both the No. 5 main and No. 6 connecting rod journals is made.

The explanation in this paragraph doesn't make sense. The vacuum arc remelting process is used specifically to remove dissolved gases such as oxygen and, in particular, hydrogen. Hydrogen is generally accepted as the cause of flaking or cold cracking.

The proposition of a seam defect extending from the No. 5 main bearing journal to the No. 6 connecting rod journal is not based on any substantive evidence and is also not supported by McSwain who reported that 'no indication of... an oxide seam were observed'.

12.62

Dr Powell disagreed with that analysis. He argued that any thermally induced cracking would have occurred circumferentially around the crankshaft, rather than radially. Secondly, he argued that a thermally induced crack on a nitrided surface would have been intergranular through the prior austenite grain boundaries by iron nitrate, as was the case with other thermal cracks in the crankshaft which occurred after the crankshaft failed (T3399-3400). An explanation for this highly technical analysis is at T3411.

12.64

Further, Dr Powell offered the opinion that if the fatigue crack had been initiated by a thermal crack coming down from the surface of the nitrided layer, the appearance of the 'beach marks' would have been different. Photographs taken by Mr Hood (C194) and Mr McLean (Exhibit C221a), clearly demonstrate that the beach marks are of a 'bullseye' configuration, with a small circular defect at the centre, approximately 1 millimetre below the surface. If the fatigue crack had been initiated by thermal cracking, the beach marks would have been 'moon shaped or crescent shaped' coming down from the thermal crack (T3425).....

ATSB comment

The proposal by Dr Powell that cracks in the nitrided (hardened surface) zone created by thermal expansion stresses can only be formed in a circumferential direction with respect to the journal and not in the radial direction is made without any basis. There are numerous examples of crankshafts that have been heated locally in the region of journal fillets through contact with other engine components or grinding wheels that exhibit radially oriented thermal cracks.

For the case of localised circumferential heating expansion along the axis of the journal is constrained by the adjacent cool material. In contrast the expansion of the narrow region of heated material is free to expand in the circumferential direction. Thermal strains in the circumferential direction will result in cracks transverse to the circumferential direction (that is oriented parallel with the axis of the journal). This was accepted by Mr Mclean during his evidence and he agreed that thermal cracks would form longitudinally (or axially) rather than circumferentially.

The claim that the pattern of beach marks would be moon shaped extending from a thermal crack ignores the more likely existence of thermal cracks oriented parallel with the journal axis. For axially oriented cracks a stress concentration is created at the end of the thermal crack creating a likely site for fatigue initiation. Fatigue initiation from these types of thermal cracks has been observed.

Fatigue initiation below the surface of a hardened crankshaft journal does not mean that fatigue was a result of a material defect. The distribution of stress from the surface into the crankshaft under applied bending loads combined with the extent of the compressive residual stress state results in the highest alternating stresses being developed at the boundary between the hardened surface zone and the core. The development of stresses that exceed the design allowable stress for the crankshaft will normally result in subsurface fatigue crack initiation. Only when the applied stresses greatly exceed the design allowable stresses will fatigue cracking initiate at the journal surface.

12.65

It is noted that Dr Powell was not cross-examined by counsel for the ATSB on 11 November 2002 or when he was recalled on 12 November 2002 to give further evidence.

ATSB comment

ATSB's senior counsel was unavailable at short notice and this was the major reason he did not cross-examine Dr Powell. In addition, this observation by the Coroner is an indication of the adversarial nature of the inquest. The ATSB believed that its experts were attending to assist the Coroner. However, there appeared to be an expectation from the outset that the ATSB should act as a 'party' and mount some form of legal case, involving extensive cross-examination as would be more appropriate in an adversarial environment. The ATSB does not have the resources or the remit to become involved in such processes.

12.73

Taking the combined evidence of Dr Powell and Mr McLean, it can be concluded that:

- *There were iron oxide ‘inclusions’ in the sample of the material taken from the No. 5 journal of the left engine crankshaft;*
- *The ATSB initially argued that these were not inclusions but were artefactual results of corrosion since the sample was taken. In respect of some of the abnormalities, this was advanced as merely a ‘possible’ explanation;*
- *On the balance of probabilities, I reject the ATSB’s arguments, and find on the basis of Dr Powell’s evidence that these were high-temperature oxide inclusions in the crankshaft material of sufficient size to materially affect the tensile and torsional strength of the crankshaft;*
- *The presence of inclusions in the No. 5 journal gives rise to the possibility that there were similar inclusions in the No. 6 journal, where the fracture occurred because, having regard to the way the crankshaft was made, it would have been in the same ‘seam’;*
- *Such an inclusion was not found at the origin of the fracture site but this does not exclude the possibility that it was lost during the fracture process;*
- *The nature and physical features of the fatigue crack in the left engine crankshaft are indicative of a subsurface defect in the crankshaft material.*

ATSB comment

The proposal put forward by Dr Powell and supported by Mr McLean that an iron oxide filled seam was responsible for fatigue crack initiation is at odds with the random metallurgical defect referred to in all publications by the FAA on the failure and recall of Lycoming crankshafts. The morphology of oxide inclusions formed in a seam (flattened discs, with the major dimension of the disc oriented parallel with the axis of the journal) would not result in the appearance of a spherical void in the plane of the fatigue crack (cross section of the journal). Thus the proposal of the presence of an oxide filled seam as the fatigue initiating defect is at odds with the proposals of Mr Hood and Mr Murphy. (See also p 76 above and Attachments B and C).

12.79

Mr Braly particularly disputes the assertion that deposit-formation on the pistons led to detonation, and drew attention to the fact that, as I have already identified, this is a function of the engine running rich, not lean. He said that the debate about deposits causing detonation was a ‘red herring’ (Exhibit C196a).

12.97

Mr Braly was critical of the ATSB’s conclusions in relation to the presence of lead oxybromides and their alleged role in the failure of the two engines in MZK. In particular, at page 52 of Exhibit C97 there is reproduced, from an American website, a picture of the piston of an engine which failed in what is known as the ‘Sacramento Sky Ranch’ incident, and which was used by the ATSB as an example of abnormal engine deposits. The caption to figure 24 on that page reads as follows:

‘Combustion deposits associated with detonation/preignition resulting from the combustion of aviation gasoline contaminated with aviation turbine fuel (Sacramento Sky Ranch)’ (Exhibit C97, p52)

12.103

The evidence of Mr Braly leads to the following conclusions:

- *Even if Whyalla Airlines was using lean fuel mixtures in the cruise phase of flight, this would have led to ‘benign’ and not abnormal combustion events in the engine, and fewer deposits. The discussion of lead oxybromides is a ‘red herring’;*

- *The mixture settings used by Whyalla Airlines in the climb phase would probably have led to detonation which would have been exacerbated by the advancement of the engine timing in February and March 2000 as evidenced by the trend monitoring data;*
- *This abnormal combustion may have initiated or exacerbated this fatigue cracking of the left engine crankshaft;*

ATSB comment

The ATSB does not assert that deposit-formation on any pistons led to detonation or that lead oxybromide deposits played any part in causing the right engine damage. Mr Braly's statement that the debate about deposits causing detonation was a 'red herring' (which is adopted by the Coroner at para 14.95) is therefore not relevant. The ATSB examination of more than 11 failed engines indicated that lead oxybromide deposits were more likely when the engines were operated closer to peak EGT, that is leaner, but still on the rich side of peak EGT. Apart from Whyalla Airlines, none of the operators of the failed engines reported operating on the lean side of peak EGT.

12.84 *Mr Braly rejected the idea proposed by the ATSB that the fuel mixture settings adopted by Whyalla Airlines during the cruise phase of flight were harmful to the engine. He said that the engine settings of around 28–30 inches of manifold pressure, 2,200 RPM, and using 11 or 12 gallons of fuel per hour would produce peak cylinder pressures of only around 400 psi. He said that this would produce 'an extremely benign combustion event – probably the most benign cruise operating environment of any of the reports of cruise power condition contained anywhere in the survey that was conducted and included in the ATSB report' (T3143).*

ATSB comment

The suggestion that the cruise mixture settings by Whyalla Airlines were harmful to the engine was included in the Draft ATSB Report, but discarded as the investigation progressed and more information became available. ATSB Report 200002157 has not proposed that the cruise mixture settings of Whyalla Airlines were directly harmful to the engines. Rather, the ATSB has identified a possible connection between lead oxybromide deposition and mixture settings close to, but still rich of, peak EGT and recommended further research. The cruise mixture settings used by Whyalla Airlines were within the limits stipulated in the Piper Chieftain POH as stated in Report 200002157.

12.85 *On the other hand, the settings used by Whyalla Airlines during climb, which was not an area examined by the ATSB, were a different story. Using 36 inches of manifold pressure, 2,400 RPM, and 27 gallons per hour to a maximum of 1500°F EGT will produce a very high peak combustion pressure, peak temperature and exhaust gas temperature which are likely to be harmful to an engine (T3144). He said:*

'This mixture setting for climb operations, especially if referenced to the 1,500°F EGT (actually, TIT) value is an 'engine operating technique' that, based on observed engine test stand operation of the same engine, is likely to result in episodes of at least light or moderate detonation during some climbs on at least some cylinders. The use of a maximum EGT (TIT) setting as a method for setting mixture during a climb is an excellent technique that is reliable in a wide variety of ambient conditions. However, one has to find the correct value for the EGT (TIT) and a value of 1500°F is one that is clearly too high for the climb phase of flight with this engine. A value similar to that adopted by operators number 2 and 7 (1,350°F) is a value that engine test standing operating data supports as being conservative with respect to the internal values of peak cylinder pressures and the associated issue of detonation.' (Exhibit C196a, p19–20)

ATSB comment

It is erroneously stated that the ATSB did not examine the fuel and engine settings used by Whyalla Airlines during climb (cf para 9.27 where the Coroner states that:

The assertion that leaning during the climb, rather than in cruise led to formation of these deposits, which in turn led to preignition was also first raised in the final report [ATSB Report 200002157].

(See also ATSB Report 200002157 pp ix and 89). It is difficult to understand why the Coroner included such inaccurate and inconsistent commentary in his findings.

12.88

Mr Braly demonstrated by running an identical engine to those installed in MZK, and monitoring the entire range of its engine parameters which were displayed digitally on a computer screen, the effects of running the engine in various conditions. This demonstration elicited an enormous amount of very useful information

ATSB comment

The demonstration of the climb power settings referred to here also included a demonstration of the peak cylinder pressures at takeoff power setting, which are equivalent to or slightly higher than those at the climb power settings used by Whyalla Airlines. Those pressures were assessed during the demonstration as equivalent to light to medium detonation that was unlikely to incur engine damage. The conservative fuel settings suggested are in keeping with the ATSB's October 2000 recommendation.

The Coroner has not mentioned that the demonstration also included the engine producing power greater than its maximum rated power, and producing significantly more than 315 bhp at 2400 RPM. (see Attachment D, fig 4).

12.89

Mr Braly's comments on the ATSB report

Mr Braly was highly sceptical that the crankshaft in the left engine in MZK fractured at around 1838 on 31 May 2000, and remained 'dogged together' such that the aircraft maintained performance until 1847:15. He said that the torque or torsional forces on the crankshaft would have been so enormous that it would have been 'virtually impossible' (T3212).

ATSB comment

Mr Braly has no professional expertise in metallurgy and mechanical engineering; his qualification is as an aeronautical engineer and he gave evidence that in undertaking those studies 'there was not one single minute of instruction on piston engines in the four years of that course. We were building rockets; we weren't building piston engines at the time. We were still trying to put man on the moon.' The ATSB has investigated a number of cases in which an engine continued to operate with a fractured, but dogged crankshaft, including the occurrence involving VH-JCH on 14 December 2001, VH-LAN, and VH-SJQ (see A2 pp 41 and 42). The metallurgical evidence of the cracks in other main bearing journals (c 20,000 striations) is clear with respect to the VH-MZK left crankshaft continuing to operate dogged.

12.90

Mr Braly also disagreed with the ATSB contention that the left engine failed at 1847 and that, thereafter, the aircraft was able to maintain 147 knots true airspeed on the right engine alone. The ATSB asserted that to achieve this performance would require the right engine to produce 375 brake horsepower (bhp). Mr Braly said that the engine was not capable of doing so. His estimate was the engine would produce no more than about 315bhp, assuming that the density controller on the turbocharger was appropriately set (T3217).

ATSB comment

The information provided here is incomplete and grossly misleading. Mr Braly's assertion that the engine would produce no more than 315 bhp has no logical or scientific basis. For example, engine test run data from Mr Braly's facility, and demonstrated by Mr Braly in the presence of the Coroner and other parties to the inquest, included the example of the engine operating at 2397 RPM and 45.8 inches MP, and producing 359 bhp (see Attachment D, fig 4).

12.91 *His belief was that at 1847:15 the right engine had been throttled back so that it was producing 105 to 115bhp, and the left engine was still producing the bulk of the power (T3217-18).*

ATSB comment

This is a significantly different belief from Mr Braly than that noted in para 12.80 on page 133 of the Coroner's Report.

12.92 *Mr Braly pointed out that the operation of the density controller is temperature related, so that on a cold day it will allow only 42.5 to 43 inches of manifold pressure to be produced, whereas on a very hot day, with ambient temperatures of 110–120°F, it will allow the turbocharger to produce up to 46.5 or 47 inches of manifold pressure. Of course, on the night of 31 May 2000, when MZK was flying at 6,000 feet, the temperature was close to zero, so the density controller would only have been producing at the lower end of that range (T3220-21).*

ATSB comment

Mr Braly is correct that the density controller will increase the wide open throttle manifold pressure as temperature increases, to compensate for the associated reduction in density of the compressor discharge air. However, the Coroner's report neglects to mention the significant effect of increasing altitude on the wide open throttle manifold pressure. As an aircraft climbs, the density controller increases the wide open throttle manifold pressure to compensate for the reducing ambient air pressure. The Textron Lycoming Operator's Manual indicates that under standard conditions, the wide open throttle manifold pressure would increase by approximately 0.2 inches as the aircraft climbed from sea level to 6,000 ft. The temperature at 6,000 ft on the night of the accident was reported as slightly higher than standard for that altitude. (See also Attachment E).

12.93 1847:15

As to the events at 1847:15, Mr Braly said:

'At the point where the aeroplane diverged right on page 3 at 1847:15, I think the pilot had been wrestling with problems with the right engine since some point in the climb. I believe at about that time he decided to simply throttle the engine. He could do that, and it's my opinion that at that point in time he had experienced an episode of pre-ignition on the right engine. Whether or not it had already put a hole in the piston is debatable, but he did not, unlike the gentleman that was shown in the recreation of the data yesterday, the benefit of that sort of instrumentation and he would not have likely been able to stop the event before it did damage to the cylinder and, as indicated yesterday, once that sort of thing starts to happen in the cylinder, even if he throttled the engine, if you later reapply power, it's going to happen again, assuming he had a hole in the piston already.

It is my opinion that the pilot decided simply to throttle the right engine and, in the process of that, the aeroplane yawed to the right slightly. In my experience teaching multi-engine pilots to fly during training, a momentary lapse in the heading control of the aircraft during major left/right power discrepancies is more common than not,

even among good pilots, and I think the right-hand turn data is consistent with that, and a prompt re-correction back on course is consistent with him having done that and then retrimmed the aeroplane by use of the rudder trim control and what not to put the aeroplane back on course.

At that point in time the pilot had an unknown problem with the right engine, but it was still operating, and he had a 250- or 260-hour left-hand engine, and he made the decision to continue on. In the process he would have likely pushed up the power on the left-hand engine to something approaching climb power. He may have in fact used climb power - that would be a common training scenario for a multi-engine pilot, that if you lose an engine, you put the other engine up to climb power. That's not necessarily the most optimal training exercise, but it's a common method of teaching multi-engine pilots.

So I believe he increased the power on the left engine as he reduced the power on the right engine, and pressed on.

Some time just before 1901:10 when the MAYDAY was transmitted I think the crankshaft failed on the left engine. When the aircraft hit the water the left engine was feathered - I think the left engine would have virtually auto-feathered from the oil pressure loss. The right engine was still turning and not feathered, which is consistent with the previous power reduction.

I think if he had not already had a hole in the piston at the time - 1847:15 - when he throttled that engine, or when he tried to power up the right engine after the failure of the left, that he would have holed it promptly, because it would have gone back into pre-ignition.

It would have been a very confusing and difficult situation for the pilot. They simply do not train for simultaneous engine failures, and they certainly do not do it at night with a full load of passengers over water.' (T3221-23)

ATSB comment

The suggested sequence discussed is confusing. However, it is noted that one option proposed in the second to last paragraph is that the right engine piston hole developed after the left engine failed which is the sequence proposed by the ATSB. The ATSB endorses the comment by Mr Braly that the situation would have been 'very confusing and difficult' for the pilot.

12.96

Mr Braly reported that flying the aircraft at 2,400 RPM, with a manifold pressure of 40 inches resulted in an indicated airspeed of 130-131 knots, which converted to a true airspeed (TAS) of approximately 144 knots. Allowing for the fact that the test aircraft was 350 pounds lighter, and was equipped with intercoolers on both engines and 'winglets', whereas MZK was not, Mr Braly expressed the opinion that MZK would not have been capable of producing more than 140 knots TAS on the night of 31 May 2000. He said:

'At the observed 2400 RPM, the engine would have been capable, at 43' of MP, of delivering only approximately 326 BHp. At 45' it would produce no more than about 335 to 340BHp - - and none of these power outputs would be anywhere sufficient to produce the claimed speed of 149KTAS asserted and described in the ATSB report.'

(Exhibit C196m, p3)

ATSB comment

The test flight was actually travelling at 147.7 kts true airspeed, the calculation of 144 knots TAS having neglected to take calibrated airspeed into account. In addition, the test flight was conducted at 40 inches manifold pressure and 2400 RPM, even though there was no

evidence indicating the manifold pressure at any stage of the accident flight, or the RPM during most of the cruise. (As clearly stated in ATSB Report 200002157 and made clear to the Coroner many times, the identification of 2400 RPM was a snapshot of the propeller RPM shortly before top of descent, and provides no conclusive information regarding engine RPM settings at other stages of the flight.)

Mr Braly's evidence relating to brake horsepower at 2400 RPM is inconsistent with that observed using his engine test facility where at full rich mixture 43.2 inches MP delivered 333 bhp and 45.8 inches MP delivered 359 bhp (see Attachment D figs. 3 and 4).

12.97

Lead Oxybromides

Mr Braly was critical of the ATSB's conclusions in relation to the presence of lead oxybromides and their alleged role in the failure of the two engines in MZK. In particular, at page 52 of Exhibit C97 there is reproduced, from an American website, a picture of the piston of an engine which failed in what is known as the 'Sacramento Sky Ranch' incident, and which was used by the ATSB as an example of abnormal engine deposits. The caption to figure 24 on that page reads as follows:

'Combustion deposits associated with detonation/preignition resulting from the combustion of aviation gasoline contaminated with aviation turbine fuel (Sacramento Sky Ranch)' (Exhibit C97, p52)

ATSB comment

The ATSB did not suggest that lead oxybromide deposits had any role in relation to the right MZK engine. The photograph on page 52 of the ATSB final report was not included as an example of 'abnormal engine deposits'. It was the carbonaceous nature of the deposits rather than the swirl pattern that was being illustrated. It is not known why the Coroner chose to dismiss the ATSB's explanation (T4068) for the use of this image in his findings and, instead, favour an emotive interpretation from Mr Braly.

12.99

As to the identification of lead oxybromides as an issue in this case, Mr Braly said

that the floating of this issue has caused considerable confusion in the aviation community. He said:

'...as the principal focus and the cause of this kind of an accident in the face of the accumulated experience to the contrary for the last 60 years, it was entirely inappropriate and misdirected ...'

12.100

From the photographs of the six pistons from the right engine of MZK appearing on pages 50 and 51 of Exhibit C97, Mr Braly described the deposits as 'minimal' (T3235). In one of his reports, Mr Braly said:

'It is my further opinion that lead oxybromide deposits in each engine were normal or even minimal, as compared to countless other engines with more or less operating time, and played absolutely no role whatsoever in the failure of the crankshaft.'

(Exhibit C196f, p3)

ATSB comment

Mr Braly's contention that levels of lead oxybromides in various engines was normal or minimal and played no role is surprising given that he had no knowledge of lead oxybromides before the ATSB and ANU identified them through the VH-MZK investigation. Mr Braly has not seen the other engines examined by the ATSB that exhibited similarities in failure modes with the MZK left engine. The possibility that Mr Braly may have a vested interest in selling his engine devices to enable engine operation at leaner fuel mixture settings and that this may have in part, prompted his and his

associate Mr Deakin's vitriol against the ATSB does not seem to have been assessed by the Coroner.

The Coroner also took no account of the information provided by the ATSB regarding the pattern of similar failure modes in other engines (ATSB Report 200002157, p 84) that, along with the information regarding the left engine of MZK, formed the basis for the ATSB recommendations regarding combustion chamber deposits and anti-galling compounds.

The ATSB made a carefully worded recommendation about monitoring devices in July 2002.

12.102

Mr Braly outlined his view on the cause of the left engine crankshaft failure in his final report as follows:

'It is my further opinion that the crankshaft on the left engine of MZK would not have broken on the night of May 31, 2000, but for the operating conditions under which the engine suffered from February 13, 2000 until March 9, 2000. A review of the trend data for that period of time indicates that the left engine was returned to service on February 13 (see Table 1, below) with the timing advanced (sparks too early) by a substantial and harmful amount. There is no other competent cause for the left engine CHTs to be so exceptionally hot (+62.5 degrees F) compared to the right engine and, at the same time, the left engine EGTs to be so cold (-76 degrees F) compared to the right engine, than an error in setting the timing on the left engine too early in the Feb. 13 to March 9 time frame – and to show resolution of those substantial differences immediately after the March 9th maintenance event. The intolerable insult that this condition imposes on the engine can be demonstrated for the Coroner on the engine test stand. The crankshaft in question suffered the initiation of a fatigue crack. That crack continued to grow until the static strength of the remaining material in the crankshaft was no longer able to sustain the peak torsional loading imposed by the engine combustion events. Had the crankshaft not suffered from the insults resulting from the improper February 13 to March 9 operation of the engine, the crankshaft may have still broken at some later date, but, more likely than not, such failure would have happened at some time after May 31, 2000.' (Exhibit C196f, p3)

ATSB comment

The ATSB considered the suggestion that the left engine was not timed correctly following installation in February 2000 and that the timing was not corrected until 9 March 2000. The physical evidence from the fracture surfaces from the failed crankshaft indicated that the fatigue crack had been progressing for approximately 50 flights prior to the final failure. Between 9 March and the accident flight the aircraft completed significantly more than 50 to 70 flights, suggesting that the initiation of the fatigue crack did not occur during February and March, but in about early May (see para 5.9 of the Coroner's Report).

12.103

The evidence of Mr Braly leads to the following conclusions:

- *Even if Whyalla Airlines was using lean fuel mixtures in the cruise phase of flight, this would have led to 'benign' and not abnormal combustion events in the engine, and fewer deposits. The discussion of lead oxybromides is a 'red herring';*
- *The mixture settings used by Whyalla Airlines in the climb phase would probably have led to detonation which would have been exacerbated by the advancement of the engine timing in February and March 2000 as evidenced by the trend monitoring data;*

- *This abnormal combustion may have initiated or exacerbated this fatigue cracking of the left engine crankshaft;*
- *It is highly unlikely that the left engine failed completely, and suddenly, at 1847:15 because the right engine alone was not capable of producing enough power to propel the aircraft at the speeds indicated;*
- *The yaw to the right was more consistent with partial reduction of power from the right engine, and Mr Mackiewicz would have made a Pan call.*

ATSB comments

The conclusions are at odds with the Coroner's findings elsewhere that the possible February and March 2000 engine timing issues were well before the 50 or so flights prior to the accident when the left engine crankshaft fatigue crack was initiated.

12.110 *Disappointingly, it was ascertained after our arrival in the United States of America, and shortly before the hearing in New York, that this destructive testing had not been undertaken and that a definitive answer to these questions had not yet been obtained.*

ATSB comments

Given that Mr Hood of McSwain Engineering stated that destructive testing would only take a few days, it is surprising that the Coroner did not insist on this as soon as he found out and prior to the US hearings being concluded.

12.115 *As to the oxide inclusions in the bakelite-mounted samples from the No. 5 main bearing journal, Mr Hood arranged for these inclusions to be examined under SEM and x-ray energy dispersive spectroscopy (EDS), which characterised the inclusions as oxide in nature.*

ATSB comment

There is no dispute by the ATSB that there were oxide inclusions in the left crankshaft (a normal outcome of the manufacturing process) of a size and disposition that met the specifications for the crankshaft material or that there was corrosion (oxidation) at the surface of the old sample from the No. 5 main bearing journal. McSwain did ultimately agree (see Coroner's findings para 12.123 page 150) that there was no evidence of massive high temperature oxide inclusions at the fracture site. (See also A2 pp 39 and 40 and Attachments B and C of this report).

12.116 *As I have mentioned earlier in these findings, Mr McIlwaine SC spent considerable time cross-examining Mr Hood about the peaks in the EDS spectra attributable to chlorine, and introduced for the first time in New York, the suggestion that these samples had been etched with concentrated hydrochloric acid (T2981). When we returned to Australia, this was later clarified in the evidence of Dr Romeyn and Mr Blyth. It was alleged that the samples were etched with a substance known as Marbles reagent, one of the components of which is hydrochloric acid. However, as I have already discussed in relation to Dr Powell's evidence, this issue became irrelevant after the dialogue between Dr Romeyn and Dr Powell in December 2002, as a result of which Dr Romeyn abandoned the idea that hydrochloric acid played a part in the creation of the anomalies on the surface of the sample.*

ATSB comment

It is not known why the Coroner states that the ATSB 'alleged' that the sample was etched with Marbles reagent as this is accepted elsewhere. Dr Romeyn's view was that most of the large grey oxides observed near the surface were the result of simple atmospheric corrosion but that traces of chlorine may be the result of leaching of marble's reagent (which includes hydrochloric acid).

12.119 *Mr Hood pointed out that the presence or absence of oxide inclusions at the very point of initiation of the fracture may or may not be determinative. He said:*

‘When you get a separation in a fatigue crack, the inclusion can reside in one piece of the fracture. You can fracture the inclusion or it can remain on either half of the fracture, and the void may be the hole that has been left by an inclusion being separated.’

(T3016-7)

ATSB comment

Unlike the testing in the US, the ATSB’s destructive testing in March 2003 did look at both sides of the fracture and found no material defect on either fracture surface that could have initiated the fatigue crack under normal operating conditions. (See Attachment C)

12.121 *After detailed and extensive negotiations, representatives of McSwain Engineering, Textron Lycoming and the ATSB gathered at the R J Lee Inc laboratory in Pittsburgh, Pennsylvania on 13–16 January 2003, to conduct further testing. Amazingly, this session still did not culminate in the destructive testing of the samples.*

ATSB comment

The ATSB was present at the testing as an observer only. It was the ATSB that reported and objected on 17 January to the Coroner’s Counsel that the testing had not been completed.

12.122 *Following further negotiations, the destructive testing was finally completed on 27-28 January 2003. An objection was noted from the ATSB that by this latter time their representative had left the USA. The circumstances in which this came about are complicated and indeed tiresome, but I am satisfied that there was no attempt to mislead the ATSB by waiting until after its representative had left the USA before proceeding. What in fact happened was that the representatives of McSwain and Textron Lycoming were reluctant to proceed to destructive testing, being obviously cognisant of the litigation which was still extant in America, and no doubt taking into account advice received from lawyers for the relatives of the deceased and for Textron Lycoming. It was only after my further insistence, communicated through Mr Kernahan, that the destructive testing was finally carried out.*

13.15 *After the final destructive testing carried out by McSwain Engineering Inc in the United States of America was completed, the Executive Director of the ATSB, Mr Kym Bills issued a Notice pursuant to section 19CC of the Air Navigation Act 1920 dated 13 February 2003, directed to me. The notice required me to produce for inspection the following items:*

‘To produce the crankshaft (serial number V537912936) from the left engine of Piper PA31-350 Chieftain VH-MZK in its entirety, including any pieces or mounted specimens, currently held in the United States.’^{13.16} *The notice to produce carries the following warning:*

‘IMPORTANT NOTICE: Failure to comply with this notice may incur a penalty. Compliance affords protection.’

Indeed, section 19CC(4) of the Act creates an offence of failing to comply with such a requirement, and prescribes a penalty of ‘30 penalty units’.

13.17 *The lawfulness of a government official, whose organisation has been given leave to appear as a party to an inquest, issuing such a notice while the inquest is still sub-judice is, in my opinion, debatable. I believe there are sound arguments based upon recent authority emanating from the High Court*

considering section 109 of the Constitution, which suggests that such an action may constitute an unreasonable interference with State legislative powers (see Austin v The Commonwealth of Australia [2003] HCA 3).

- 13.18 *Leaving the legality of the notice to one side, the propriety of a party given leave to appear at an inquest using legislative powers directed at a judicial officer while a matter is still sub-judice is even more debatable. When applying for leave to appear at an inquest pursuant to section 21 of the Coroners Act 1975, a person can be taken, in my opinion, to have submitted to the jurisdiction conferred upon the Coroner by that Act. Any such party who then invokes Commonwealth statutory power, with the threat of criminal sanctions against the Coroner, who is a judicial officer in such proceedings, is behaving, in my opinion, in a completely unacceptable way. At the very least, it may have justified a reconsideration of whether leave to appear should continue.*

ATSB comment

The Coroner omits to mention that the ‘tiresome’ circumstances of the US testing being halted led to the ATSB on 17 January requesting the engines be sent back to Australia for testing by the ATSB and that a section 19CC legal mechanism was first discussed (positively) with the Coroner’s Counsel Assisting to this end. Despite these discussions, the US testing was resumed without independent witnesses and was not advised to the ATSB in contrast to the Coroner’s order of 3 January 2003 that the ATSB was ‘entitled to attend any testing which takes place on 13 January 2003 or thereafter’. The ATSB offered to provide sworn evidence on these issues after an invitation from the Coroner’s solicitor to do so but the Coroner himself wrote a letter on 14 March 2003 stating that this would not be required as the ATSB’s ‘grievances do not touch upon the issue before me’. Nevertheless, the Coroner’s findings do address the matters raised by the ATSB. Prior to issuing the s19CC instrument to the Coroner, Mr Bills obtained extensive legal advice including from senior counsel.

- 12.123 *The results of the destructive testing were set out in the final McSwain report dated 7 March 2003.*

ATSB Comment

The results set out in the McSwain report are at Attachment B along with the ATSB response to the McSwain conclusions. It is significant to note that the McSwain report stated that ‘no indications of large oxide inclusions or of an oxide inclusion seam were observed.’ In addition the Coroner omits to acknowledge the flaws in the argument presented by McSwain that a laboratory-induced impact fracture from the subject crankshaft did not exhibit typical overload fracture features (see A2 p 44 and Attachment B of this report).

- 13.5 *It seems to me that the ATSB’s decision to limit their investigation by adopting that approach was inappropriate. The overwhelming weight of the evidence before me suggests that these two engine failures were independent of each other, and it is not enough for the ATSB to simply dismiss that conclusion on the basis that its likelihood is too remote. If that conclusion is to be dismissed, it should be dismissed on a scientific basis rather than on a statistical one. From that starting point, the ATSB has set out to establish that the failure of these two engines was a dependent failure and, in doing so, has unnecessarily fettered the scope of their investigation.*

ATSB comment

The ATSB did not dismiss the possibility of two independent engine failures as being too remote, as evidenced by the draft ATSB report which proposed precisely that. Rather the statistical likelihood of two independent failures in comparison with one independent and one dependent failure was one of the factors taken into consideration when considering

the likely sequence of events. In contrast to the Coroner's suggestion, the use of statistics is integral to the scientific method. Setting aside the statistical factor, the damage to the engines and radar and audio evidence indicated that the sequence proposed by the ATSB is significantly more likely to be correct.

- 13.6 *Dr Romeyn disagreed with the opinions expressed by Dr Powell, Mr McLean, Mr Hood and Mr Murphy, that the fatigue crack initiated as a result of a 'point defect' approximately 1mm below the journal surface at the junction between the nitrided layer and the core of the crankshaft. He argued that Mr Hood's explanation that the discontinuity was in fact a 'tear ridge' was unlikely (T4039). Dr Romeyn conceded that there was really no evidence to confirm which of these two opposing views is the correct one (T4043).*

ATSB comment

The Coroner does not make it clear that the suggested 'concession' from Dr Romeyn was prior to the evidence obtained with the benefit of destructive testing in March 2003 (see Attachment C).

- 13.9 *As to Professor King's evidence that the only sign of lead oxybromide in the left engine of MZK was that found by the Australian National University investigation at one point on the No. 6 piston, Dr Romeyn said that his analysis of other engines over the previous two years led him to the conclusion that such oxybromides are often present. He suggested that when the big end of the connecting rod broke, the piston was projected into the cylinder head and the subsequent collision may have caused the deposits to have been dislodged from the crown of the piston (T4055). He also speculated that immersion in seawater may also have loosened those deposits (T4056). He also pointed out that any such abnormal combustion may have occurred up to 50 flights previously, and the deposits may have built up and then blown away with subsequent operation of the engine (T4057).*

- 13.19 *These arguments, it seems to me, are examples of the artificiality which can develop when an investigation tries to make the available evidence fit a theory, rather than the other way around. When faced with the opinion of Professor King and Mr Braly that the amount of deposits was insignificant, Dr Romeyn was forced into speculation that there may have been more deposits but they have since disappeared. Such speculation is of little value.*

ATSB comment

Dr Romeyn was not forced into speculation. It was an integral part of the ATSB's scenario logic in ATSB Report 200002157 that the important time for lead oxybromide to have reached a critical mass sufficient to cause preignition was about 50 flights before the accident when the fatigue crack was initiated, not on the accident flight. The ATSB recommended further research on the processes involved which could well include cycles of build up and removal. In the ATSB's opinion, this 'speculation' may be important for future aviation safety. The very different draft ATSB report shows that the ATSB investigation was not trying to make available evidence fit a theory

- 13.12 *Mr Eriksen, counsel assisting me, put to Dr Romeyn the weight of evidence in favour of the proposition that the failure of the left engine crankshaft in MZK was due to a manufacturing defect. This evidence included the similarity with the Sharp Aviation crankshaft, the knowledge of 14 other failures, the American information in the FAA briefing paper already referred to, the mandatory recall of engines fitted with similar crankshafts on three separate occasions, the last of which included the left engine crankshaft of MZK. Dr Romeyn conceded that a material defect in the crankshaft, rather than thermal cracking, was a possible explanation for the failure. He said:*

'I would certainly, on the basis of all that information, consider it as a possibility, and I guess on the basis of having that information at the time would have prompted me to examine that fatigue fracture origin more closely, and I suppose more closely as (at) the fracture surface, but the material in that location, to see if there was evidence of a material defect of that kind.' (T4275)

ATSB comment

The ATSB senior metallurgist conceded that if the various service bulletins from Textron Lycoming relating to Piper Chieftains in Australia had been issued at the time he was examining the crankshaft, then he would have looked at the fracture origin even more closely. However, the metallurgist had that opportunity when the ATSB obtained the crankshaft for subsequent testing conducted during March 2003 at the ATSB laboratory in Canberra. No significant material defect was identified during that examination. The report of that subsequent testing is at Attachment C.

13.20 *The ATSB expressed the wish to conduct further testing having regard to the fact that on 21 November 2002, the Executive Director of the ATSB officially reopened their inquiry into the tragedy, not because of anything which had arisen as a result of my inquiry, but because, according to a press release issued by the Executive Director of the ATSB on that day:*

'Ongoing delay with such testing has led to ATSB formally re-opening the investigation based on the 16 September 2002 service bulletin alone. The ATSB has also been told that some US litigation settlements require that engine parts be destroyed - such a loss of evidence would, of course, undermine the current inquest and future aviation safety. ATSB wishes to ensure that every effort is made to test the crankshaft without delay to resolve the question of whether a manufacturing material problem was a causal factor.'

(Exhibit C216)

The 16 September 2002 service bulletin was the one which recalled crankshafts because of a material defect, and which specifically identified the left crankshaft of MZK as one of the crankshafts involved (see paragraph 10.31).

ATSB comment

The delay in the US testing that was to have occurred prior to the Coroner taking evidence in the US in October/November was related to the inquest. The Coroner omits to mention that the timing of the ATSB re-opening its investigation was to facilitate testing by the US NTSB which subsequently did not occur because of NTSB concerns related to intrusion of legal processes. (See also pp 3–5 of this report). Service Bulletin 553 issued on 16 September 2002 did not specifically identify the left crankshaft of MZK as having a material defect. The vast majority of crankshafts tested in accordance with the service bulletin (almost 70 per cent) did not have any material defect and were returned to service.

13.21 *This testing should have been performed by the ATSB in 2000-2001 when they still had custody of the components. It was not enough that they assumed that because there were no defects apparent upon this inspection of the sample from the No. 5 journal, and from a microscopic examination of the fracture site, that no such defect existed in the No. 6 journal. Thoroughness and scientific accuracy demanded a detailed and, if necessary, destructive examination of the fracture site. I find the explanation offered by Dr Romeyn (T4083), Mr Blyth (T3876-77) and Mr Cavenagh (T3572), namely that they wished to preserve the fracture site 'so that it would be available for others to examine or test', merely disingenuous and unworthy of credit. It was never made clear whom they anticipated*

would be testing the components subsequently. It is clear to me, from events in 2002, that it was not done for my benefit.

ATSB comment

The criticism of the ATSB for not destructively testing the left crankshaft fracture in 2000 and 2001, should be seen in the context of service bulletins indicating a possible manufacturing defect relevant to Australian Piper Chieftains being progressively issued in 2002 (ie after ATSB Report 200002157 was released in December 2001). At the time the ATSB conducted the initial examination of the crankshaft, there was no evidence, circumstantial or otherwise, of a manufacturing defect and sufficient evidence was obtained to support the findings in ATSB Report 200002157. This included chemical analysis by an external laboratory. As such, destructive examination of the fracture did not appear necessary.

The Coroner had control of the crankshaft in Adelaide from late March 2002 until early August 2002 and did not suggest or require such testing. Indeed, his Counsel Assisting advised the Coroner during inquest hearings on 2 August 2002 that:

I have made enquiry from engineers at the Adelaide University that we have commissioned, and they say that they do not need further access to any of these parts in order to complete their reports which they are in the process of doing.

On that basis, the Coroner allowed the engines to go to the US for further testing on behalf of parties to litigation there. In October 2002, after the 16 September 2002 service bulletin that first listed the MZK left crankshaft among those possibly affected by a manufacturing defect, the Coroner authorised destructive testing. Despite the ATSB's representations, this was not commenced until January 2003 and not concluded until the ATSB insisted on getting the crankshaft back and did its own (independently witnessed) further testing in March 2003. Those assisting the Coroner were invited to be present during the testing of the crankshaft at the ATSB laboratory in March 2003, however none chose to be present. That further testing further supported the findings in ATSB Report 200002157 (see Attachment C). The Coroner's criticism of the ATSB is in hindsight and would apply with even greater force to his own expert inquiry which occurred after service bulletins had been issued.

13.22

I also found the actions of the ATSB in this regard somewhat mystifying, having regard to the following factors:

- *Dr Romeyn had conceded in cross examination that there was no evidence to confirm whether the two opposing views as to the causation of the failure of the crankshaft in the left engine was initiated by thermal cracking, as he suggested, or by a material defect in the crankshaft, as postulated by Mr Hood, Dr Powell, Mr McLean, Mr Murphy and others (T4043);*
- *Dr Romeyn acknowledged that if he had been aware of the opposing views which I have outlined above, he would have examined the origin of the fatigue fracture more closely, particularly at the fracture surface, when he was examining the crankshaft failure, before the engine parts were released by the Executive Director of the ATSB ostensibly to the aircraft owners, Whyalla Airlines, until that process was interrupted by the issue of a warrant for seizure of the engine parts for the purposes of this inquiry;*
- *The fact that all of the expert witnesses acknowledged, often at the instigation of cross-examination by counsel for the ATSB, Mr McIlwaine SC, that testing the fracture site to the extent that it is destroyed is the only way in which outstanding questions about the presence of an inclusion at the fracture site origin can be established;*

- *On the basis of such evidence, such destructive testing was indeed carried out by McSwain Engineering Inc in the United States of America to the extent that it was no longer possible to examine the origin of the fracture first-hand;*
- *The ATSB had maintained a consistent line that the presence of inclusions in the No. 5 journal, even if established, did not necessarily indicate that there were inclusions at the fracture site in the No. 6 journal. After the fracture site had been destructively tested, testing of adjacent areas was the only testing which remained available to the ATSB for the purpose of their reopened inquiry, yet they insisted that it was necessary to do so.*

ATSB comment

The Coroner omits to mention that Dr Romeyn's 'concession' preceded the March 2003 destructive testing conducted by the ATSB (see Attachment C). The Coroner also omits to mention that the ATSB liaised with those assisting the Coroner and specifically held all evidence at its premises in Canberra pending appropriate documentation from the Coroner for the release of the engine components under s19FM(3) of the Air Navigation Act and other third party items such as maintenance documentation and ATC audio and radar tapes under warrant. The parts were not released by the Executive Director to Whyalla Airlines. It is also incorrect to claim that the US destructive testing by McSwain was undertaken to the extent that it was no longer possible to examine the origin of the fracture first-hand.

13.23

In any event, the parts were returned to Australia pursuant to the orders I made, and further testing was carried out by the ATSB at its laboratories in Canberra. Their further report, consisting of 50 pages, is unsigned, although it bears the name Dr A Romeyn on its cover, and is dated April 2003. It is sufficient to quote the conclusions set out on page 50 of the report as follows:

'The chemical composition of crankshaft s/n V537912936 was within the limits specified in AMS 6414H with check test variation limits applied, with exception of two of the four carbon analyses. The results of carbon analysis show a higher degree of scatter than the other elements. The scatter range for carbon was 0.036 per cent. The use of different analysis techniques and four independent analyses indicates that this degree of scatter appears to be inherent in the analysis of carbon in steel. The two carbon analyses that exceeded the upper check test variation limit did so by 0.02 per cent, a value within the scatter range for the analyses conducted.

The strength of the crankshaft core as determined by hardness testing is consistent with strength levels achieved by a single stage nitriding process. The strength of the core is determined by the tempering temperature. If the nitriding temperature exceeds the tempering temperature the strength will be reduced. The strength of the steel is not affected by the variations in carbon content within the range specified for the steel.

The nitrided surface hardened zone complies with the specified requirements for case depth and surface hardness.

The inclusion content of the steel is consistent with a steel treated with calcium and magnesium and produced by the vacuum arc remelted process. No inclusion stringers were observed. The maximum dimension of the inclusions observed was approximately 13mm.

No inclusions of a size greater than normal, or of a type different from the normal inclusions, were identified in the volume of steel surrounding the site of fatigue crack initiation.

There was no evidence of a non-metallic inclusion being the site of fatigue crack initiation.

Pullout features created under impact loading are considered to be a feature of the fracture of steels containing very low levels of non-metallic inclusions. These features do not represent material flaws or sites of lower material strength. No evidence of this type of feature was found in the vicinity of the fatigue initiation site.

Evidence of cracking, aligned with the axis of the journal with a microstructurally influenced crack path, was found extending from the step feature on both sides of the fracture. Cracking of this nature is consistent with cracking created by the localised thermal expansion of surface hardened zones.

The fracture surface features at the site of fatigue crack initiation had been damaged during the processes of final fracture and torsional separation.'

13.24 *When these conclusions are considered in light of the body of knowledge we already have, it is clear that final, definitive proof that there was a non-metallic inclusion acting as a stress riser at the fracture site will never be found.*

13.25 *On the basis that this most recent investigation by the ATSB takes the matter no further, I am content to rely on the evidence before me.*

ATSB comment

It is unclear why the fact that the 50 page ATSB report was unsigned has been highlighted. It was provided through the ATSB's Solicitor. A copy of the report is at Attachment C. It is also important to note the Coroner's comment at 13.24 above, particularly when considered in light of all of the evidence that indicates that a material defect was unlikely to have been the cause of the fatigue crack.

Surprisingly, the Coroner concludes that the ATSB's 50 page documented test report 'takes the matter no further' and therefore relied on earlier opinion, including from the US firm acting for the parties to US civil damages litigation, that there may have been a significant non-metallic 'inclusion' in the steel that had 'dropped out', concluding that 'such an inclusion was not found at the origin of the fracture site but this does not exclude the possibility that it was lost during the fracture process'. The Coroner also relied upon the circumstantial evidence of the 2002 service bulletins indicating a potential manufacturing defect without acknowledging that a substantial majority of potentially affected crankshafts tested were not defective.

The ATSB had been advised by the Coroner's Solicitor in May 2003 that the metallurgists engaged by the Coroner during the inquest were reviewing Dr Romeyn's report. However, the ATSB was not privy to any such review. In the interests of aviation safety and to ensure all evidence had been considered before finalising the ATSB's re-opened investigation, the ATSB wrote to the Coroner seeking copies of any written advice or file notes relating to the left engine crankshaft and to the engine failure sequence which had not already been made available to the ATSB during the inquest.

After several exchanges in correspondence with the Coroner's Solicitor, in which the ATSB clearly indicated the nature and extent of the material requested, the ATSB was advised by the Coroner's Solicitor that 'We do not intend to respond to further attempts by your client to impugn the findings of the State Coroner...'. The ATSB had a responsibility, in the interests of aviation safety, to ensure that all evidence had been considered in the re-opened investigation and was naturally seeking the results of any review of its work.

The ATSB subsequently used its powers under Section 19CC of the *Air Navigation Act 1920*, and issued Notices to Produce to the Coroner's metallurgists for any material relating to a review of Dr Romeyn's report. Little of substance was received in response and it was stated that no report was provided to the Coroner due to the incomplete nature of the work done and because time and costing prohibited further investigation. The

Coroner's solicitor subsequently confirmed that advice and stated that no such material was provided to the Coroner. As such, it appears that the Coroner's conclusion regarding Dr Romeyn's report taking the matter no further was not based on any specialist review or advice.

As previously noted, the assertion that the ATSB's March 2003 destructive testing and April report 'takes the matter no further' is incorrect given that the ATSB found no manufacturing defect in the left crankshaft steel that could have caused the fatigue fracture under normal operating conditions.

A4. Comments in relation to Chapter 14 of the Coroner’s report, ‘Issues discussion and conclusions’

The ATSB response to the issues raised by the Coroner in Chapters 14 and 15 have, for the most part, been addressed earlier in this attachment, as indicated by the page references included. Additional comment has been included where considered helpful and appropriate.

14.1 *Was there anything abnormal about the takeoff and climb phases of Flight 904? If so, does this indicate that damage occurred to either engine during these phases?*

ATSB comment

See Section 5 and A2 pp 42–46 of this report.

14.4 *However, other pilots who gave evidence told me that these symptoms are not necessarily noticeable (see the evidence of Mr Usher T1652 and Mr Kuch T1414).*

ASTB comment

Other pilots who had experienced melted pistons commented that symptoms such as vibration and rough-running may not be evident. The cylinder head temperature sensors in the engines fitted to MZK were on the No. 6 cylinder. Therefore, if overheating had occurred in a cylinder other than No. 6, it may not be evident to the pilot on the CHT gauge. However, the No. 6 piston of MZK’s right engine was the one that was holed by melting. Therefore, assuming the gauge was working (there is no evidence to suggest otherwise) the overtemperature condition would have been indicated in the cockpit regardless of when it occurred during the flight. Even if there was no rough running and/or vibration evident, the cylinder head temperature gauge would have indicated an excessive temperature.

14.6 *It is difficult to form definite conclusions on this issue. I accept Mr Braly’s evidence which was so clearly substantiated by the demonstration at his test facility in Ada Oklahoma, that the settings adopted by Whyalla Airlines during climb were quite capable of producing detonation. It is now impossible to know whether some damage had already occurred to the No. 6 piston in the right engine but had not yet extended to the stage that it was causing the engine to lose power. It could be, as happened in the incident on 9 September 1999, that the damage was done, but the vibration in the engine did not become apparent until the end of climb and the beginning of the cruise phase of flight. On the evidence before me, I am not prepared to agree with Mr Cavenagh that it was ‘very unlikely’ that the right engine of MZK was damaged during the climb phase of flight.*

ATSB comment

While Mr Braly demonstrated that mild detonation was possible at the climb power settings used by Whyalla Airlines, those settings were in accordance with the Pilot Operating Handbook. Further, they were the settings that had been used by Whyalla Airlines throughout the 10 or so years that the company had operated Chieftain aircraft.

There was no history of melted pistons/cylinders in company Chieftain aircraft and the Coroner provides no explanation as to why there would have been a problem on the accident flight. The performance characteristics of the aircraft during climb and the initial part of the cruise recorded on radar were entirely normal and consistent with recordings of other flights by Chieftain aircraft, including the earlier MZK flight from Whyalla to Adelaide, on the day of the accident.

14.12 *Why did the ground speed of MZK change at 1837:41 (in that it became variable and reduced to an average of approximately 176 knots) over the ensuing 10 minutes?*

ATSB comment

See Section 4 of this report.

14.16 *It is at this point that the ATSB's experts part company with all of the other experts who gave evidence in the inquest. They argued that at 1837:41, the No. 6 crankshaft journal on the left engine fractured, but the two crankshaft sections remained dogged or keyed together and continued to rotate. It is speculated that 'relative movement between the journal fracture surfaces would have altered engine timing, causing rough running and loss of performance' (Exhibit C97, p110).*

ATSB comment

See A2 pp 40–42 of this report and ATSB Report 200002157 pp 59–60.

14.19 *However, it must be remembered that in the Sharp Aviation case, the failure of the crankshaft did not result in a hole in the crankcase which would have caused a much quicker loss of oil.*

ATSB comment

The Coroner has assumed that the No. 6 connecting rod in the left engine of MZK breached the crankcase at the time that the crankshaft initially fractured but remained dogged. There is no factual basis from which to determine the stage in the left engine failure sequence that the big end housing 'let go', or when the crankcase was holed. However, bluing of the connecting big-end material supports the conclusion that the big-end was subject to heat stress that likely occurred while it remained connected to the dogged crankshaft.

14.20 *It seems to me that the failure sequence in the case of JCH is just as difficult to interpret as the sequence in the left engine of MZK, and that it is difficult to use one as an aid to prove the other.*

ATSB comment

The failure sequence in the case of JCH provides strong support for the failure sequence suggested by the ATSB. The two crew members on JCH provided the ATSB with a written report (subsequently supplied to the Coroner) detailing the various symptoms that became evident after the crankshaft fractured but remained dogged. That account was consistent with the reduction in aircraft performance evident on the radar data for MZK after 1837:41.

14.21 *Certainly, Mr Malcolm Sharp acknowledged that it was possible for the crankshaft to remain dogged after it completely fractured, but he doubted that it would remain so for an extended period (T2424).*

ATSB comment

See A2 pp 40–42 of this report and ATSB Report 200002157 pp 59–60.

14.22 *Mr Barry Sargeant, the ATSB Senior Investigator who wrote the draft ATSB report, said that so long as the connecting rod end cap and bearing remained in place, the crankshaft would remain dogged and the engine should continue to operate at the same RPM (T3675). Consequently, he was unable to see that there would be any change in the power output of the engine, and inferentially, any difficulty in synchronising the engines. He said that it is difficult to conceive that there would be enough room within the end cap of the bearing for the two sections of the crankshaft to move at different speeds sufficiently to cause rough running, and the bearing remaining intact (T3676).*

ATSB comment

As was evident from the power fluctuations in the case of JCH, there is no question that once the big end housing separated, the loads exerted on the crankshaft would have caused relative movement between the two dogged sections that would have increased as the engine continued to operate. This relative movement would have increasingly affected the timing of the engine and rough running and loss of power would almost certainly have resulted.

See A2 pp 40–42 of this report and ATSB Report 200002157 pp 59–60.

- 14.23 *Mr Les Lyons, the CASA Technical Specialist - Powerplants, was also sceptical about this ‘dogging’ effect. He examined the surfaces of the two pieces of the fractured crankshaft (pictured page 55, Exhibit C97), and said that there was no evidence of significant fracture surface ‘smearing’, which would be caused by movement of the two pieces of the crankshaft against each other (T4488).*

ATSB comment

Contrary to the views that seem to have been accepted by the Coroner, there was significant evidence of fracture surface smearing caused by movement of the two pieces of the crankshaft, to the extent that significant damage to the two fracture surfaces of the crankshaft sections was evident (see figs 28 and 29 of ATSB Report 200002157). This smearing damage contributed significantly to the difficulty in examining the fracture surfaces.

- 14.24 *Mr Braly in his characteristically unequivocal manner, suggested that it would be virtually impossible for the crankshaft to remain dogged for the period of time suggested by the ATSB (T3211). He said that the enormous torsional forces involved in these engines are difficult enough for an intact crankshaft to withstand, let alone a fractured one.*

ATSB comment

The comments ignore the evidence of VH-JCH and other examples provided to the Coroner by the ATSB of engines that have continued to operate after the crankshaft has fractured but remained dogged (see Note 1 p 41). The comments also ignore the physical evidence of the secondary fatigue cracks in the No. 5 connecting rod journal and the No. 3 main bearing journal (see ATSB Report 20002157 p 60) that indicate that the engine continued to operate for 8–10 minutes after the crankshaft fractured.

- 14.25 *If the opinion of Associate Professor Richard Taylor of the Department of Aviation, Ohio State University in the United States of America is to be accepted, the variations in groundspeed from 1837:41 onwards may have no significance at all. Professor Taylor suggested that the variations in groundspeed recorded by the radar equipment might simply have been due to variations in the strength of the signal, rather than actual variations in the speed of the craft. This opinion received some support from Mr Kell who conceded that fluctuations in groundspeed between 1836 and 1847 had been influenced by periods where one radar sensor had lost the track (T3756).*

ATSB comment

See A3 p 63 of this report. In addition, Professor Taylor was not privy to the radar data on the other Chieftain aircraft.

14.27 *At 1847:15 the ground speed of MZK reduced by another 10 knots or so, its altitude increased by 100 ft., and its track diverged to the right by 19°. What do these events indicate about the phase sequence of the engines of MZK?*

ATSB comment

See A2 pp 46–48 of this report. While it is not possible to state with certainty the exact timing and nature of the failure of the left crankshaft, there is considerable evidence to support the ATSB scenario. The alternative theories are opinion-based with little or no supporting evidence. As a general comment, the Coroner consistently confuses aircraft yaw and aircraft track changes, and has used the term 'yaw' incorrectly.

14.41 *After 1847:15, MZK continued to fly at an average groundspeed of approximately 167 knots. What does this indicate about whether either or both engines were still operating, and to what extent, during this period?*

14.58 *In considering the totality of this evidence, I am not satisfied, even on the balance of probabilities, that the right engine of MZK was capable of propelling the aircraft by itself at 147 knots TAS for eight minutes. It seems so highly improbable that the pilot would either deliberately or accidentally overboost the engine to that extent, thereby putting its integrity at risk, when he had already lost one engine, and was flying over water, in circumstances where it was completely unnecessary to do so, and where the remaining engine was quite capable of propelling the aircraft at a lower speed and maintaining altitude in relative safety.*

ATSB comment

Detailed explanation regarding the maximum groundspeed achievable by MZK operating on one engine has been included at Attachment F.

Irrespective of what assumptions might be made in hindsight regarding expected or prudent human behaviour, the damage to the right engine indicated that it did operate at an abnormally high temperature for sufficient time to raise the temperature of the No. 6 piston sufficiently to melt a hole in it. The ATSB has consistently argued that damage to the right engine could only have occurred if that engine was operated beyond the normal limits.

There is no information available about how the pilot manipulated the engine controls in the period immediately after 1847:15. The Coroner claims that the ATSB argued that the pilot 'firewalled' the right engine at that time, and had that happened, the engine RPM would have been 2575 and not 2400 as detected. The ATSB indicated that, if the pilot had 'firewalled' the engine, then the resultant engine operating conditions could have led to severe detonation. The ATSB also indicated that if the pilot had fully advanced the throttle without also appropriately adjusting the other engine controls, then that would also have created engine operating conditions to cause the damage evident in the right engine.

14.65 *MZK commenced its descent into Whyalla 1855:54, and Mr Mackiewicz has advised Adelaide Flight Information Service that he was estimating arrival at Whyalla 1908. Those events were in accordance with usual practice. What does this indicate about the failure sequence of the engines of MZK?*

ATSB comment

Based on the ATSB suggested likely sequence, it is entirely possible for the pilot to have commenced descent at the usual position on the basis that, at that time, as far as the pilot was aware, the right engine was still functioning normally.

14.70 *At 1858:30, the rate of descent of MZK increased from the usual 400 to 650 ft. per minute. What does this indicate about the failure sequence of the engines of MZK?*

ATSB comment

The ATSB position is that, at that time, the performance of the right engine deteriorated due to the extent of melting, and the resultant holing of the No. 6 piston.

See also ATSB Report 200002157, p 116.

14.77 *Why was no Pan or Mayday call made prior to 1901:14?*

ATSB comment

See A2 pp 51–52 of this report.

14.85 *What was the cause of the failure of the left engine of MZK?*

ATSB comment

See pp 7–8 and Attachment C of this report and ATSB Report 200002157 Section 1.17.

14.90 *Although the information I have about the engine failures in the United States of America is meagre, it would appear that this is the only incident in a series of fifteen or more in which these conclusions have been reached – in the others, a defect in the material of the crankshaft has been identified as the cause in seven cases, and is suspected as the cause in the others. It seems to me that the ATSB is ‘swimming against the tide’ to some extent, having regard to the overwhelming nature of the recalls by Textron Lycoming on a world-wide basis in 2001 and 2002 since this incident, citing defective crankshafts.*

ATSB comment

The Coroner does not acknowledge that all the information regarding crankshaft defects became known after ATSB report 200002157 was released on 19 December 2001. He also does not acknowledge that within the batch of crankshafts that included the MZK left engine crankshaft, 70 per cent were found to be unaffected and that examination of the crankshaft by a number of specialists, including Dr Powell, McSwain and the ATSB did not reveal any physical evidence of irregularities or defects linked to the service bulletins or that could have initiated the fatigue fracture under normal engine operating conditions.

See pp 7–8, and Attachments B and C of this report.

14.99 *What was the cause of the failure of the right engine of MZK?*

ATSB comment

See Section 4 of this report and ATSB Report 200002157 Section 1.17.

14.103 *Having regard to the totality of the evidence, I reject the argument put forward by Mr Cavenagh and Mr Fearon that the damage to the right engine was caused as a result of Mr Mackiewicz ‘overboosting’ the right engine as a result of the left engine having failed first. For reasons which I have already expressed, I do not regard this as the most likely scenario. Having regard to the evidence of Mr Braly and Dr Zockel and others, it seems more likely that the right engine of MZK was damaged due to end gas detonation during the climb phase of Flight 904 and that Mr Mackiewicz reduced the power on that engine in order to conserve it at 1847:15.*

ATSB comment

As highlighted earlier, there was no indication of any loss of performance or other abnormality during the climb phase of the flight. Further, the Coroner has not offered an explanation for the pilot not observing the elevated cylinder head temperature that would have accompanied right engine damage during the climb, when the pilot was operating in an apparently normal, stress-free stage of the flight. Holing of the piston 8 minutes into the cruise would have likely led to oil loss prior to the impact some 29 minutes later. See Section 4 and 5 of this report.

14.104 *Did the left engine failed first? If so, at what stage of flight 904?*

ATSB comment

See Sections 3, 4 and 6 of this report and ATSB Report 200002157.

A5. Comments relating to Chapter 15 of the Coroner's report 'Recommendations'

15.10 *It follows, then, that I reject any suggestion that the ATSB were constrained or limited by section 19CA of the Air Navigation Act, 1920 in this investigation. In my opinion, the remarks of the Director of the ATSB, Mr Kym Bills, to the Australian Senate on 11 February 2003 reflect this misconception:*

'For many years there have, from time to time, been difficult issues in some state and territory coronial inquests. The ATSB has been seeking better mutually cooperative relationships with coroners in the context of the legislation currently before the parliament and will continue to do so. However, problems remain when the bureau is criticised at inquests for not spending more money on a particular investigation to satisfy legal queries such as those relating to future civil litigation; when the high cost of inquests redirects our resources from higher safety priorities; where a particular inquest encounters difficulties with the Commonwealth no-blame legislation; under which we operate in accordance with international agreements; or where legal certainty is sought from an investigation, whereas the evidence often does not allow this and the ATSB's focus is on the action necessary for future safety.'

The notion that 'legal certainty' (by which I assume Mr Bills means the finding of a fact to the requisite standard of proof) is somehow inconsistent with the ATSB's role to ensure 'future safety' is not in accordance with logic. Surely an investigation must demonstrate, to an appropriate degree of certainty, that an incident has occurred in a particular way before remedial or preventative measures can be taken.

ATSB comment

The opinion given by the Coroner based on evidence given to an ongoing Senate Committee inquiry does not seem appropriate and also does not reflect the main points Mr Bills was seeking to make. At the invitation of the Coroner's solicitor on 4 March 2003, the ATSB's Australian Government Solicitor (AGS) lawyer on 12 March 2003 offered to provide sworn statements by Mr Bills and two AGS lawyer witnesses, to the Coroner covering the issues of concern to the ATSB and to be available for cross-examination upon them. The Coroner wrote back to AGS stating that he did 'not propose to allow the inquest to be used to ventilate your clients grievances when they do not touch on the issue before me'. However, the Coroner subsequently did make findings about the issues of concern to the ATSB (eg the US testing, see para 12.122). In this paragraph the Coroner asserts that in his opinion Mr Bills was suggesting to the Senate Committee that the Air Navigation Act constrained or limited the ATSB's investigation and that this was a 'misconception' and 'not in accordance with logic'. Mr Bills was not making the point to the Senate Committee suggested by the Coroner and this could have been clarified if the Coroner had allowed Mr Bills to give evidence to the inquest.

15.11 *I note that there is currently a Transport Safety Investigation Bill 2002 before the Commonwealth Parliament. Section 7 of the Bill repeats the statements of section 19CA of the current Act, about what are not the objects of the legislation, and adds to that list:*

- (c) assisting in court proceedings between parties (except as expressly provided by this Act);*
- (d) allowing any adverse inference to be drawn from the fact that a person is subject to an investigation under this Act.'*

ATSB comment

The Transport Safety Investigation Bill 2002 was not currently before the Commonwealth Parliament on 24 July 2003. The Transport Safety Investigation Act 2003 received Royal assent on 11 April 2003 and the Act had been in force since 1 July 2003.

15.15 *Combustion deposits*
Recommendation R20010254 suggests ‘a review of the certification requirements of piston engines with respect to the operating conditions under which combustion chamber deposits that may cause preignition are formed’. I have found that combustion deposits played no part in the failure of either engine of MZK on 31 May 2000, so I do not adopt that recommendation.

15.16 *Anti-galling compounds*
Similarly, ATSB Recommendations R20010255 and R20010256 deal with anti-galling compounds. I have found that they played no part in the failure of MZK’s engines on 31 May 2000, so I do not adopt those recommendations.

15.17 *Reliability of Aircraft Propulsion Systems within Australia*
ATSB Recommendation R20010257 is as follows:

‘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.’ (Exhibit C97, p121)

On my findings, there was no demonstrated defect in operating or maintenance procedures which may have led to the failure of either of MZK’s engines on 31 May 2000, so I do not adopt that recommendation, except the issue discussed in the next paragraph.

ATSB comment

The ATSB recommendations have not been withdrawn and the proposed safety action is still regarded by the ATSB as appropriate and important in the interests of aviation safety.

15.18 *Fuel Mixture Leaning Practices*
ATSB Recommendation R20000250 was as follows:

‘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.’ (Exhibit C97, p122)

The final report records that CASA’s response was as follows:

‘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.’

(Exhibit C97, p122)

On my findings, the only departure from appropriate fuel leaning practices, as stipulated in the Pilot Operating Handbook (Exhibit C170g) which may have been causative of damage to either engine of MZK on 31 May 2000 was the leaning to 27usg/hr during the climb phase of Flight 904. I am satisfied, on Mr Braly’s evidence, that the fuel leaning guidelines stipulated by Whyalla Airlines in its Operations Manual (Exhibit C73h), were inappropriate and may have caused or exacerbated damage to the piston of the right engine.

15.19 *I agree with the submission of Messrs Harvey and Roser, counsel for CASA, at page 32:*

'The evidence discloses an urgent need for the technical review of the detonation survey upon which the procedures of the FAA approved Flight Manuals and Lycoming endorsed, Piper POHs are based. That review should be undertaken in a cooperative effort by all of the relevant USA interests. The evidence discloses that CASA does not have the laboratory facilities, or the technical staff to perform such a task. CASA submits that a recommendation should be made to the effect that the engine operating procedures – in particular, the power and mixture settings – set out in the various versions of the Pilot Operating Handbooks and Flight Manuals for Piper Chieftain aircraft be reviewed with the object of ensuring (a) accuracy of the detonation limiting conditions and (b) clarity of all engine operating procedures.'

15.20 *I recommend that engine operating procedures set out in the various versions of the Pilot Operating Handbooks and Flight Manuals for Piper Chieftain Aircraft be reviewed with the object of ensuring:*

- (a) accuracy of the detonation limiting conditions; and*
- (b) clarity of all engine operating procedures.*

ATSB comment

The ATSB is pleased that the Coroner has supported its recommendation and adopted the submissions by CASA and the ATSB in proposing additional safety action.

15.21 *International Cooperation*

Much was made by Mr Cavenagh in his evidence about the fact that Australia is a signatory to the Chicago Convention on International Civil Aviation and that investigative agencies cooperate and exchange information about aircraft incidents. This is a very desirable thing.

15.22 *Unfortunately, in this case it would appear that this cooperation ceased as soon as it became apparent that there might be litigation in the United States of America. I was told that a number of requests for information, by both CASA and the ATSB, to their American counterparts were not successful once this fact became apparent. As a result of this, it is abundantly clear that the ATSB had little information about other crankshaft failures in the United States with which to compare this incident. The ATSB may have led the authorities in the United States to believe that this incident was unrelated to the United States failures. The February 2002 briefing by the FAA, reported that the Australian incident had been attributed to engine detonation due to engine leaning procedures adopted by several Australian operators.*

15.23 *In my opinion, this lack of free information exchange may well have seriously hampered the ATSB in understanding what happened here, causing them to take a path of inquiry different to that taken by the United States investigators.*

15.24 *I therefore recommend that CASA and the ATSB consider how lines of communication could be improved so that communication continues to flow even in circumstances where litigation might be threatened or instigated.*

ATSB comment

Like the Coroner, the ATSB was disappointed that legal processes, including those surrounding the inquest and US civil damages litigation, significantly curtailed international cooperation with the ATSB's safety investigation role. The legal approach adopted in the inquest was unable to produce significant further information. International cooperation will never be perfect and communication can always be improved. The much better protections in the Transport Safety Investigation Act 2003 for sensitive 'restricted'

information and the inability for draft or final ATSB reports to be used in civil or criminal litigation should assist. However, it will remain the case that the ATSB must rely on international cooperation and cannot force bodies in other countries to assist. See also p 27 of this report.

15.25 *Cockpit Flight Recorders / On-Board Recorder Systems*

It can be seen from these findings that the ascertainment of the precise failure sequence of the two engines in MZK on 31 May 2000 has been a difficult task because of the paucity of evidence about what happened during the flight.

ATSB comment

The Coroner's acceptance here of the difficulty of ascertaining the engine failure sequence because of the paucity of evidence even three years after the accident is welcome but in stark contrast to his earlier vitriolic criticisms of the investigation undertaken by the ATSB and published in good faith in December 2001.

15.27 *One way to improve the fact-finding capabilities of investigators examining an incident such as this would be to require that all aircraft involved in conveyance of passengers for payment, or at least all aircraft engaged in RPT, should carry a Cockpit Flight Recorder, also known as an On-Board Recorder (OBR).*

15.28 *I note that these instruments were recently considered by the State Coroner for Western Australia, Mr Alastair Hope, during an inquest into the deaths of eight people in September 2000 as a result of an aircraft accident, known colloquially as the 'Ghost Flight'. An aircraft bound for the Western Australian goldfields lost pressurisation, and continued to fly on autopilot, with the occupants incapacitated or dead, until it ran out of fuel and crashed in Northern Queensland.*

15.29 *I agree with Mr Hope's comments at pages 68–70 of his finding...*

I note that CASA has already considered Mr Hope's recommendation, which was adopted by the ATSB as Recommendation R20020149.

15.32 *I recommend that CASA consider how the development of On-Board Recorders suitable for use in light commercial aircraft might be facilitated. Should fitment of On-Board Recorders in these aircraft become feasible, I further recommend that their use be mandatory in the carriage of passengers for payment, or at least in RPT operations.*

ATSB comment

An On Board Recorder (OBR) is defined in the *Transport Safety Investigation Act 2003* and is a generic multi-modal term that includes an aircraft Cockpit Voice Recorder (CVR). In high capacity air transport operations an OBR/CVR records crew voices and comprises one of two 'black boxes' required under safety regulations. The other 'black box' contains entirely separate recordings of aircraft flight data and is referred to as a Flight Data Recorder (FDR). The WA State Coroner's recommendation to consider the wider installation of devices such as those that monitor and record aircraft systems and operation was not 'adopted by the ATSB as Recommendation R20020149' but rather the reverse occurred. The WA State Coroner adopted the ATSB's July 2002 recommendation on 12 September 2002. The ATSB recommendation that the Civil Aviation Safety Authority examine whether the potential safety benefits from devices such as those that monitor and record aircraft fuel and engine system operation are sufficient to warrant them being required in general aviation aircraft used in air transport operations, did not cover black box type OBR/CVR recorders as suggested by the SA State Coroner. On the

assumption that the SA State Coroner's recommendation about On Board Recorders is intended to refer to low cost devices that measure flight data (as with the ATSB's R20020149), the ATSB supports it.

15.33 *Self-deploying Emergency Locator Transmitters*
I have described the fact that the pilot of VH-FMC heard an emission from an Emergency Locator Transmitter (ELT) at about 7:06pm on 31 May 2000.

15.41 *I recommend that the ATSB and CASA undertake a research program to ascertain whether it is feasible to fit a self-deploying ELT system to all aircraft engaged in carriage of fare-paying passengers, whether by RPT or charter operations, over water. If it is feasible, the use of such instruments in those circumstances should be mandatory.*

ATSB comment

The ATSB believes that adequate ELTs fall within its recommendation R20000249 made in October 2000 and is pleased with the Coroner's support. The ATSB believes that the Coroner's recommendation concerning ELTs is best addressed by CASA, AusSAR (AMSA) and Defence.

15.42 *Lifejackets*
Having regard to the evidence of Dr Brock, it seems clear that even if MZK had been required to carry lifejackets on 31 May 2000, they would not have assisted anyone on board that night (see Exhibit C168, p8).

15.43 *Dr Brock pointed out that lifejackets would have been important if MZK had ditched without major damage, did not sink quickly, and one or more of the occupants could have exited the aircraft with lifejackets and inflated them outside. I refer to the information in paragraphs 3.11-3.12 herein, where such cases have been recorded. Both Mr Gherzi and Dr Urquhart managed to exit their aircraft before it sank, and if they had lifejackets their chances of survival would have been better.*

15.44 *Dr Brock pointed out that if a lifejacket had been inflated inside the aircraft, it would have constituted a 'menace' (T1223-24).*

15.45 *I was advised by Mr Harvey, counsel for CASA, that as from 1 July 2003 it will be compulsory for aircraft carrying passengers for payment to be equipped with a lifejacket or flotation device for each passenger 'on all flights where the take-off or approach path is so disposed over water that in the event of a mishap occurring during the departure or arrival, it's reasonably possible the aircraft would be forced to land on to water' (T2945).*

15.46 *While this is a step in the right direction, I agree with the ATSB's recommendation R20000249:*

'The Australian Transport Safety Bureau recommends that the Civil Aviation Safety Authority ensure that Civil Aviation Orders provide for adequate emergency and life saving equipment for the protection of fare-paying passengers during over-water flights where an aircraft is operating beyond the distance from which it could reach the shore with all engines inoperative.' (Exhibit C97, p123)

15.47 *I recommend that CASA amend the Civil Aviation Orders to make it mandatory that aircraft should carry lifejackets and/or a life-raft for the protection of fare-paying passengers whenever the aircraft is operating beyond the distance from which it could reach the shore with all engines inoperative.*

ATSB comment

The ATSB is pleased that the Coroner has made a recommendation which reinforces the ATSB's October 2000 recommendation on carriage of lifejackets and other flotation devices.

- 15.48 *Multi-probe Cylinder Head Temperature (CHT) Gauges and Knock Sensors*
It was common ground at the inquest that the CHT gauges on MZK (depicted in Exhibit C97, p14) are connected to only one probe in the engine, usually in the No. 6 cylinder, which should be the hottest.
- 15.49 *Mr Braly told me that in his opinion, it was far more satisfactory to have an engine monitoring system which monitors the temperature of all six cylinders, as well as the exhaust gas temperature for all six cylinders and the turbine inlet temperature as well. The system he demonstrated scans all cylinders sequentially, and an alarm can be programmed to sound if an engine parameter exceeds a set value (T3154).*
- 15.50 *The same instrument can also monitor the air temperature, fuel flow rate, voltage in the electrical system, oil temperature, all of which are important engine parameters, and in relation to all of which the traditional gauges are somewhat primitive and in some cases inaccurate.*
- 15.51 *Mr Braly said that it was possible to detect engine trouble very early in the piece using this instrument, and avoid catastrophic engine damage initiated by, say, a failed spark plug. He demonstrated, using a PowerPoint display, an actual event where such damage was averted this way (T3161-3173).*
- 15.52 *There was a division of opinion, though, as to whether such instruments should be retro-fitted to older aircraft such as MZK. Mr Heyne thought it might make the pilots job more complex (T296), and Mr Thompson (T3833) and Mr Beattie (T1954-55) referred to 'information overload'. Messrs Kuch (T1418), Reymond (T1600) and Usher (T1650) disagreed. Mr Kym Brougham thought that fitting such gauges would not be useful so long as regulators continued to insist that the original gauges be the first point of reference (T2324-25).*
- 15.53 *Mr Sharp thought that such instruments would be useful so long as they are not used to run the engine close to its limits (T2396).*
- 15.54 *Mr Lyons, from CASA, said:*
'CASA has no evidence that requiring multi-probe gauges to be installed on piston engine aircraft is necessary.' (T4415)
- 15.55 *It was also suggested that 'knock sensors' could be installed in aircraft engines of this type, to detect 'knock' or detonation. (See the evidence of Mr Murphy T2153-54, Mr Brougham T2325-6 and Dr Zockel T3463). Modern automotive engines are fitted with such devices, which are connected to the electronic engine management system. When the sensor detects detonation, it automatically adjusts the timing to prevent this. Of course, aircraft like MZK do not have an electronic engine management system, the engine is managed by the pilot.*
- 15.56 *Mr Lyons also took a conservative view of knock sensors. He said:*
'In the history of piston aviation there's never been any real evidence to suggest that knock sensors would be of benefit. Going back to when airliners were piston engine powered and running under extreme load, there was instrumentation provided to the flight engineer to be able to monitor those loads, but in the current generation of piston engines, the loading - provided the engine is operated conservatively - doesn't require such instrumentation to ensure the engine remains reliable.' (T4416)

- 15.57 *I do not have enough information before me to make a formal recommendation on either of these areas. I cannot be satisfied that the use of a multi-probe gauge or a knock sensor would have prevented this incident. It does seem surprising that these engines have relatively primitive manual management systems, compared with the system to be found in even the most inexpensive car these days.*
- 15.58 *Mr Lyons' conservatism is understandable, but the evidence before me is quite cogent, and suggests that the fitment of multi-probe gauges would be likely to improve the pilot's ability to manage the engines appropriately. I note the offer made by Mr McIlwaine SC, on behalf of the ATSB, to assist in the formulation of a recommendation to CASA. I am grateful for the offer, but since I am unable to make the recommendation, for the reasons expressed, I will leave it for the ATSB to take up.*
- 15.59 *Oil testing*
Mr Braly suggested that if the bearings had failed progressively over the 50-70 flights before 31 May 2000, and this had not been detected by a visual examination of the oil screens and filters, as I have found it was not, then it may have been detected by a spectrographic examination of the oil by a laboratory. He said that he had been doing that since about 1991 (T3300).
- 15.60 *This also seems to be an idea that should be considered by the ATSB with a view to making a recommendation to CASA. I am not in a position to make a recommendation that it be done, because I am not satisfied that, in this particular case, the failure sequence of the engine involved progressive bearing failure. However, I believe that in the general course of aviation, it is a matter that deserves further consideration by the regulator.*

ATSB comment

The ATSB has further examined the potential safety issues raised by the South Australian State Coroner and additional issues that the Coroner did not fully consider. See Section 9 and 10 of this report.

Attachment B: ATSB response to the conclusions in the final McSwain report dated 7 March 2003 concerning the failure of the crankshaft from Whyalla Airlines aircraft VH-MZK, left engine

ATSB comments on the McSwain conclusions refer to specific texts from the McSwain report (in italics).

4.0 Conclusions

After further evaluation of the failed left engine crankshaft, I have reached the following conclusions to a reasonable degree of engineering certainty in my field:

1. *The subject aircraft's left engine was a Lycoming TIO-540-J2B with approximately 262 hours since overhaul by Textron Lycoming.*

ATSB Comment

Agree

2. *The subject aircraft's left engine crankshaft failed due to fatigue at the No. 6 connecting rod journal.*

ATSB Comment

Agree

3. *The fatigue cracking in the subject aircraft's left engine crankshaft was subsurface initiated.*

ATSB Comment

Agree that fatigue cracking was initiated below the nitrided surface of the No. 6 connecting rod journal surface forward fillet. There are several reasons why fatigue cracking may initiate in the region of the case/core interface of a surface hardened crankshaft. For instance, higher loads than allowed for during design, the presence of a physical discontinuity extending through the hardened zone (case), the presence of a physical discontinuity in the region of the case/core interface or the presence of material of lower strength than that allowed for during design. Subsurface initiation does not imply that a non-metallic inclusion of a size greater than that normally present in the steel alloy, produced by a particular processing route, is the only reason for fatigue crack initiation. The ATSB's re-testing of the crankshaft in March 2003 confirmed its original findings detailed in ATSB report 200002157.

4. *The fatigue cracking physical evidence in the subject aircraft's left engine crankshaft is not consistent with thermal cracking.*

ATSB Comment

Disagree

No compelling case has been made to explain the presence of the step feature extending from the site of fatigue initiation to the journal surface. The argument presented that the step feature is a tear ridge created by the bi-planar propagation of the fatigue crack from the site of its initiation to the surface is overly simplistic.

No consideration is given to the effect of the nature of the discontinuity that created a site of local stress concentration. If fatigue initiated at a site of local stress concentration then crack growth would be expected to extend concentrically away from the discontinuity under the influence of the local stress fields. The effect of microstructural variations or the presence of some physical discontinuity may result in changes in the extension of a fatigue crack and result in the crack propagating on different planes. Note: there was no

biplanar fatigue crack extension towards the core of the crankshaft. In the case of fatigue crack propagation on separate planes the nature of the step created on the fracture surface is affected by the changes in the local stress field created by the influence of overlapping cracks. As the cracks overlap, the local tensile stresses (those responsible for crack extension) are no longer parallel with the applied tensile stresses and the cracks bend toward each other, by tilting, and eventually intersect. The stress fields change progressively as the cracks grow so the fracture path is smooth and continuous. The step feature, although it has been mechanically damaged during the engine failure process, is not consistent with the smooth and continuous tilting of two overlapping crack fronts.

The presence of a planar physical discontinuity extending through the surface hardened zone would allow the separation of the plane of fatigue cracking under the applied alternating stresses. The presence of a planar discontinuity extending through the surface hardened zone of the crankshaft journal would provide a site of high stress concentration. Fatigue crack initiation can occur from the base of such planar discontinuities.

The location and orientation of the discontinuity in the No. 6 journal is consistent with local fracture created by local thermal strains.

5. *The fatigue cracking physical evidence in the subject aircraft's left engine crankshaft is not consistent with a shift of the No. 6 connecting rod bearing resulting in rubbing at the crankshaft journal radius.*

ATSB Comment

Disagree

The location of the discontinuity associated with the site of fatigue crack initiation is located at a point in the forward fillet radius close to the transition between the journal surface and the fillet radius. The axial location of bearing inserts in the big end housings of connecting rods may change during engine operation if the primary insert retention force (friction force created between the back of the insert and the bore of the housing by a designed interference fit) is reduced. The incorporation of materials such as anti galling lubricants/compounds between the insert and housing will reduce the coefficient of friction between the insert back and therefore the friction force created by the interference fit. Note: bearing manufacturers, eg Clevite Engine Parts Division, state in technical publications that the locating tang/lug at the end of a bearing insert is provided to locate the insert accurately within the housing. The tang/lug is not intended to prevent bearing insert rotation under the forces imposed on the bearing during engine operation. While the tang/lug is not designed to prevent bearing rotation over the operational life of the engine it can resist some degree of bearing rotation force for a limited period of engine operation. Continued engine operation with the tang/lug providing the primary resistance to bearing insert rotation results in, tang/lug deformation and/or the development of cracks at the sides of the tang/lug, and eventual loss of the ability of the tang/lug to locate the bearing insert in the centre of the big end housing.

The potential range of bearing insert axial movement before contact between the connecting rod bolt guide section and the bolt clearance cutout, following tang/lug failure, will result in contact between the edge of the insert and the journal fillet radius.

Contact between the edge of the bearing insert and the journal surface can create localised thermal strains in the journal surface with the result that short, axially oriented, cracks in the hardened surface of the journal are created. The length of these cracks may be in the range 0.5 to 1mm.

6. *The failure of the subject aircraft's left engine No. 6 connecting rod was secondary to the failure of the crankshaft.*

ATSB Comment

Unclear wording (eg as regards use of the term 'failure').

The No. 6 connecting rod big end housing fractured as the result of fatigue crack growth in the connecting rod cap. The fracture of the housing allowed the piston to strike the cylinder head with considerable force, indicating that the fracture and release of the piston and connecting rod assembly occurred while the engine was operating in the normal rpm range. This event obviously occurred prior to the separation of the fractured halves of the No. 6 connecting rod journal and the consequent loss of drive to the camshaft, magnetos and engine accessories. Clearly the failure of the No. 6 connecting rod was not secondary to the separation of the fractured halves of the No. 6 connecting rod journal.

The failure mode of the connecting rod big end housing – growth of fatigue cracks from the outer surface of the housing at the counterbore for the connecting rod bolt head – is indicative of excessive flexure of the housing during engine operation. Excessive flexure can occur with the progressive breakdown/deformation of the bearing insert. Examples of this mode of failure have been observed without crankshaft fracture.

Fatigue crack initiation and growth in both crankshaft connecting rod journals and connecting rod big end housings can be related to the loss of insert location in the housing and progressive breakdown/deformation of the insert. Note: there are several mechanisms that result in bearing insert breakdown/deformation, for example:

- Fatigue of the bearing surface resulting in spalling that leads to increased clearances and disturbance of the lubricating oil film.
- Momentary seizures under conditions of marginal lubrication.
- The effects of increased bearing temperatures associated with high bearing loads and/or a reduction in the ability to transfer heat away from the bearing surface.
- Bearing insert loss of retention, allowing insert axial movement and/or rotation within the housing.

Depending on the precise nature of the loss of retention, breakdown/deformation, fatigue cracking may initiate in either the journal or the housing, or both. In the case of initiation in both the journal and housing the final failure mode of the assembly will be dependent on the rate of crack propagation in each element of the assembly.

7. *The subject aircraft's left engine crankshaft had cracking at the No. 4 and No. 5 connecting rod journals and the No. 3 main bearing journal that were secondary to the No. 6 connecting rod journal failure.*

ATSB Comment

Agree – the physical evidence provided by these cracks indicate that the crankshaft remained dogged and the engine continued to operate for 8–10 minutes after the crankshaft fractured.

8. *The laboratory induced impact fracture from the subject crankshaft did not exhibit typical overload fracture features.*

ATSB Comment

Disagree

Ductile fractures in quenched and tempered low alloy steels (for example the type used in the manufacture of the crankshaft) created by overload or impact at room temperatures involve the process of microvoid coalescence. The nature of non-metallic inclusions, in

particular their size, shape and distribution, plays a dominant role in development of fracture surface features, eg dimple size and shape.

A comparison of fracture surface features between two steel alloys must be made on the basis of the knowledge of the non-metallic inclusion shape, size and distribution.

It should be noted that 'older vintage Lycoming 540 crankshafts' were manufactured from air melted steel. The inclusion size, shape and distribution of non-metallic inclusions in air melted crankshaft steel is very different from that in vacuum remelted, calcium and magnesium treated crankshaft steel.

The differences in ductile fracture surface features reported in the McSwain Report can be explained by the effect of differences in steel production.

Note: a degree of confusion is created in the comparison of fracture features from crankshaft s/n V537912936 and an 'older vintage Lycoming 540 crankshaft' by the publication of scanning electron micrographs at differing magnification – the magnification of micrograph B in enclosure 10 is 2500 times while the magnification of micrograph B in enclosure 11 is 1000 times.

9. *The failure of the accident aircraft's left engine crankshaft No. 6 connecting rod journal was due to a manufacturing related material condition that resulted in subsurface fatigue crack initiation.*

ATSB Comment

Disagree

Fatigue initiation below the surface of a connecting rod journal may be associated with any feature that acts as a site of stress concentration. Non-metallic inclusions can act as sites of stress concentration as can thermally induced cracks in the hardened zone of the journal or any other planar discontinuities in the subsurface region.

The magnitude of stress concentration of a feature is a function of its size and shape.

The initiation of fatigue cracking under operational loading will depend on whether the increase in local stress created by the feature exceeds the fatigue endurance strength of the material at that site. Note: the increase in stress magnitude will have to exceed the safety factor established during design.

The McSwain Report infers that the material related condition in the 'pocket area' marked in micrograph A, enclosure 6, is the result of an inclusion. The scanning electron and reflected light micrographs presented to support the contention that an inclusion was present at the site of fatigue initiation do not establish the presence of an inclusion. It is likely that the feature purported to be the result of an inclusion is a function of the imaging conditions, such as topographic shadowing.

EDS Xray analysis of the purported site of the inclusion was also inconclusive. Elements such as iron, silicon and potassium were present in higher concentrations than aluminium, calcium and magnesium. The presence of calcium and magnesium was very minor.

Metallographic sectioning through the fatigue initiation undertaken by McSwain Engineering did not provide any evidence for the presence of an inclusion.

The method of cutting used by McSwain Engineering to remove the section of the crankshaft containing the fatigue initiation site resulted in extensive pitting of the fatigue fracture surface in the region of the step feature and the site of fatigue initiation.

The presence of cracking extending from the end of the step feature (at the site of fatigue crack initiation), perpendicular to the plane of fatigue crack growth was not commented on in the report. Micrographs recorded during the various stages of the examination, compiled on a CD, clearly show the feature.

It was reported that the size of inclusions present in the steel was 5 to 10 microns in diameter. This size is normal for vacuum arc remelted steel. The effect of inclusions of this nature is included in the fatigue test data upon which design stresses are established. Fatigue crack initiation from an inclusion of 5 to 10 microns in diameter would indicate that the engine operating loads were in excess of the design limits.

- 10 *The subject aircraft's left engine crankshaft, S/N V537912936, is identified as having a material related issue that could result in failure by Textron Lycoming Mandatory Service Bulletin No. 553 dated September 16, 2002.*

ATSB Comment

Disagree

It is agreed that the crankshaft s/n V537912936 is included in the range addressed by Service Bulletin No. 553. However, the material related issue has not been specified. Preambles to service bulletins and airworthiness directives only mention the forging process (hammer forging) and some tightening of heat treatment parameters. Notes in Cessna correspondence on the issue mention a 'small randomly occurring metallurgical condition' and detail that improvements to eliminate the metallurgical condition include a change in forging process to automated press forging, positive induction temperature control and 100 per cent metallurgical sampling of a sample coupon from each shaft.

The apparent randomness of the metallurgical condition is highlighted by the results of crankshaft testing in accordance with Service Bulletin No. 553. It has been reported that of the crankshafts that were subject to that service bulletin, almost 70 per cent were not defective and were permitted to continue in service after testing.

No specific, clearly characterised, material defect has been identified.

Attachment C: ATSB detailed examination of the fatigue crack origin, Number 6 connecting rod journal, crankshaft S/NV537912936, left engine VH-MZK

1. Summary

A detailed examination was undertaken of the fatigue crack origin of the No. 6 connecting rod journal of crankshaft s/n V537912936 from the left engine of VH-MZK. The examination reviewed the destructive testing undertaken by McSwain Engineering Inc. in the US and included detailed additional testing in the ATSB laboratories in Canberra. Additional tests were also undertaken by external laboratories to complement the initial testing completed through the ATSB and recently through McSwain.

None of the testing or physical evidence indicated the presence of material features created by steelmaking, crankshaft forging, crankshaft heat treatment or crankshaft journal surface nitriding that could have initiated fatigue cracking while the engine was operated within design limit loading conditions.

The initiation of fatigue cracking from a site below the surface of a component does not always imply that a material deficiency or defect was responsible. The initiation of fatigue is dependent on the magnitude of the loads applied to the component, the increase in local stress levels by geometric features such as surface notches, discontinuities created by inclusions, and the strength of the material in the region of stress concentration. Surfaces and, in particular, sites of stress concentration at surfaces, are the most common initiators of fatigue cracks.

Steels are not homogeneous materials. They are composed of a variety of microstructural features, including small non-metallic compounds or inclusions. Fatigue strength data determined by testing specimens takes into account the effect of all the features normally present in a steel manufactured by a particular processing method. The initiation of fatigue cracking from one of these microstructural features may occur if the magnitude of the alternating stress developed in a component exceeds the maximum design allowable stress.

The process of surface hardening a crankshaft by nitriding introduces considerable complexity to the determination of the most likely site for fatigue crack initiation. Firstly, the hardened surface zone has higher fatigue strength. Secondly, the process of nitriding creates a state of residual compressive stress in the surface zone with the effect of reducing the magnitude of alternating stresses at, and close to, the surface. Under conditions of alternating flexure, the site of maximum alternating stress in a nitrided component is located at the case/core interface. If the loading applied to a nitrided component exceeded the maximum design loading for fatigue free operation it would be likely that fatigue cracking would initiate at a point below the surface of the component. Additionally, discontinuities may be created in the surface hardened zone through the effects of localised thermal expansion. For example, localised, unlubricated, contact between other engine components and the surface hardened zone can result in the creation of thermal expansion cracks that may act as a sites of stress concentration and lead to the initiation of fatigue cracking.

The crankshaft s/n V537912936 complied with the compositional limits for AMS 6414H with check test variation limits applied. The analysis of carbon content by four independent analyses (three testing laboratories) showed a range of scatter of 0.036 per cent. Two results of two analyses were within the check test upper limit and two results

exceeded the upper limit by 0.02 per cent. The results that exceeded the upper limit are within the scatter range and are not considered to represent a significant variation from the specified limits. The crankshaft complies with the specified limits for nitriding depth and surface hardness. The hardness of the crankshaft core is consistent with the value that would be achieved with a single stage nitriding process. The type of inclusions present throughout the crankshaft and, in particular, the region in the immediate vicinity of the site of fatigue crack initiation were typical of a steel that had been vacuum arc remelted and treated with calcium and magnesium to control sulphur content and inclusion shape. No abnormality related to material processing was observed in the immediate vicinity of the fatigue initiation site.

Examination of the step feature that was present between the site of fatigue initiation and the journal surface was undertaken by the creation of a series of parallel metallographic sections through the step feature on both sides of the fracture surface. This revealed that a crack, oriented perpendicular to the fatigue fracture (parallel with the axis of the journal), with a path that followed the microstructure of the steel, was present prior to the deformation of the area during the final fracture and torsional separation processes. Cracking of this nature is consistent with cracking developed by the localised thermal expansion of the nitrified zone. The most likely source of localised heating in the region of the journal fillet where the step feature was located is contact with the bearing insert. The step feature was not typical of a tear ridge created between two overlapping fatigue crack fronts.

2. Introduction

The reliable operation of aircraft reciprocating engines depends on the maintenance of the structural integrity of the components that comprise the engine. The assurance of structural integrity occurs through the development and implementation of fracture control plans. For components that are subjected to numerous alternating load cycles during operation, the prime consideration of the fracture control plan is the avoidance of fatigue crack initiation and propagation to final fracture. Two approaches may be considered. Firstly, a restriction of the magnitude of alternating stresses developed in the component as a result of engine operation to a value less than the fatigue endurance (limit) strength of the component – the margin between operating stresses and component strength is determined by a prescribed factor of safety. The second approach addresses the situation where fatigue crack initiation during operation cannot be eliminated by operating stress limitations and relies on the detection of cracks and removal of the component from service before the critical crack size for rapid final fracture is reached. Both approaches rely on standardised methods of material and component production to ensure that material and component properties fall within the range that was used as the design basis.

Because of the large number of alternating stress cycles imposed on a crankshaft during engine operation and the inability to nondestructively inspect the crankshaft in an engine without extensive disassembly combined with the requirement to maximise the interval between major engine overhauls, the second approach is not generally applicable to engine crankshafts.

The fracture control plan is verified by testing during engine certification and continued operation. Failure of a crankshaft during engine operation represents a failure of the fracture control plan.

Fatigue failure

The fatigue failure of a component designed to have an unlimited fatigue life occurs when:

- The magnitude of the alternating loads applied during operation is greater than the maximum loads allowed for during design.
- A stress concentrating feature is present such as a physical discontinuity in the material (the size and shape of the discontinuity are important variables), or variations in detailed geometry from the normal manufactured condition, or variations in surface finish from the normal manufactured condition. Stress concentrating features may be created during manufacture, maintenance or operation.
- The residual stress state is different from the normal manufactured condition.
- A region of material of lower than normal fatigue resistance is present.

Fatigue testing

The fatigue strength of a steel alloy determined by testing a number of machined specimens is affected by the microstructure of the alloy developed through heat treatment, the morphology and distribution of non-metallic inclusions created by the steel making process, and the surface finish of the specimen. The effect of inclusions normally present in a steel alloy produced by a particular processing route is reflected in the results of the test. If tests are performed on specimens representative of the material used in components, the design allowable stress levels derived from test results will take into account the presence of the typical inclusions. Analysis of fatigue failures needs to consider the nature and distribution of inclusions that are present in the steel from which the test data has been obtained.

Material

AISI/SAE 4340 steel is a member of the medium-carbon low-alloy family of ultra high strength steels⁵. These steels are used in a number of heat treated states. Each alloy can be heat treated to a wide range of strengths. Within the family, small variations in alloy content are made for the purposes of increasing strength, improving weldability, preventing embrittlement when the steel is tempered at low temperatures, and increasing hardenability. Vanadium may be added to alloys of this family to increase toughness by acting as a grain refiner.

The crankshaft from the left engine VH-MZK was manufactured from vanadium modified 4340 steel. The steel was produced to AMS (aerospace material specification) 6414H. The 'H' in 6414 denotes a requirement to meet a specified level of hardenability.

Developments in this alloy group have been aimed at increasing ductility and toughness by improving melting and processing techniques as well as by stricter process control and

⁵ Metals Handbook 9th edition vol 1, p 421.

inspection. Steels with fewer and smaller non-metallic inclusions are produced by the use of selected raw materials and melting techniques such as vacuum-carbon deoxidation, vacuum degassing, electroslag remelting (ESR), vacuum arc remelting (VAR), and double vacuum melting (vacuum induction melting followed by vacuum arc remelting). These techniques yield (a) less variation of properties from heat to heat and lot to lot, (b) greater ductility and toughness, especially in the short transverse direction, and (c) greater reliability in service.

TABLE 1:
The effect of steelmaking method on mechanical properties⁶

<i>Steel production method and test direction</i>	<i>Tensile Strength MPa</i>	<i>Yield Strength MPa</i>	<i>Plane Strain Fracture Toughness (K_{Ic}) MPa√m</i>	<i>Fatigue Limit MPa</i>
Air melted, longitudinal	2005	1660	44.5	795 (115 ksi)
Air melted transverse	2000	1655	45.8	540 (78 ksi)
Vacuum arc remelted longitudinal	2035	1660	60.4	965 (140 ksi)
Vacuum arc remelted transverse	2015	1650	61.5	715 (104 ksi)

Average mechanical properties of air melted and vacuum arc remelted heats of 4340 steel (hot reduced to round billets 100 to 115 mm in diameter, normalised at 900°C, oil quenched from 845°C refrigerated and tempered 2h at 205°C.

Non-metallic inclusions

It is normal to find numbers of small embedded particles in steels that have their origin in the iron and steel refining processes. These particles are known as inclusions and are primarily non-metallic in nature, eg oxides, sulphides and silicates. The effect non-metallic inclusions have on the mechanical properties of steel depends on the size, shape and distribution of the inclusions. Treatments have been devised to minimize the number of inclusions and control their shape. In addition to melting practices such as vacuum arc remelting, desulphurization and deoxidation treatments involving the use of magnesium and calcium injection into the liquid steel may be used. Calcium and magnesium combine with oxygen and sulphur in the liquid metal to form stable, solid oxides and sulphides of both magnesium and calcium. The majority of these oxides and sulphides are removed during the steelmaking process⁷. Those that remain are small in diameter and retain a spherical shape during metal forming processes. Steelmaking practices such as melting in air and refining processes that do not employ calcium and magnesium injection result in an increased number of, relatively, large inclusions.

3. Examination of MZK left crankshaft

The crankshaft from MZK left engine, s/n V537912936 was re-examined at the ATSB laboratories in Canberra following the destructive examination conducted by McSwain Engineering, Inc. in the USA. Representatives from Whyalla Airlines, Textron Lycoming, and CASA were present as observers for the majority of the period of examination (they chose to depart at various times before the examination was concluded) and witnessed

⁶ ASM Handbook vol 1, p434.

⁷ Physical Metallurgy Principles, 3rd Edition, R.E. Reed-Hill, R. Abbaschian, PWS-Kent, Boston, 1992, p684-685.

examination of the parts as received, scanning electron microscopy and metallographic examination of a number of sections prepared that intersected the step feature on the forward and rear side of the fatigue fracture. The tasks undertaken comprised crankshaft material characterisation (chemistry, strength, inclusions, surface hardening), and a characterisation of the site of fatigue crack initiation. The tasks undertaken were in addition to the work undertaken during the initial analysis of the left engine failure and the work undertaken by McSwain Engineering, Inc.

The crankshaft was marked with letter codes that indicated that it had been manufactured from vacuum arc remelted steel. The prefix 'V' on the serial number indicates vacuum arc remelt.

Crankshaft material characterisation

Alloy chemistry

Additional samples of the crankshaft were removed from the No. 5 connecting rod journal for spectrographic analysis by two testing laboratories to provide a comparison with the results obtained in the initial analysis of the crankshaft failure by the ATSB and the results reported by McSwain Engineering, Inc. The results are presented in Table 1 with the compositional limits specified in AMS 6414H. The variation limits specified in AMS 2259C that are applicable to AMS 6414H are also presented. Check analyses are conducted to verify the composition of a heat or lot. The variation limits specified in AMS 2259C are the amounts individual determinations for a specified element may vary over or under the specified compositional limit.

TABLE 2:
Material compliance with specification, check analyses

<i>Element</i>	<i>Min</i>	<i>Max</i>	<i>AMS 2259C Check test Max variation*</i>	<i>Spectrometer Services 07/00</i>	<i>Spectrometer Services 25/03/03</i>	<i>Affinity Laboratories 27/03/03</i>	<i>Laboratory Testing Inc (McSwain) 31/01/03</i>
Carbon	0.38	0.43	0.02	0.47	0.44	0.47 [^]	0.434 [^]
Manganese	0.65	0.90	0.03	0.74	0.64	0.62	0.73
Silicon	0.15	0.35	0.02	0.32	0.31	0.31	0.31
Phosphorus	-	0.010	0.005	0.008	0.005	<0.01	0.008
Sulphur	-	0.010	0.005	0.006	0.005	<0.01	<0.001
Chromium	0.70	0.90	0.03	0.84	0.79	0.80	0.80
Nickel	1.65	2.00	0.05	1.92	1.8	1.8	1.84
Molybdenum	0.20	0.30	0.02	0.27	0.26	0.26	0.24
Copper	-	0.35	0.03	0.17	0.16	0.15	0.14
Vanadium□	0.07	0.11	0.01	0.08	0.08	0.08	0.062
Aluminium□	-	-	0.03	0.074	0.069	0.07	0.056
Titanium□	-	-	-	<0.01	<0.01	0.07	0.003

* AMS 2259C check analysis variation limits for low alloy steel product up to 100 square inches section area

[^] The Leco method was used for carbon analysis

□ Elements not specified in AMS 6414H (4340)

The specification AMS 6414H is a material specification that applies to the production of forging stock along with bars and tubes. Check analyses conducted in accordance with AMS 2259C are normally made by the purchaser of the forging stock to verify the composition of a heat or lot. The list of technical requirements in AMS 2259C states that 'In the analysis of finished parts, limits do not apply to elements whose percentage can be varied by fabricating techniques employed (for example carbon) unless the sample is taken in such a manner as to exclude such variations'.

With the exception of carbon, the four independent check analyses show that all other elements fall within their specified range and that there is little scatter in the results of each analysis. The maximum value for carbon with the check test variation applied is 0.45. The results of two analyses, McSwain and Spectrometer Services 27/03/03, show that the carbon content is within the check test range. The results of the other two analyses show that the upper limit of the check test range was exceeded by 0.02 per cent. On balance, considering the scatter in analysis results (0.036 per cent), the carbon content is at the upper limit of the check test range. This is not considered significant in relation to the crankshaft fracture.

Crankshaft core strength

The core strength of the crankshaft was assessed by Vickers hardness testing. Tests were conducted with a 30 kg load on metallographic specimens prepared from the No. 5 and No. 6 connecting rod journals. The results from three specimens were 379.3, 381.3, 379 HV30. The equivalent Rockwell hardness was determined to be 38.8 from the table of equivalent hardness for steel (ASM Handbook vol 8, p110). It has been reported⁸ that the specified hardness range for the crankshaft core was 32–37 HRC on some manufacturing drawings and 32–39 HRC on other drawings.

A possible explanation for the differences in the upper limit of the core hardness may reside in an understanding of the nitriding process used in the manufacture of crankshafts. Nitriding is conducted after the crankshaft has been tempered (the hardness of tempered steels is a function of the tempering temperature and the time at temperature). In order to prevent further tempering during the nitriding process the minimum tempering temperature is usually 30°C (50°F) higher than the maximum temperature used in nitriding. The core hardness of nitrided steel cannot exceed the hardness that is developed at tempering temperatures equivalent to the nitriding temperature.

For 4340 steel the nitrided case hardness is dependent on the core hardness. Consequently, in order to achieve the maximum case hardness the core is tempered at the minimum allowable temperature⁹.

Nitriding may be achieved by either a single stage process or a double stage (Floer) process. The temperature used in the single stage process is in the range 495°C to 525°C. The temperature range of the first stage of the double stage process is 495°C to 525°C and the temperature of the second stage may be increased to 550°C to 565°C. The tempering temperature used to achieve a hardness of 37HRC is approximately 570°C. If the process to manufacture crankshafts had been changed to incorporate a double stage nitriding process the specification of the core hardness upper limit would have to be reduced to 37HRC.

⁸ FAA correspondence, Terry Khaled to Dave Swartz.

⁹ Metals Handbook Ninth Edition vol 4 Heat Treating, American Society for Metals, pp 191-193.

Mechanical property data as a function of tempering temperatures for 4340 steel¹⁰ shows that a hardness of 39HRC is achieved by tempering at 540°C. If this relationship holds for the crankshaft steel then it is clear that the temperature used in single stage nitriding would not result in core softening. However, if the double stage nitriding process, with the higher second stage temperature (eg 565°C), was used then the core would be softened to approximately 37HRC.

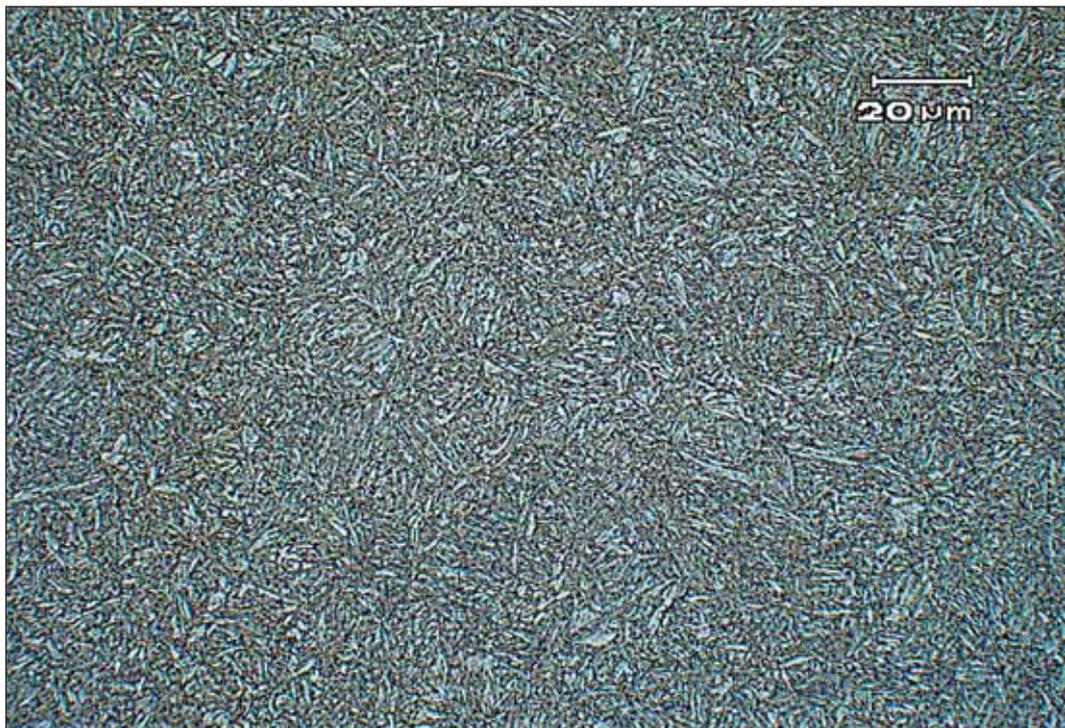
The hardness testing conducted during the present examination indicates that the core hardness is consistent with the upper limit that could be achieved by single stage nitriding. The difference in ultimate tensile strength of steel corresponding with a hardness difference of 37HRC to 39HRC is approximately equivalent to 5ksi (34.5Mpa). This small difference is not considered significant in the resistance of the crankshaft to fatigue. The more significant factor is the surface hardening and compressive residual stress state created by nitriding. Surface hardening is discussed on page 17.

Crankshaft core microstructure

The microstructure of the core of the crankshaft is typical of fine grained low alloy steel fully transformed to tempered martensite, see fig. 1.

FIGURE 1:

Reflected light photomicrograph showing the typical features of the core of crankshaft s/n V537912936, etched lightly with 1 per cent nital then immersed in a sodium metabisulphate solution



Crankshaft core impact loading properties

Three standard Charpy V notch specimens were removed from the crankarm between the No. 5 and No. 6 connecting rod journals. The results of impact testing at the test temperature of 24°C were absorbed energies of 82, 79 and 73 Joules¹¹ (range equivalent to 54–60 ft lbs). These results are typical for vacuum arc remelted 4340 steel and indicate that the steel has high toughness.

¹⁰ ASM Handbook Tenth edition vol 20 Materials Selection and Design, ASM International, p123.

¹¹ AMEC Laboratory Report No. 3A70/M1, 25/03/03.

TABLE 3:
Longitudinal mechanical properties of 4340 bar stock, vacuum arc remelted¹²

<i>Tensile Strength</i>	<i>Yield Strength</i>	<i>Elongation in Area</i>	<i>Reduction Notch Energy</i>	<i>Charpy V</i>	<i>Hardness</i>
1210 MPa	1120 MPa	16.4 per cent	61.2 per cent	65 J @ -12°C 48 ft lbs	37 HRC

Normalised at 900°C, oil quenched from 845°C and tempered 2 h at 541°C

Charpy V notch, room temperature (the precise temperature was not specified), impact tests performed during an analysis of other crankshaft failures by the manufacturer recorded results 60-65 ft-lb, 68-75 ft-lb, 63.5-64.5 ft-lb for a number of heats produced by several steel producers.¹³

The fracture surfaces of the impact test were recovered and examined in detail, from low magnification to high magnification, see figs. 2, 3 and 4. In addition, a small section was removed from the core material in the No. 6 connecting rod journal and was fractured in the laboratory by hammer blows (nick break test). In each case the fractures exhibited the features of ductile fracture.

Ductile fracture proceeds through a mechanism of microvoid coalescence. There are four main steps involved, nucleation of holes, growth and coalescence of holes to form a crack, expansion of the crack by the nucleation of holes at the crack tip, and final separation. The most common source of holes in steels is decohesion at inclusion and second phase particle (typically carbide) interfaces. The process of microvoid coalescence gives rise to a fracture surface appearance commonly described as dimpled fracture surface. The size of the dimple features is a function of the size and morphology of the non-metallic inclusions. Differences in inclusion size will result in a difference in fracture surface appearance.

A consistently reported feature of ductile fracture surfaces in quenched and tempered 4340 steel is the presence of microvoids of differing sizes – a duplex void size distribution. The larger voids are associated with non-metallic inclusions while the smaller voids have been found to be associated with fracture of coarse carbide particles precipitated at martensite lath boundaries. Fracture has been found to proceed with void growth from non-metallic inclusions and the linking of the regions of larger void growth by regions of very small voids. Features described as void sheets have been identified in circumstances where carbides are concentrated on a microstructural feature oriented in the plane of maximum strain.^{14,15}

¹² FAA correspondence.

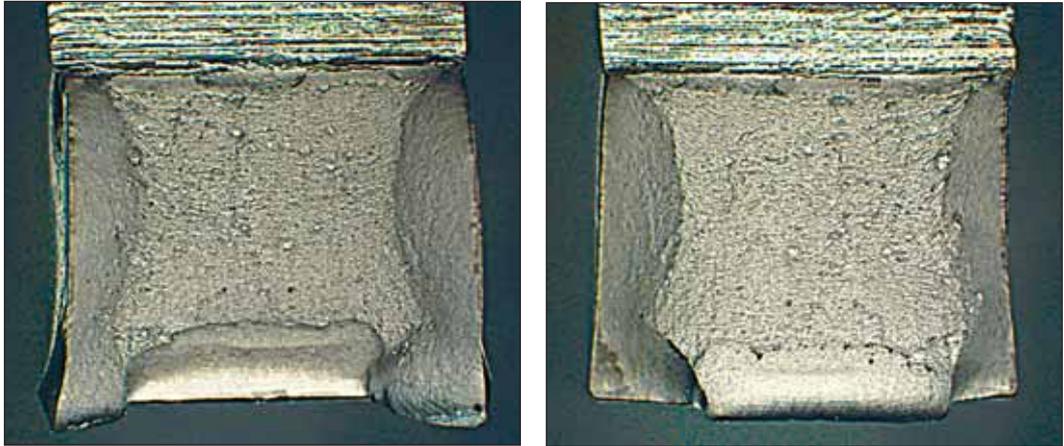
¹³ FAA correspondence.

¹⁴ ASM Handbook, 10th edition vol 19, p50.

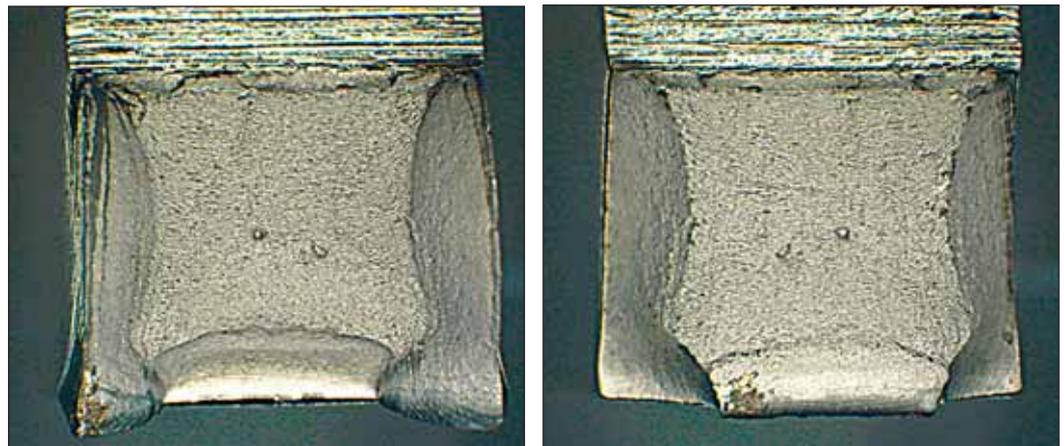
¹⁵ Application of Fracture Mechanics for selection of Metallic structural Materials, J E Campbell, W W Gerberich, J H Underwood, American Society For Metals, 1982, p61.

FIGURE 2.
Photomicrographs of both fracture surface of the three Charpy V notch impact test specimens machined from crankshaft s/n V537912936

Specimen PB



Specimen PC



Specimen PMI-A

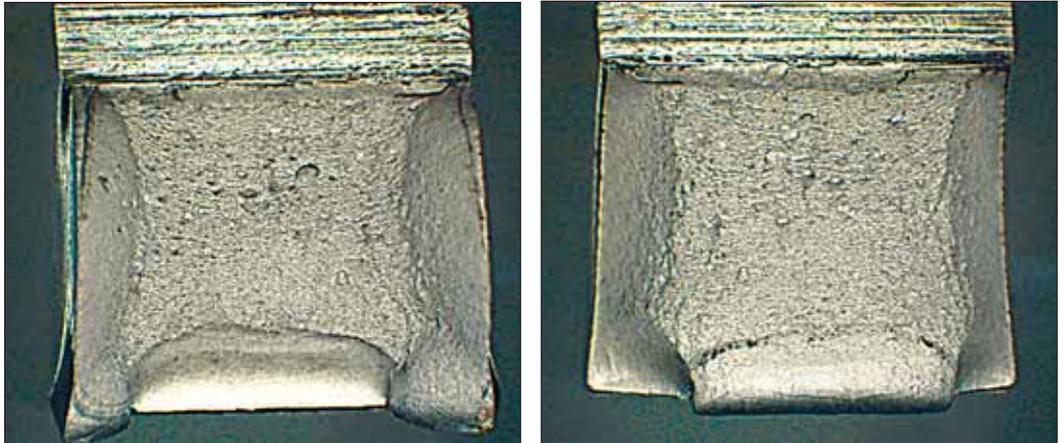


FIGURE 3:
Scanning electron micrograph showing the typical features of the fracture surface of Charpy V notch specimen PB (plane strain zone). The inclusion in the centre of the micrograph was identified as a complex sulphide. These features are typical of other ductile fractures created in crankshaft s/n V537912936

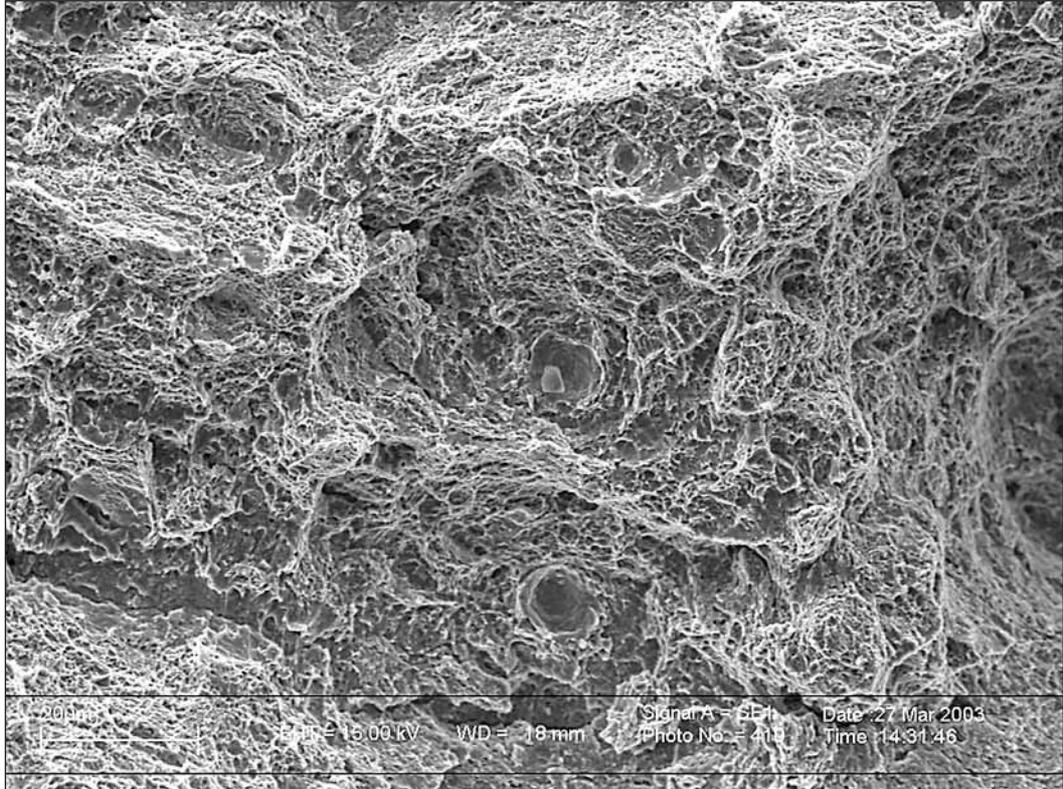


FIGURE 4:
Scanning electron micrograph showing another area of the fracture surface of specimen PB at higher magnification. Several small 'pullout' features were noted in the plane strain zone of the Charpy V notch fracture surfaces. Several of these features were examined more closely in an attempt to determine their nature

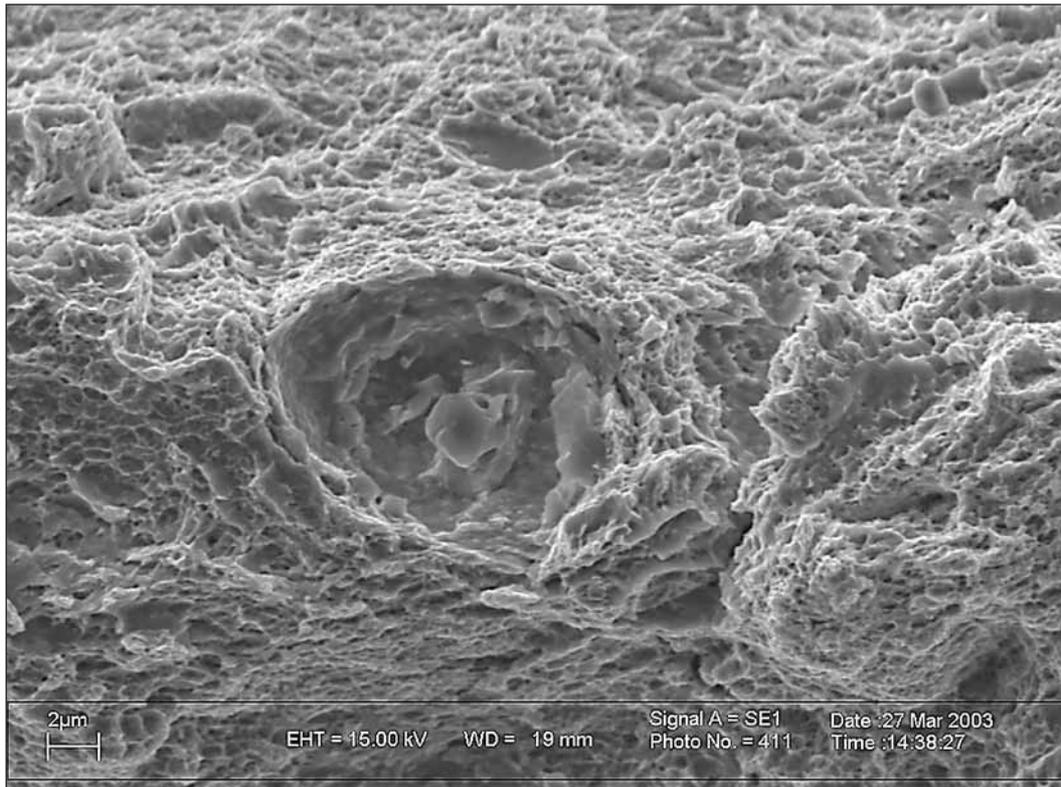


FIGURE 5:
Scanning electron micrograph, low magnification, showing a 'pullout' region in the centre of the micrograph

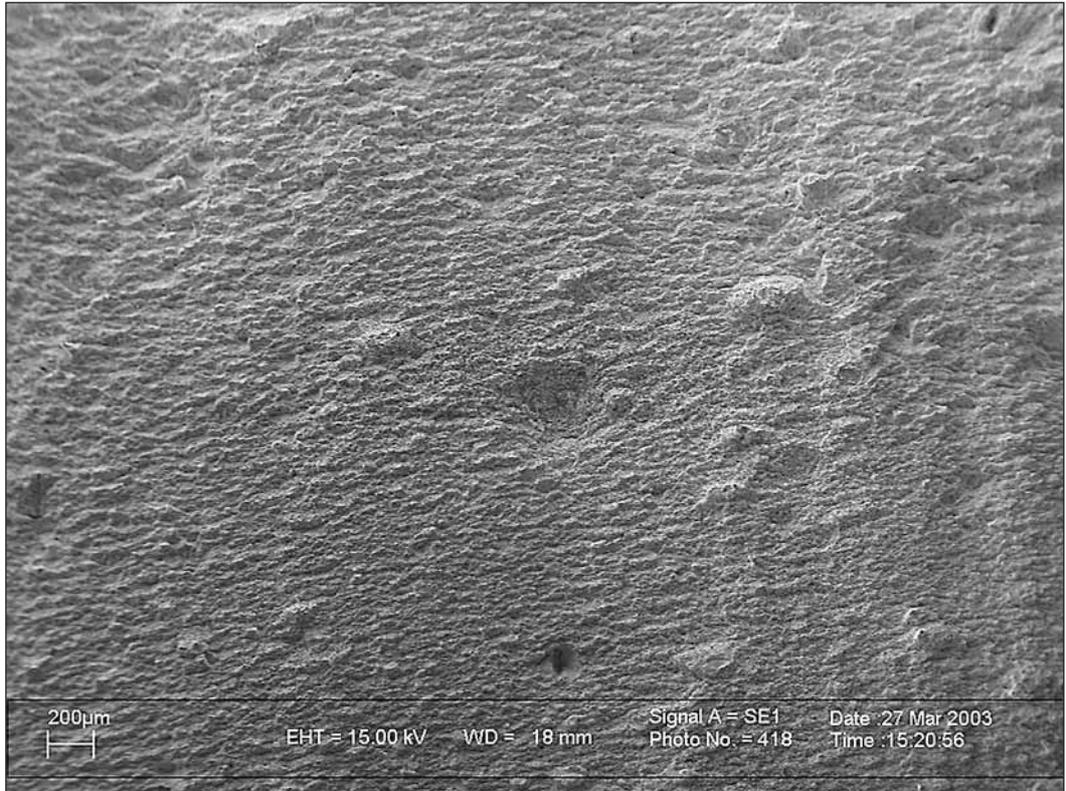


FIGURE 6:
Scanning electron micrograph showing the pullout feature

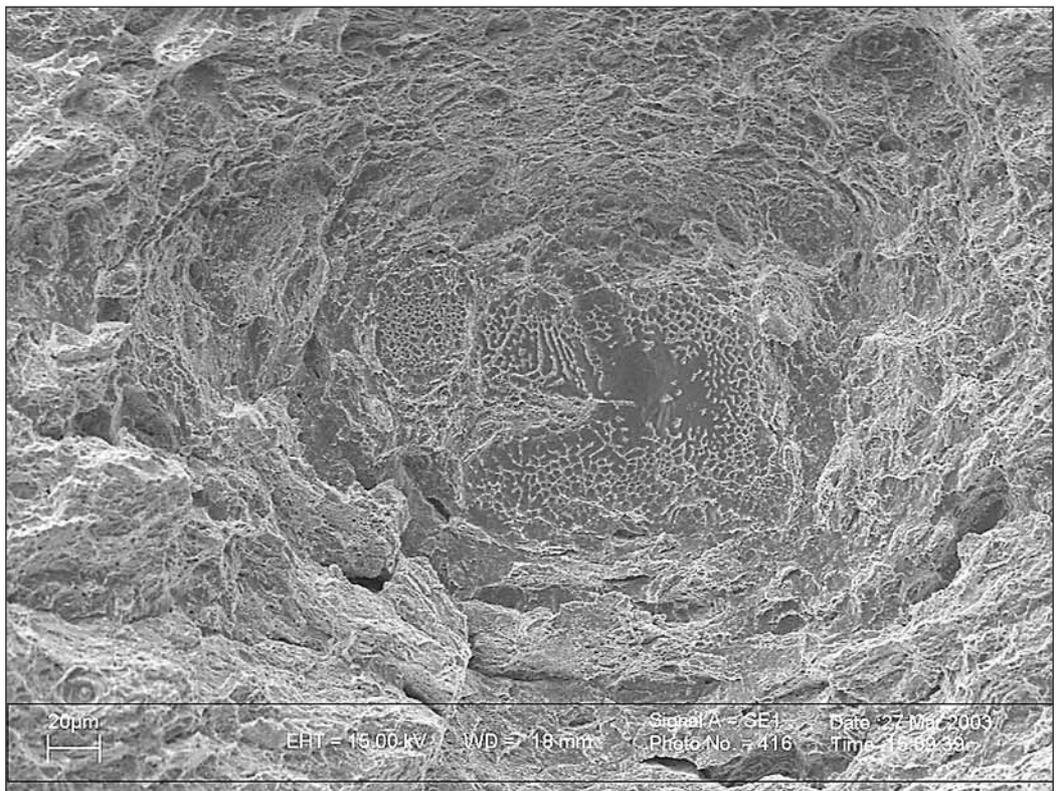


FIGURE 7:
Scanning electron micrograph showing the features at the bottom of the 'pullout' in detail

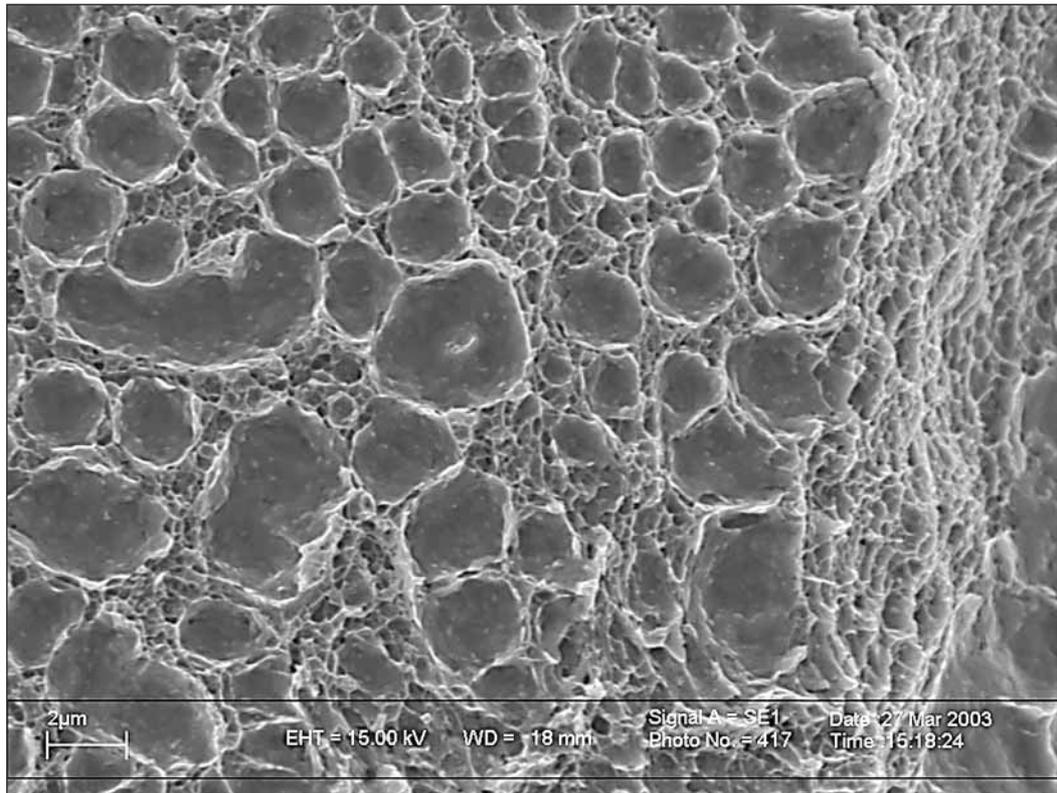
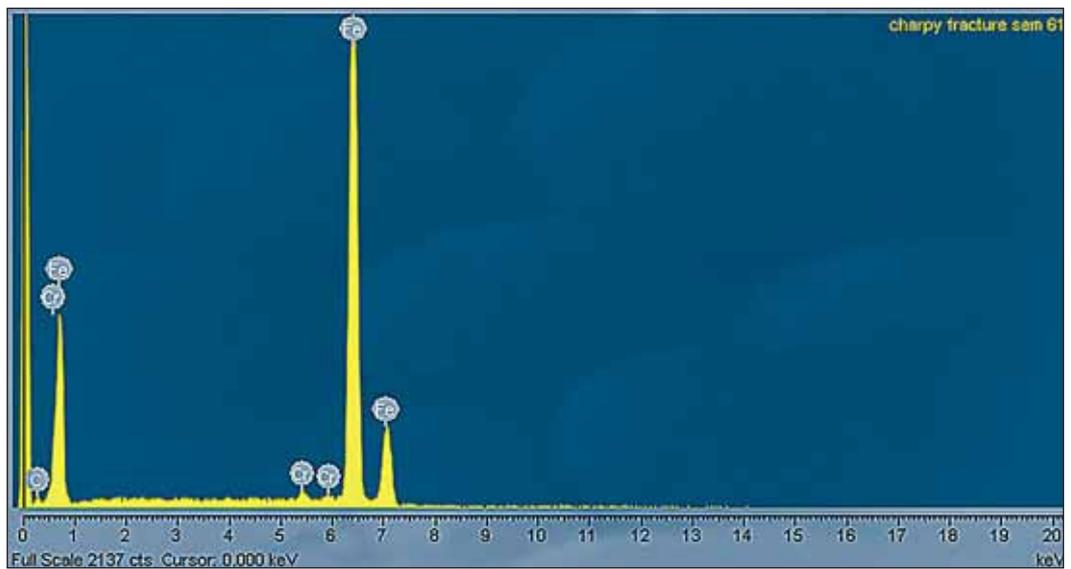


FIGURE 8:
Energy dispersive Xray spectrum obtained from an area scan of the 'pullout' feature



The relevance of fracture surface features

Features such as the ‘pullout’ feature present in the plane strain region of the Charpy V notch impact test specimen fractures are a manifestation of the fracture process. The fracture process, in turn, is a function of the state of stress and strain in the specimen created by the loading conditions and specimen geometry, and the microstructure of the material. The state of stress and strain varies throughout the section of a Charpy V notch specimen and is very different from the state of stress and strain in a crankshaft the journal fillet during engine operation.

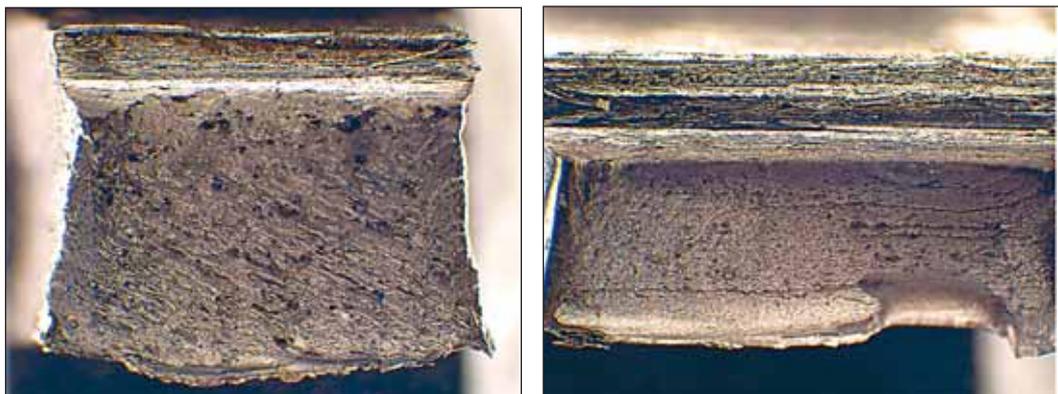
Assessments of the normality, or otherwise, of fracture surface features based on comparisons between steels containing different non-metallic inclusion types and distributions are not meaningful. For the case of ductile fracture, the process of microvoid nucleation, growth and coalescence is dominated by the nature of non-metallic inclusions in steel.

‘Pullout’ features are likely to be related to the process of void nucleation and growth in steels with very low non-metallic inclusion contents. In steels of this type it is likely that microvoid nucleation at carbides is more common and that microvoid sheet features may be created under particular conditions of strain.

In other work conducted on crankshafts¹⁶ a feature described as ‘honeycomb’ has been reported during the examination of Charpy V notch test specimen fractures from vacuum arc remelted steels. This feature has not been reported to be present in specimens from steels with a higher non-metallic inclusion content (air melted steel). It was reported that fatigue testing of the steel established that there was no significant difference in the fatigue endurance strength of the steels examined.

A comparison of ductile fracture surface features between air melted and vacuum arc remelted crankshaft steels

FIGURE 9:
Nick break fracture surfaces, air melted crankshaft core material (left), vacuum arc remelted crankshaft core material (right)



¹⁶ T Khaled, FAA, correspondence with the author.

FIGURE 10:
Nick break fracture surface, air melted crankshaft (core material). The string of inclusions in the centre of the micrograph are manganese sulphides

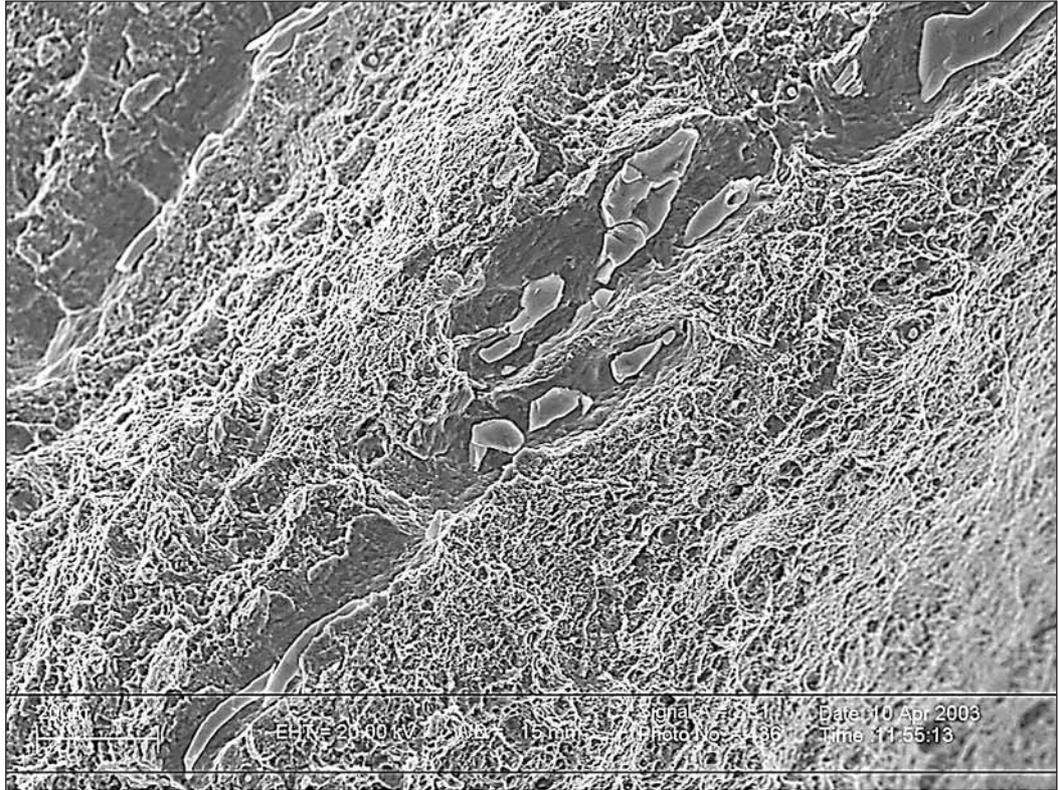


FIGURE 11:
Nick break fracture surface, vacuum remelted crankshaft (core material). The small spherical inclusion to the right of centre is a complex calcium, aluminium, magnesium oxy-sulphide

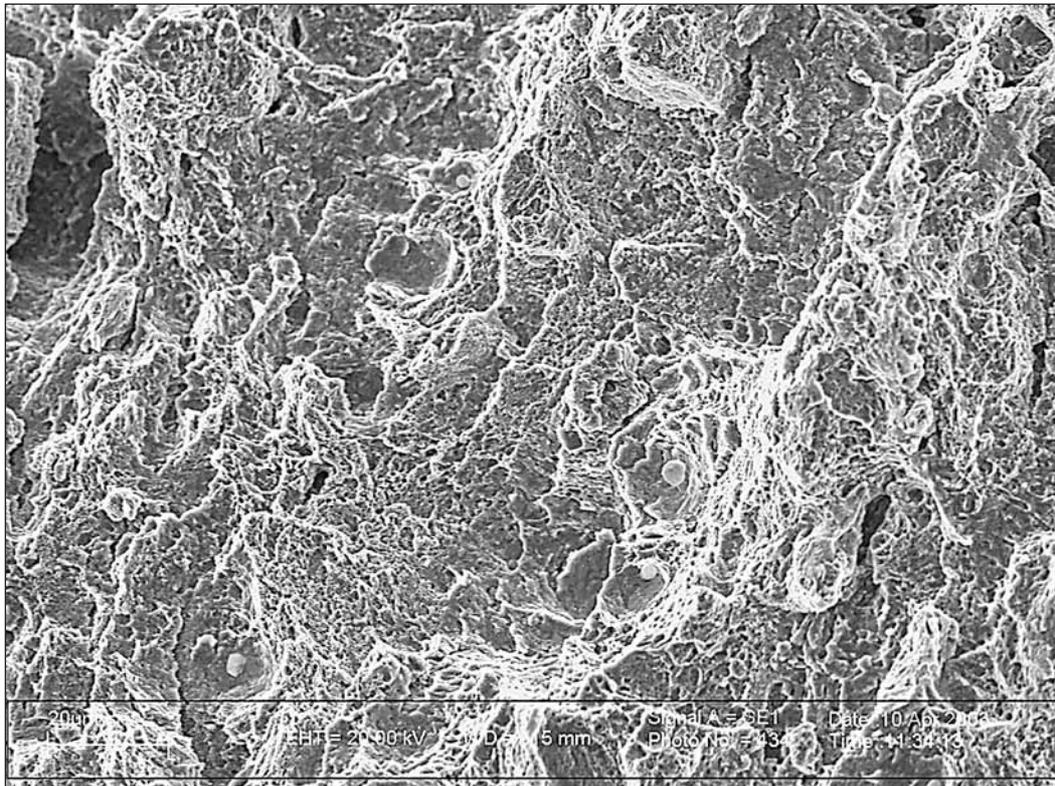


FIGURE 12:
Air melted crankshaft at higher magnification

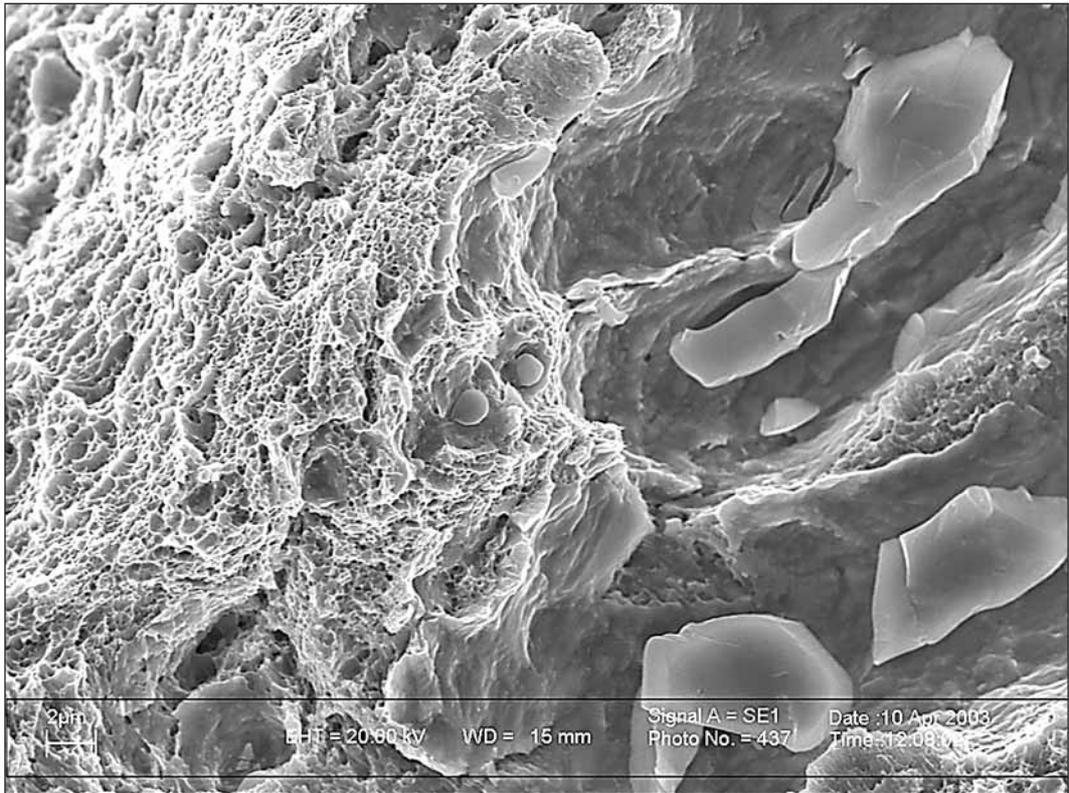
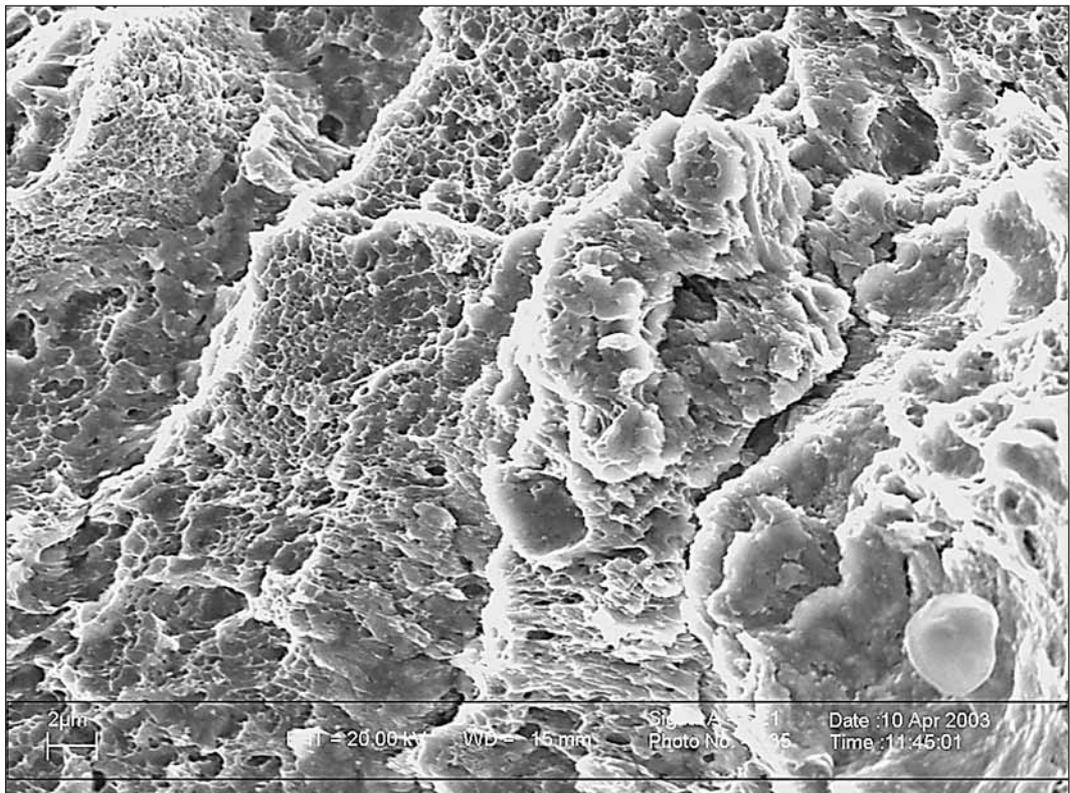


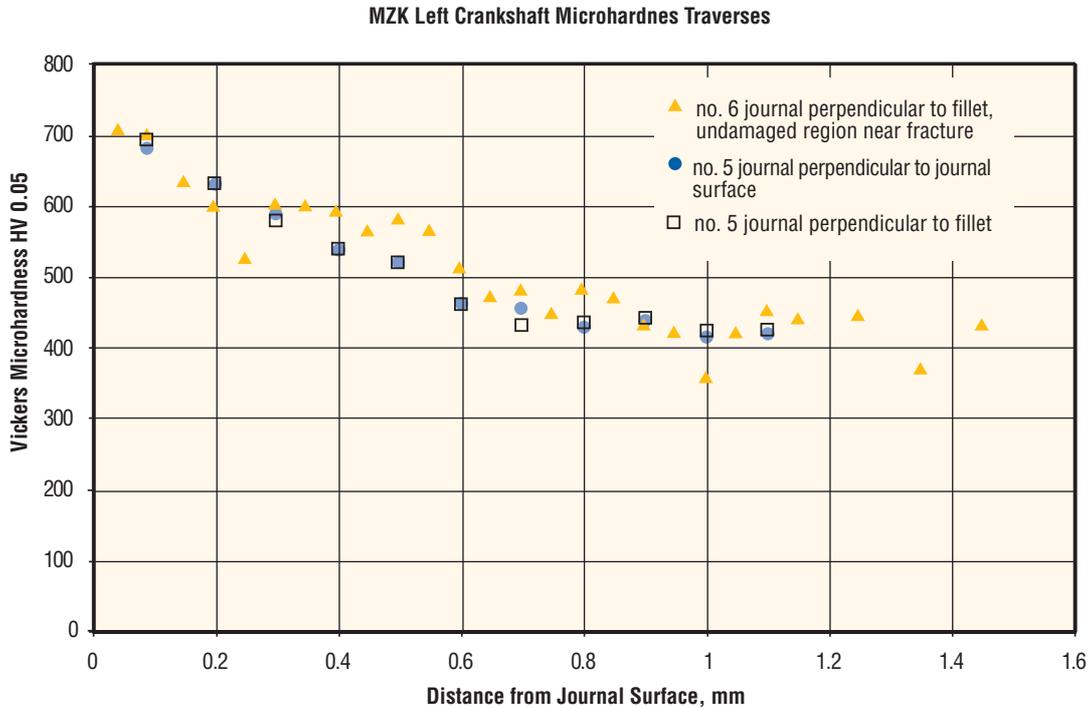
FIGURE 13:
Vacuum remelted crankshaft at higher magnification



Crankshaft surface hardening

Vickers microhardness traverses were conducted perpendicular from the journal surface to the crankshaft core. Testing was performed using a 50 gram load on metallographically polished specimens prepared from sections cut from the No. 5 and No. 6 connecting rod journals. The results of these tests are shown in fig. 14.

FIGURE 14:
Vickers microhardness traverses showing the extent of the influence of nitriding on journal hardness, crankshaft s/n V537912936.



The results show that the effect of nitriding extended to a depth of 0.8 mm. There is a gradual transition in hardness at the transition from the hardened case to the crankshaft core. Note: the microhardness results obtained for loads below 100 grams force are a function of load and cannot be compared with tests performed at loads greater than 1kgf¹⁷. Small loads were used to enable a closer spacing of the hardness test positions with respect to the journal surface and each other. The spacing of hardness indentations to avoid the influence of free surfaces and the effects of deformation created by adjacent indentations is an important factor in hardness testing.

While microhardness traverses are used to establish the total case depth, quality control tests may utilise other techniques to establish effective case depth. The specified case depth of 0.018–0.026 inches (0.457–0.660 mm) is based on a macroetching technique.

The hardness of the nitrided surface was determined to be 678 HV30, equivalent to Rockwell superficial hardness 76.7 HRC30N. This surface hardness exceeds the specified minimum surface hardness of 64 HRC30N.

¹⁷ ASM Handbook, vol 8, Mechanical Testing p94–96.

FIGURE 15:

Photomicrograph showing the nitrated case as delineated by a nital – sodium metabisulphate etch. The change in colour contrast occurs at a distance of approximately 0.4–0.5 mm (0.016–0.02 inches). The specified case depth based on macroetching is 0.018–0.026 inches

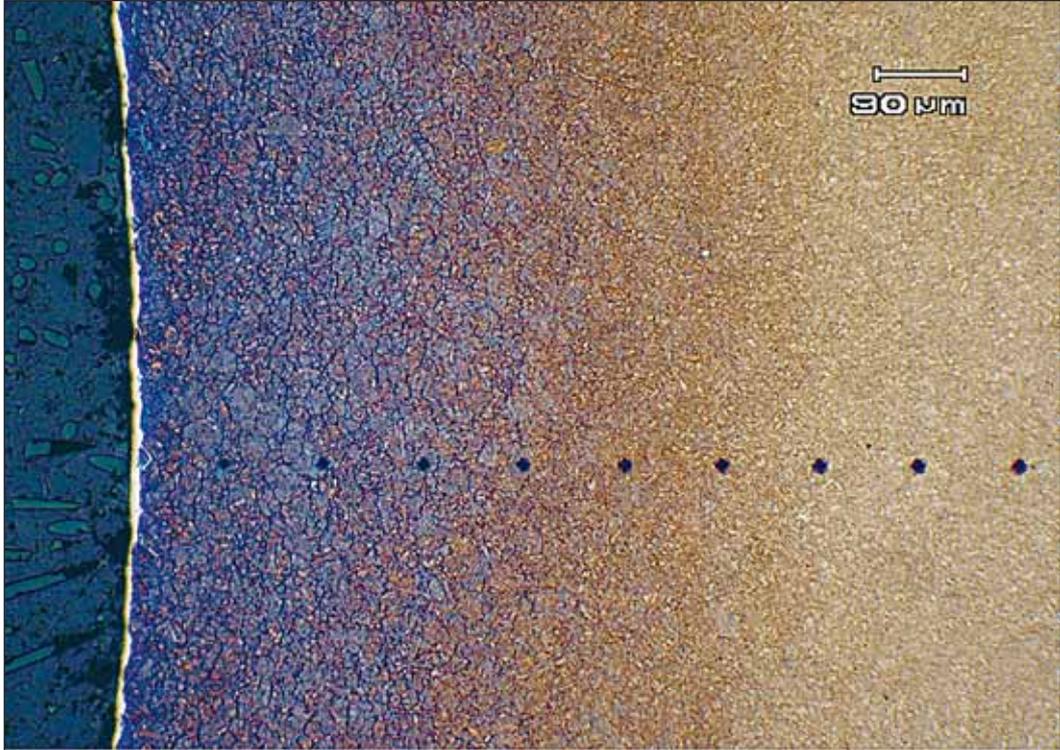


FIGURE 16:

Photomicrograph showing the case at the journal surface. The thin white etching zone at the surface is a region of iron nitride. The extent of the iron nitride zone is within the normal bounds for a crankshaft journal (metabisulphate etch)

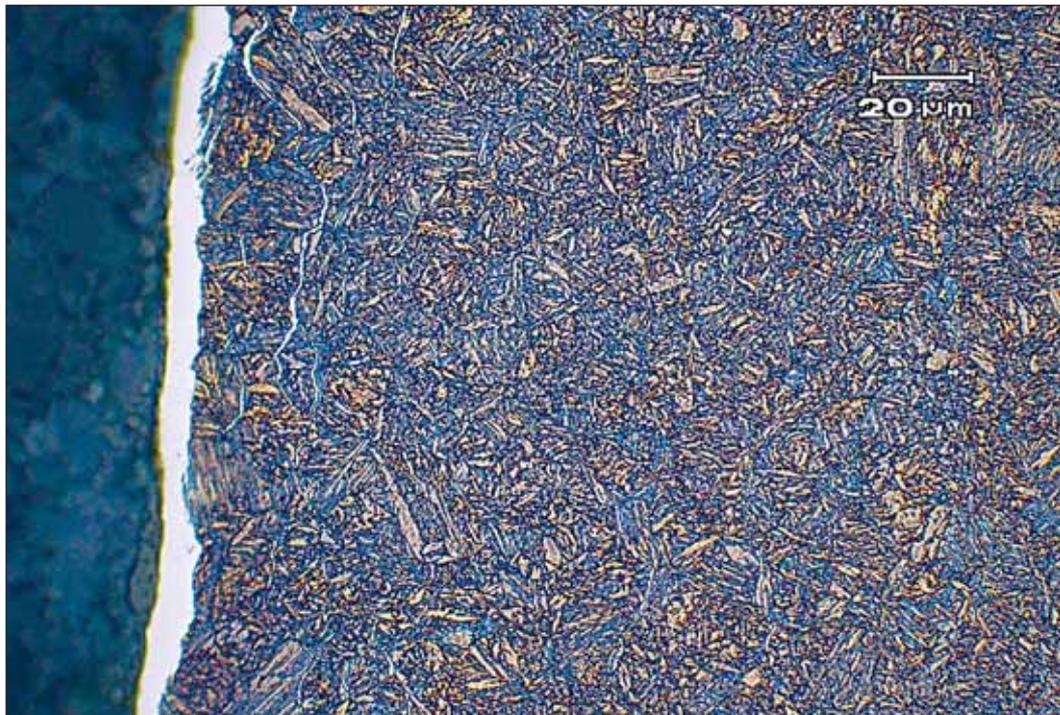


FIGURE 17:
Photomicrograph showing the microstructure of the case (metabisulphate etch)

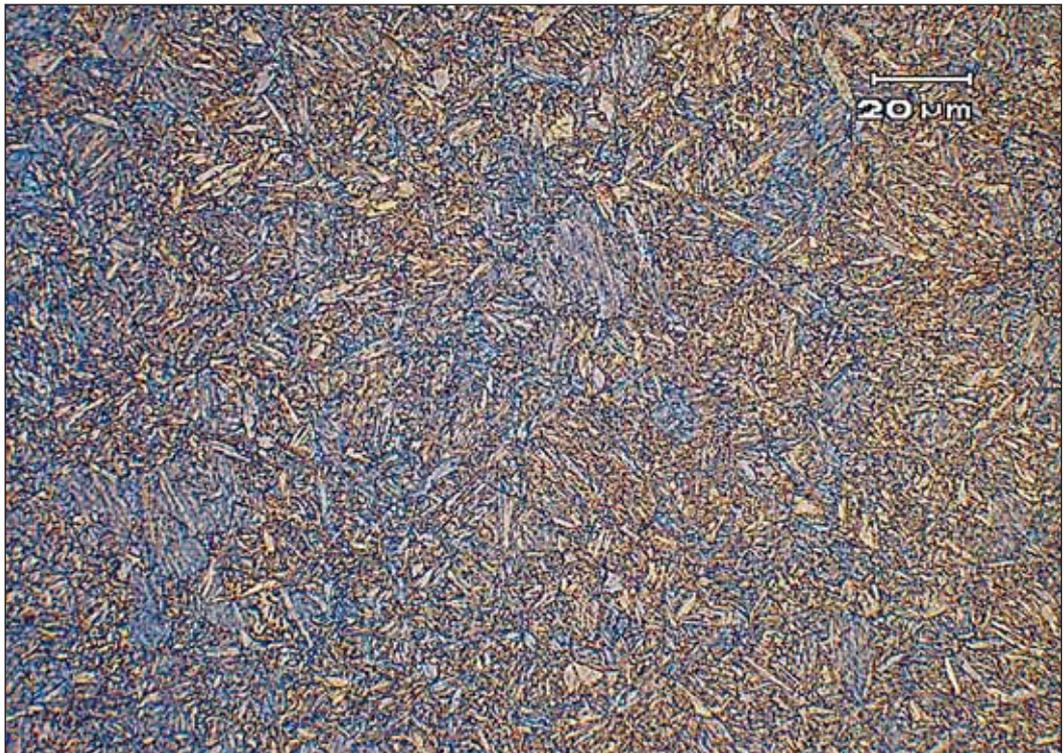
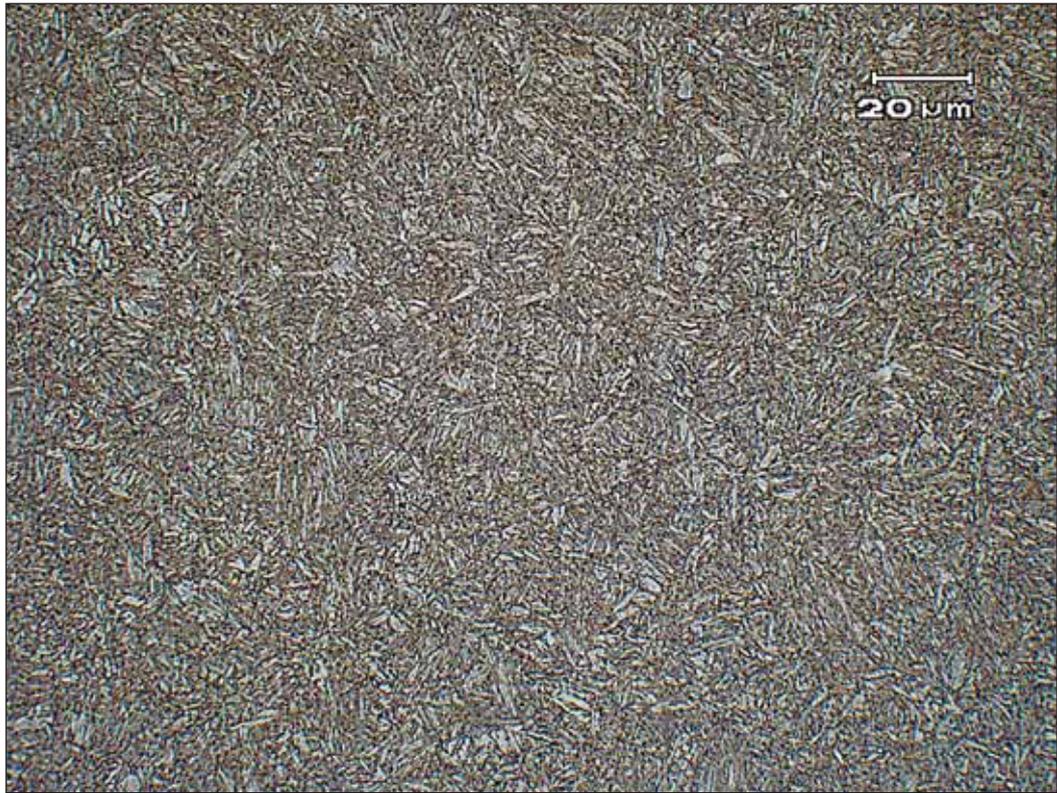


FIGURE 18:
Photomicrograph showing the microstructure at the case/core interface (metabisulphate etch)



FIGURE 19:
Photomicrograph showing the microstructure of the core near the case core interface (metabisulphate etch).



Inclusion content

The inclusion content of crankshaft s/n V537912936 was assessed through the examination of metallographic sections prepared from the No. 5 main bearing journal, the No. 6 connecting rod journal and the No. 5 connecting rod journal. Additional assessment was made through the examination of fracture surfaces created by the fatigue crack in the No. 6 connecting rod journal, a nick break specimen removed from the No. 6 connecting rod journal, a sample fractured in the McSwain laboratory and the fractures created during Charpy V notch impact testing.

The nature of the non-metallic inclusions present in crankshaft V537912936 can be characterised as a distribution of complex mixtures of silicates and sulphides of calcium aluminium and magnesium, well dispersed and small in size (maximum size observed was approximately 13 μm in diameter), and a smaller number of small, blocky, titanium, zirconium, vanadium nitrides. A series of scanning electron micrographs with accompanying energy dispersive Xray spectra obtained from the inclusions is presented in figs. 21 to 34.

FIGURE 20:

Scanning electron micrograph showing inclusions from a small area of a metallographically prepared sample from the No. 5 connecting rod journal

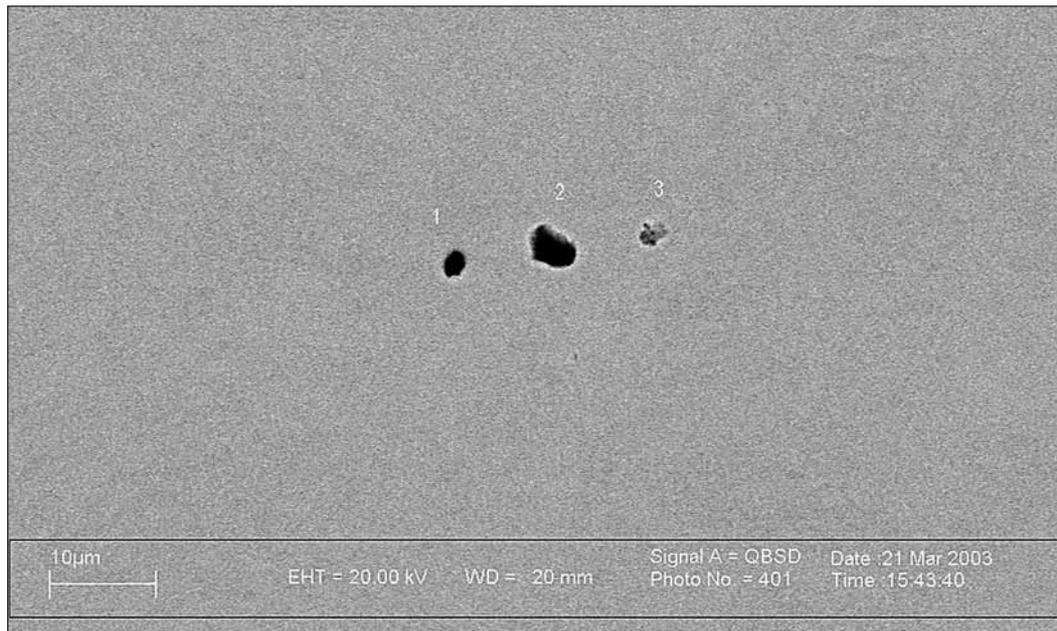


FIGURE 21:

Xray spectrum for inclusion marked 1 in fig. 20. The inclusion is a complex calcium, magnesium, silicate-sulphide

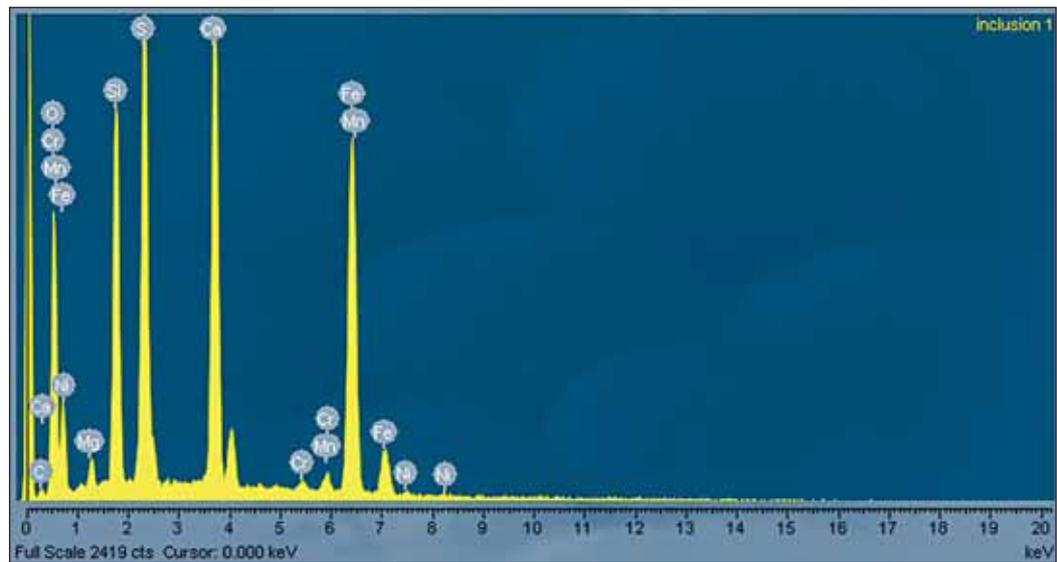


FIGURE 22:
Xray spectrum for inclusion marked 2 in fig. 20. The inclusion is an aluminium, magnesium oxide, silicate

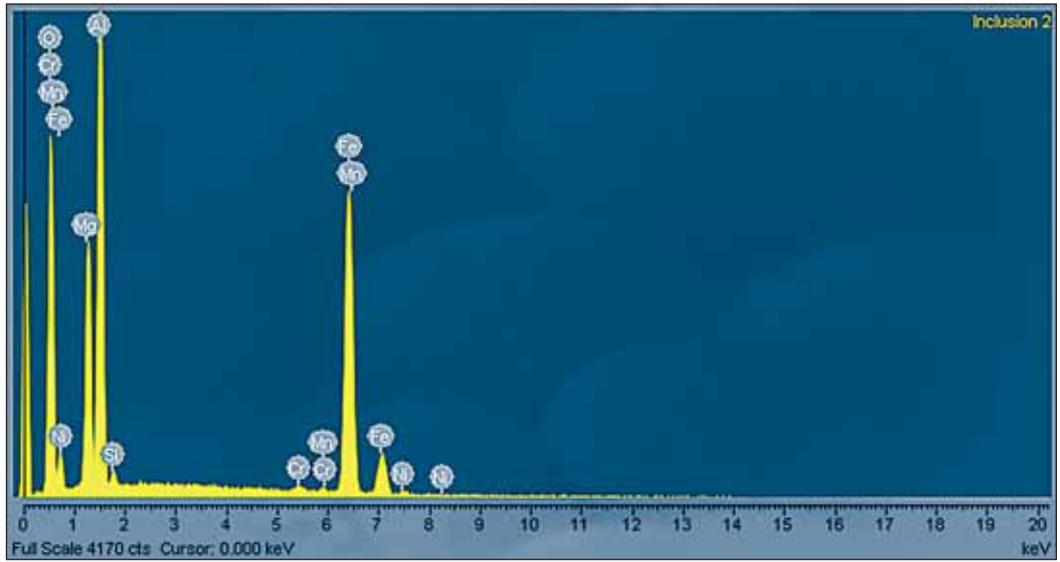


FIGURE 23:
Xray spectrum for the inclusion marked 3 in fig. 20. The inclusion is predominantly calcium sulphide

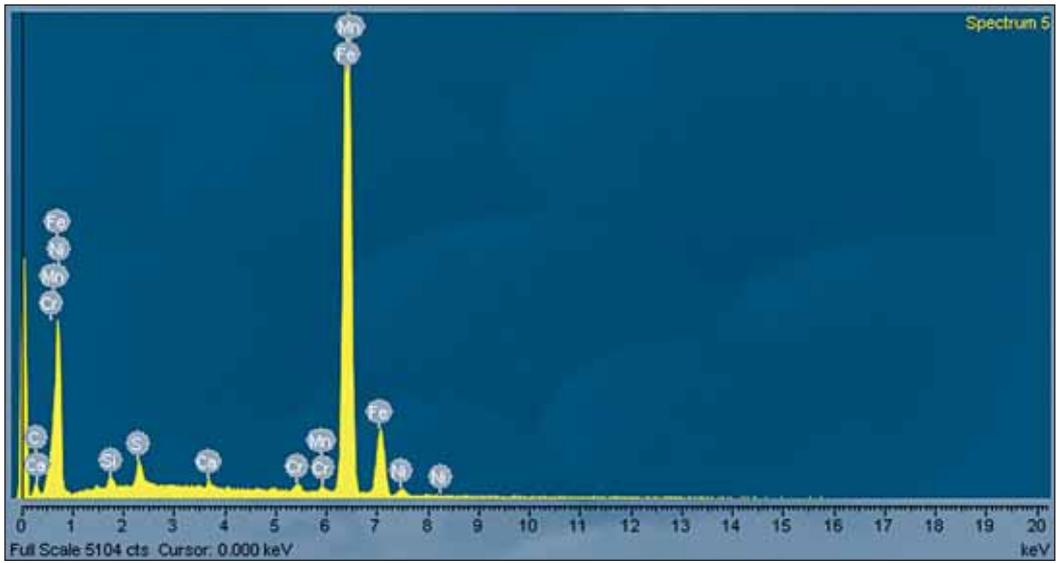


FIGURE 24:

The largest inclusion observed (maximum dimension approximately 13µm) during the current examination of a number of metallographically prepared sections from crankshaft s/n V537912936

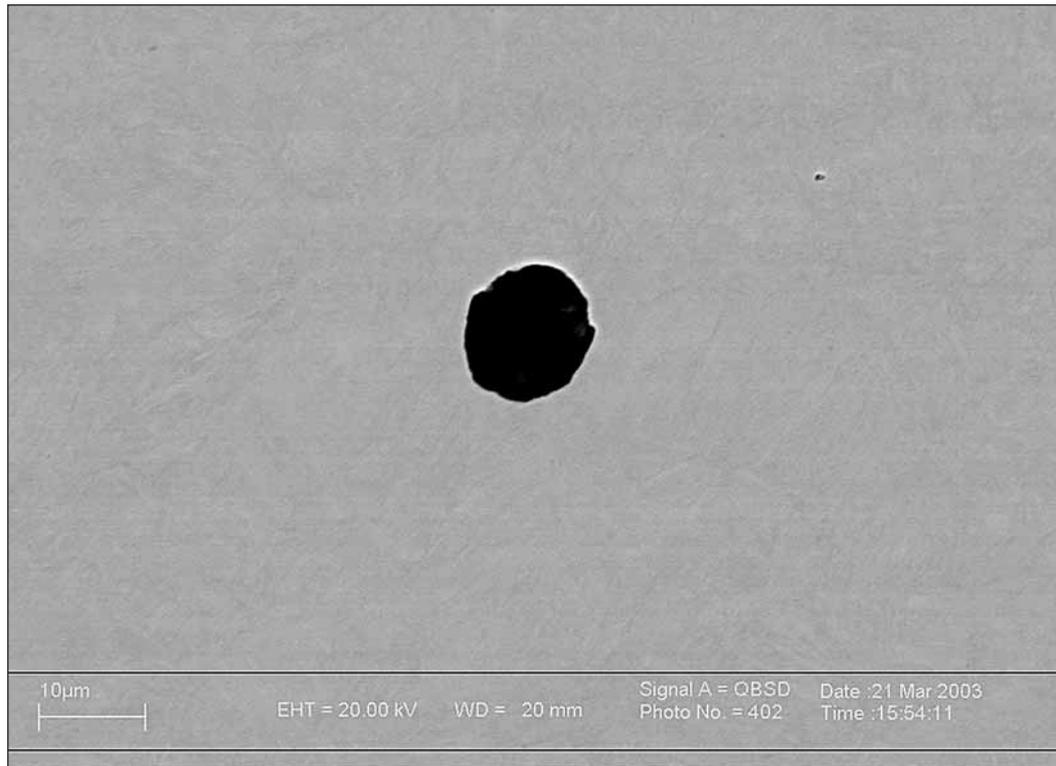


FIGURE 25:

Xray spectrum from the inclusion shown in fig. 24. The inclusion is a calcium, magnesium silicate-sulphide

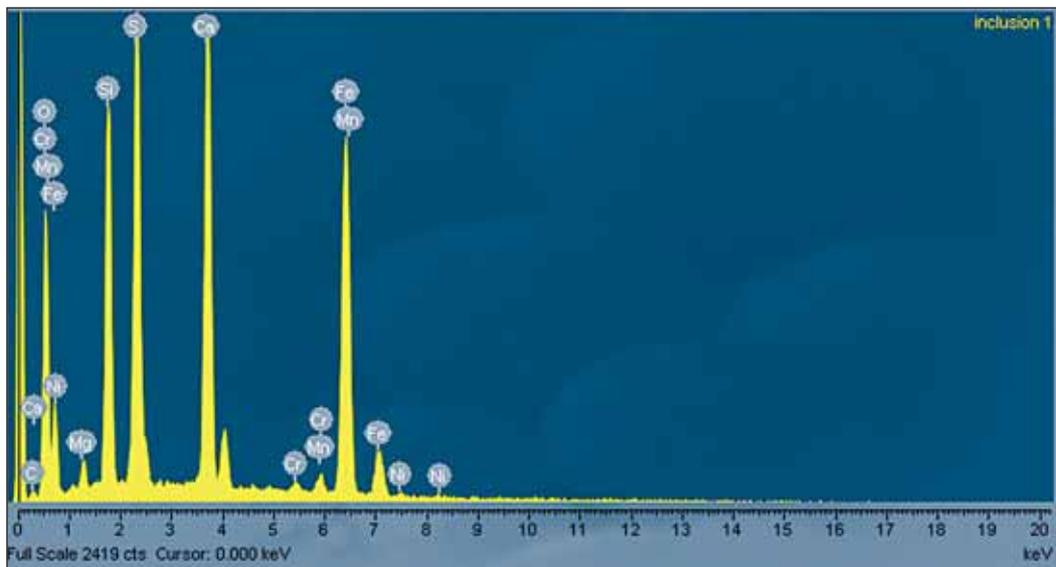


FIGURE 26:
Scanning electron micrograph showing an inclusion from a small area of a metallographically prepared sample from the No. 5 connecting rod journal



FIGURE 27:
Xray spectrum for the rounded head of the inclusion shown in fig. 26. This area is richer in calcium and sulphur, see for comparison the spectrum from the tail (fig. 28).

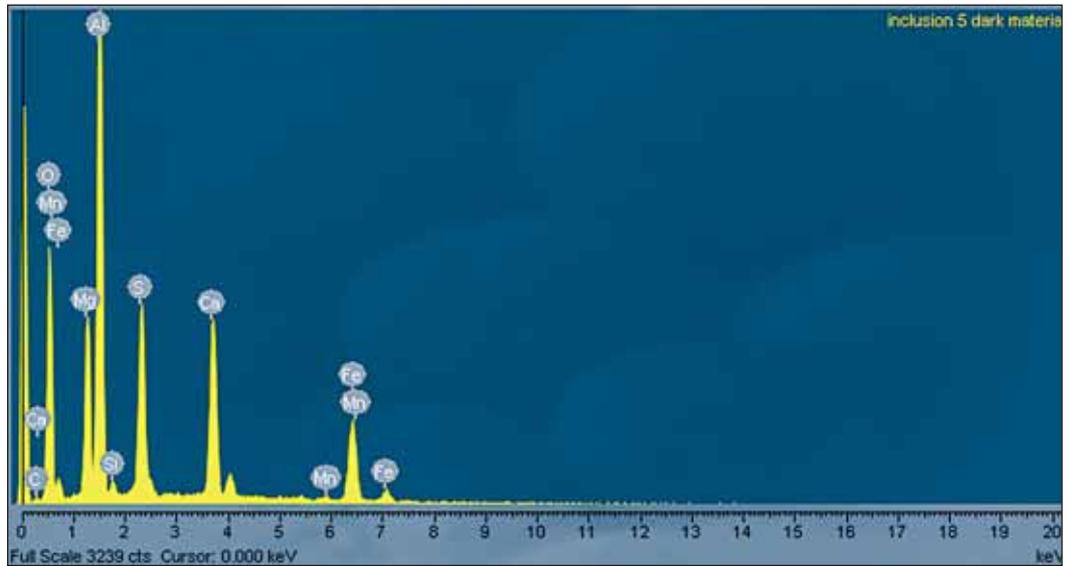


FIGURE 28:
Xray spectrum from the tail of the inclusion shown in fig. 26

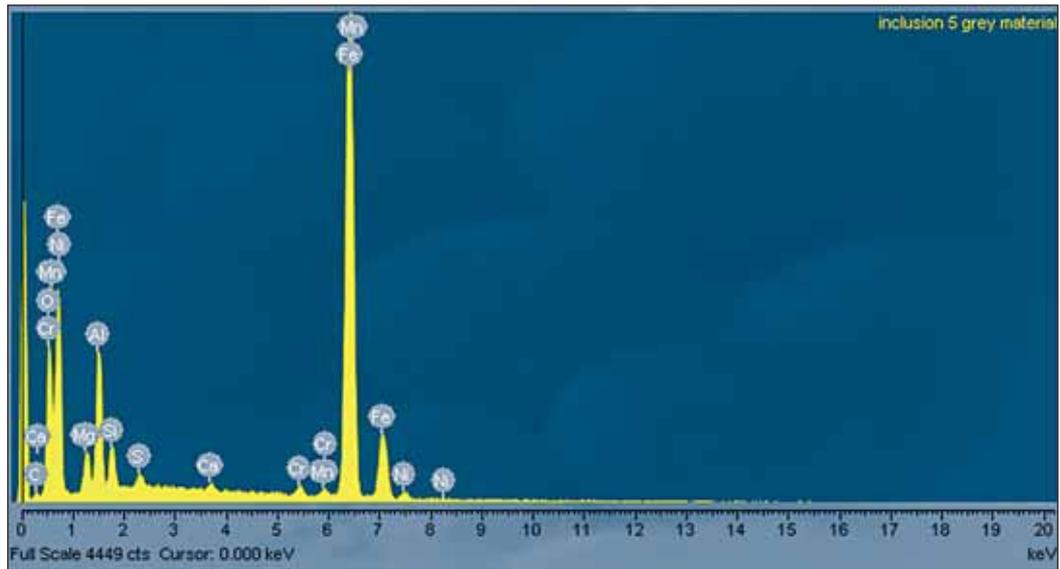


FIGURE 29:
Scanning electron micrograph showing an inclusion from a small area of a metallographically prepared sample from the No. 5 connecting rod journal

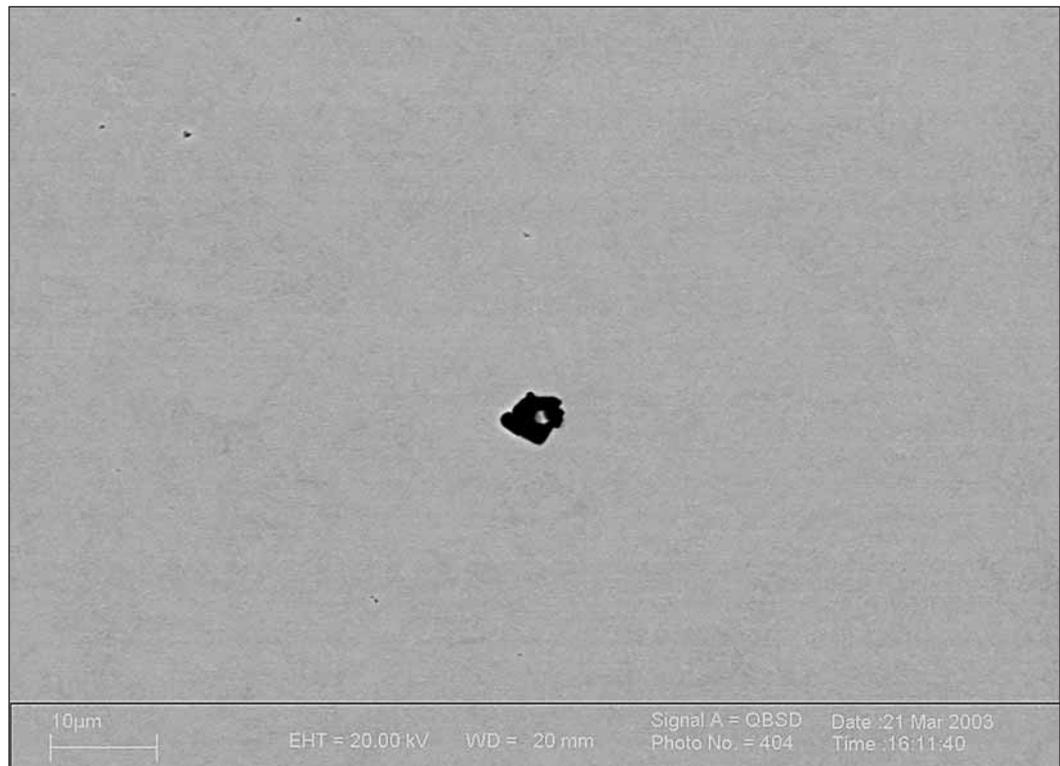


FIGURE 30:
Xray spectrum from the darker material of the inclusion shown in fig. 29. The material is predominantly magnesium oxide

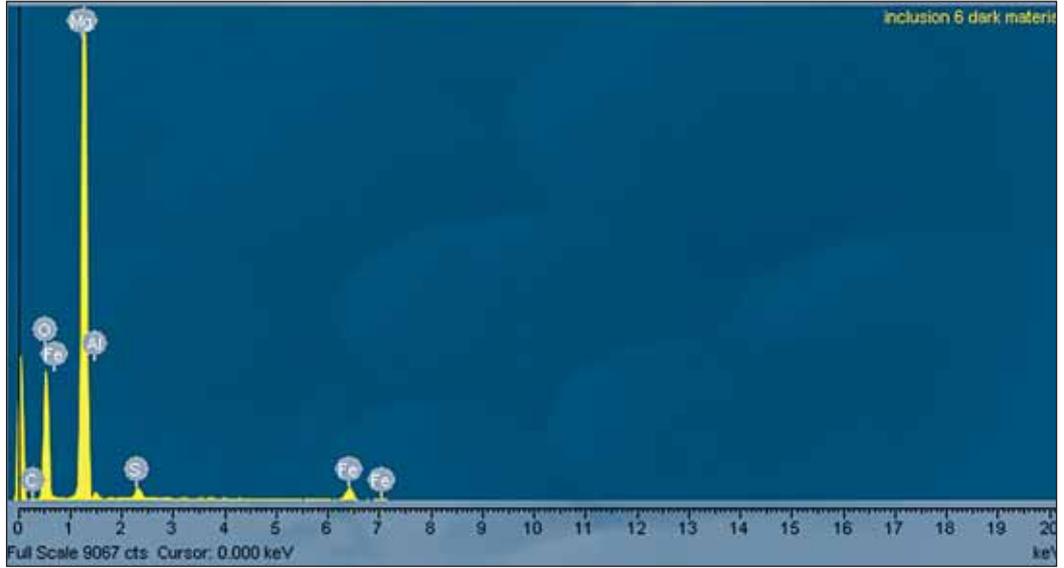


FIGURE 31:
Xray spectrum from the light coloured material at the centre of the inclusion shown in fig. 29

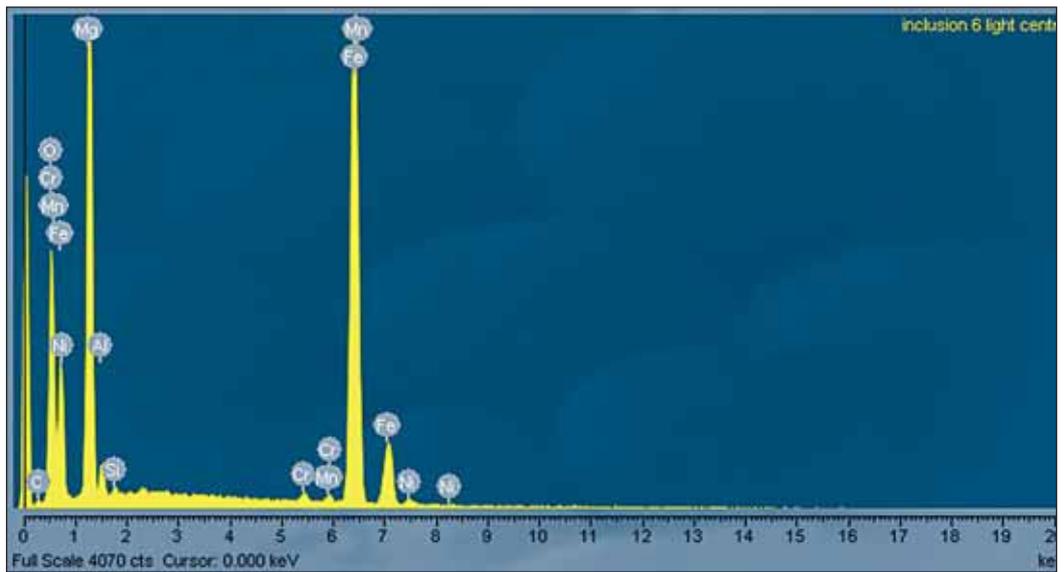


FIGURE 32:

Scanning electron micrograph showing an inclusion from a small area of a metallographically prepared sample from the No. 5 connecting rod journal

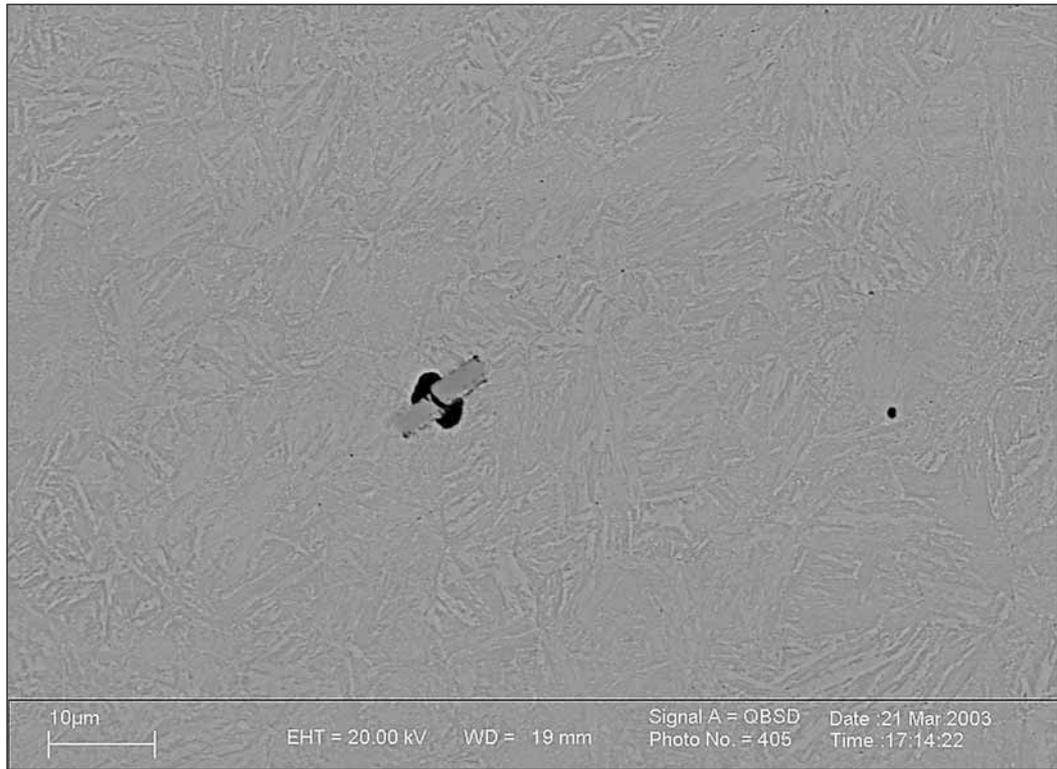


FIGURE 33:

Xray spectrum from the dark material of the inclusion shown in fig. 32. The material is a silicate in nature

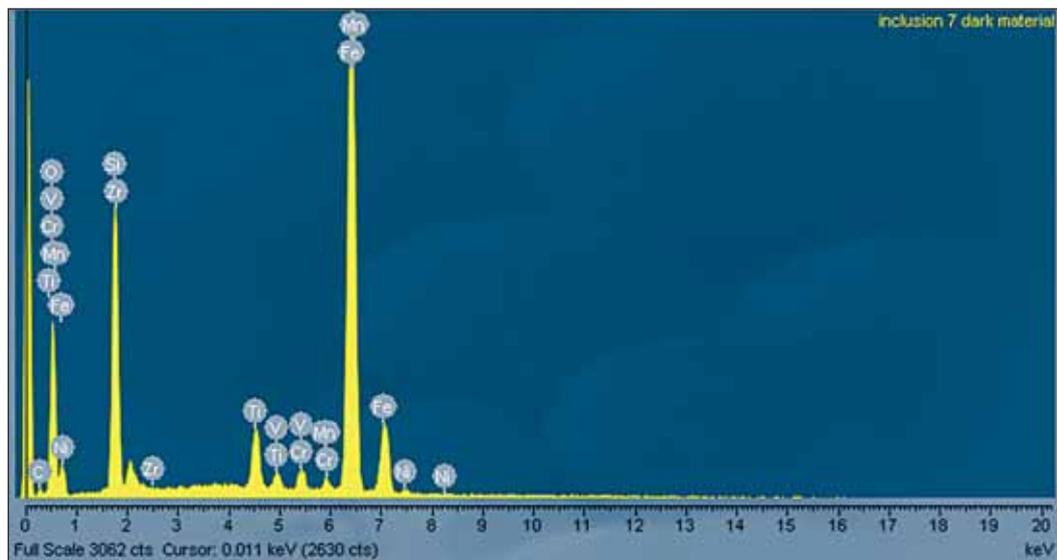
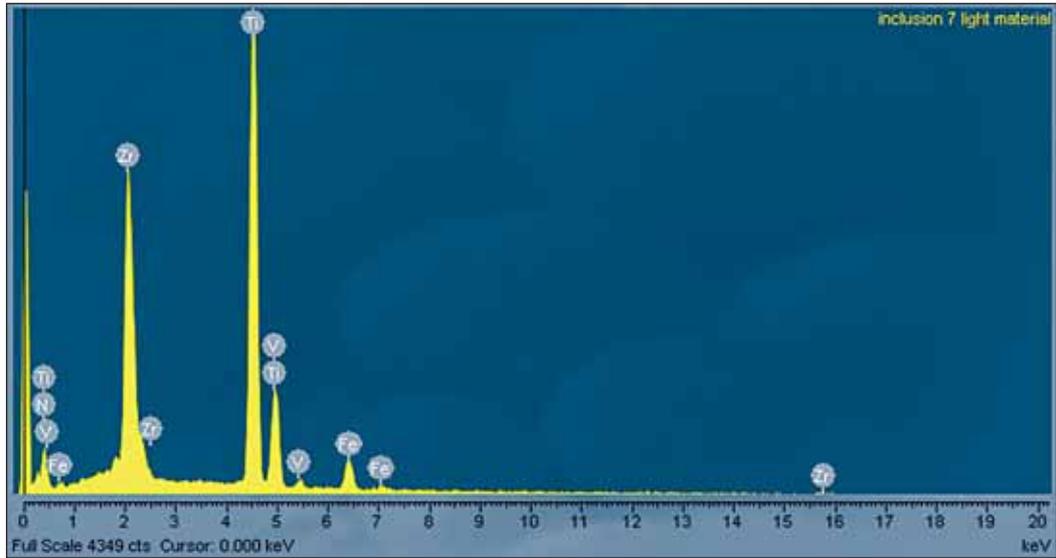


FIGURE 34:

Xray spectrum from the light 'blocky' material in the inclusion shown in fig. 32. The inclusion is a titanium zirconium vanadium nitride.



The types of inclusions present indicate that the steel had been treated by processes involving the injection of calcium and magnesium to reduce sulphur levels and control the shape of inclusions (create spherical inclusions). The size and distribution of the inclusions present in the steel is typical of that achieved by vacuum arc remelting.

No non-metallic inclusions with dimensions and or composition outside of the range determined to be typical for the steel from which crankshaft s/n V537912936 was found in the volume of steel surrounding the fatigue crack initiation site during the serial metallographic polishing of both sides of the fracture surface, see for example fig. 29.

FIGURE 35:

Multiple image photomicrograph showing the metallographic section, unetched, prepared by removing 0.04 mm from the final section prepared by McSwain Engineering Inc



The section prepared by McSwain Engineering Inc. was taken through the step feature on the crankarm side of the fracture with the plane of section oriented parallel with the journal axis and perpendicular to the journal surface. The journal surface at the fillet radius is at the top of the figure and the fracture is at the right of the figure. The journal surface at this location had been damaged during the final failure process. The small cracks extending from the surface of the journal, oriented parallel with the plane of fatigue cracking have been created as a result of the final failure process. These cracks follow the microstructure of the case hardened zone in contrast to the nature of the fatigue fracture. Crack extension along microstructural features is a characteristic of deformation of the case hardened zone.

Physical nature of fatigue initiation site

The macroscopic progression marks (beach marks) on the fatigue fracture surfaces indicated that fatigue crack initiation occurred below the surface of the fillet radius at the forward (counterweight side) of the No. 6 connecting rod journal near the centre of the crankarm on the inner side of the crank. The obliteration of fine fracture surface features during the processes of crack growth, journal fracture and final torsional separation prevented a more precise determination of the site of fatigue initiation and its nature.

A step-like feature was present on the two fracture surfaces. This feature was present between the region suspected to be the site of fatigue initiation and the journal surface. The material in the immediate vicinity of the site of fatigue crack initiation and the step feature were examined by progressively removing metal by metallographically polishing and microscopic viewing at various stages. This process enabled the volume of material in the vicinity of the origin to be examined for material abnormalities and a three dimensional view of the nature of the step feature to be developed.

The process of progressive metal removal by metallographic polishing is destructive. Each layer removed is reduced to very fine swarf. The process of progressive polishing was commenced by McSwain Engineering Inc. and involved the examination of the crankarm (forward) side fracture surface. The plane of the section was oriented parallel with the axis of the journal and angled to intersect the step feature at a shallow angle. It was apparent that progressive polishing had been performed to a point where the section plane intersected the bottom of the step and the material at the site of fatigue crack initiation had been examined.

Further progressive polishing of the section created by McSwain Engineering Inc was conducted at the ATSB laboratories in Canberra during March 2003. In addition, progressive polishing was conducted on the journal side (rear) of the fracture. The plane of sectioning was perpendicular to the journal surface with metal being removed from the journal surface down through the surface hardened zone.

Any characterisation of features in the vicinity of the fatigue initiation site must consider the effects of damage created during the growth of the fatigue crack, the effects of continued crankshaft rotation following final journal fracture and the damage created by the final torsional separation of the two halves of the journal. It is evident that the fracture surface features at the site of fatigue crack initiation and the immediate vicinity had been damaged by local deformation and local heating during the crankshaft fracture and final separation processes.

The nature of fracture surface secondary damage

FIGURE 36:

Views of the No. 6 Connecting Rod Journal, crankshaft s/n V536912936 showing the extent of damage to the crankarm (forward) side of the fracture. The location of the site of fatigue crack initiation, with respect to the crankarm, and the journal surface is arrowed

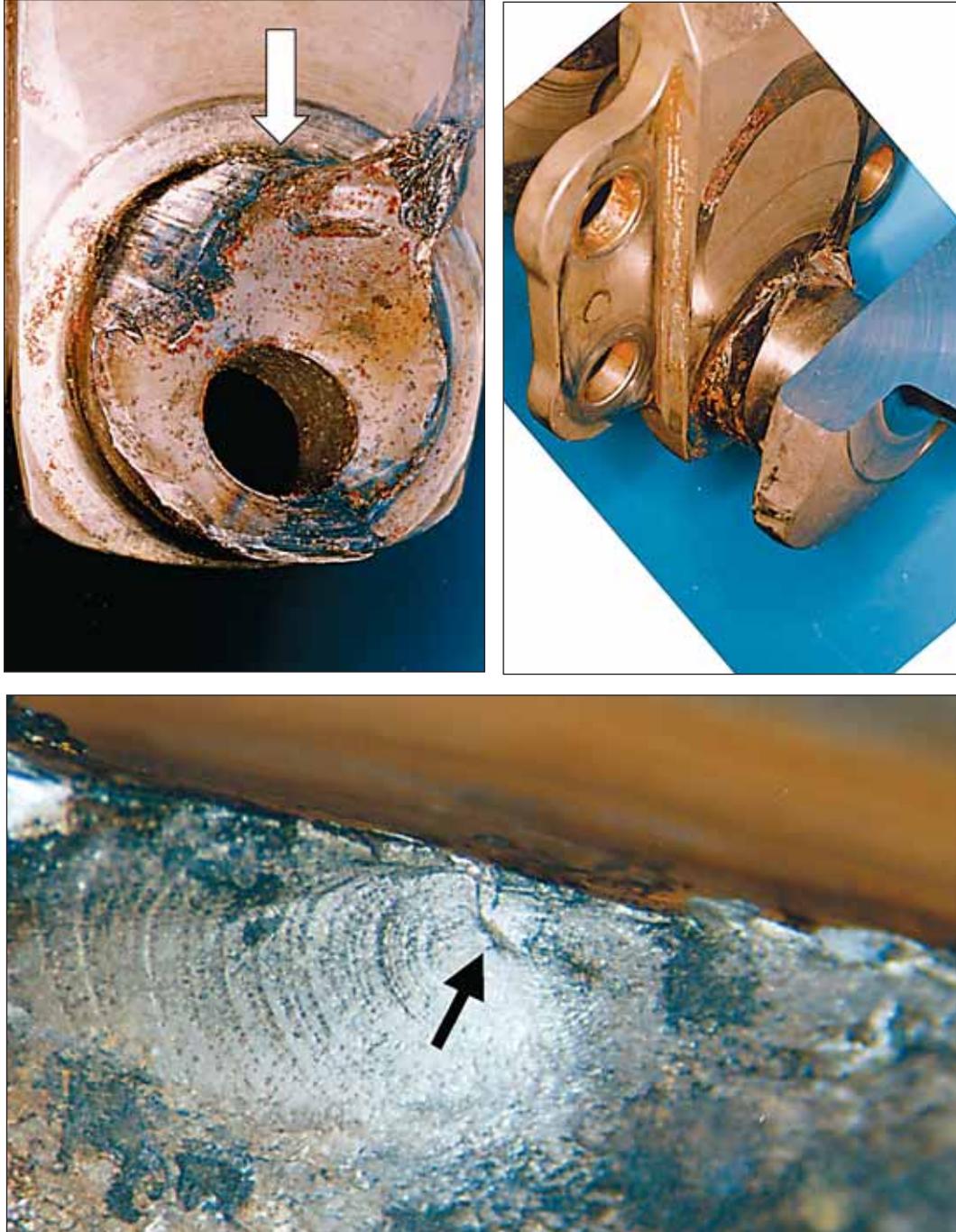


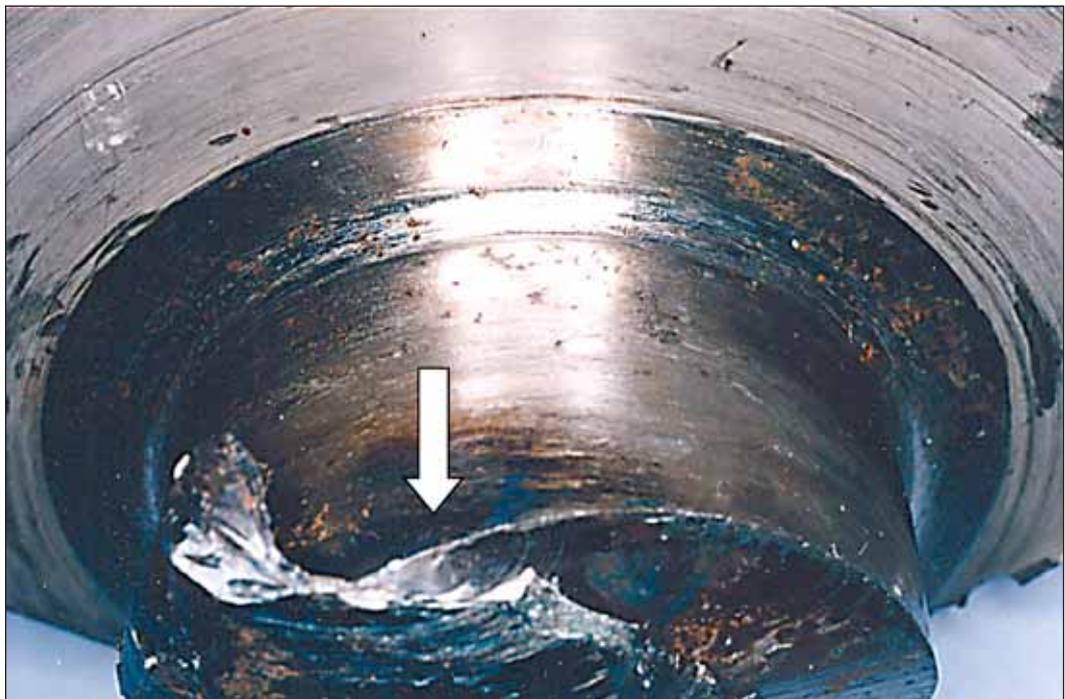
FIGURE 37:

The journal side (aft side) of the fracture, as recovered showing the extent of metal smearing over the region of the fatigue crack initiation site



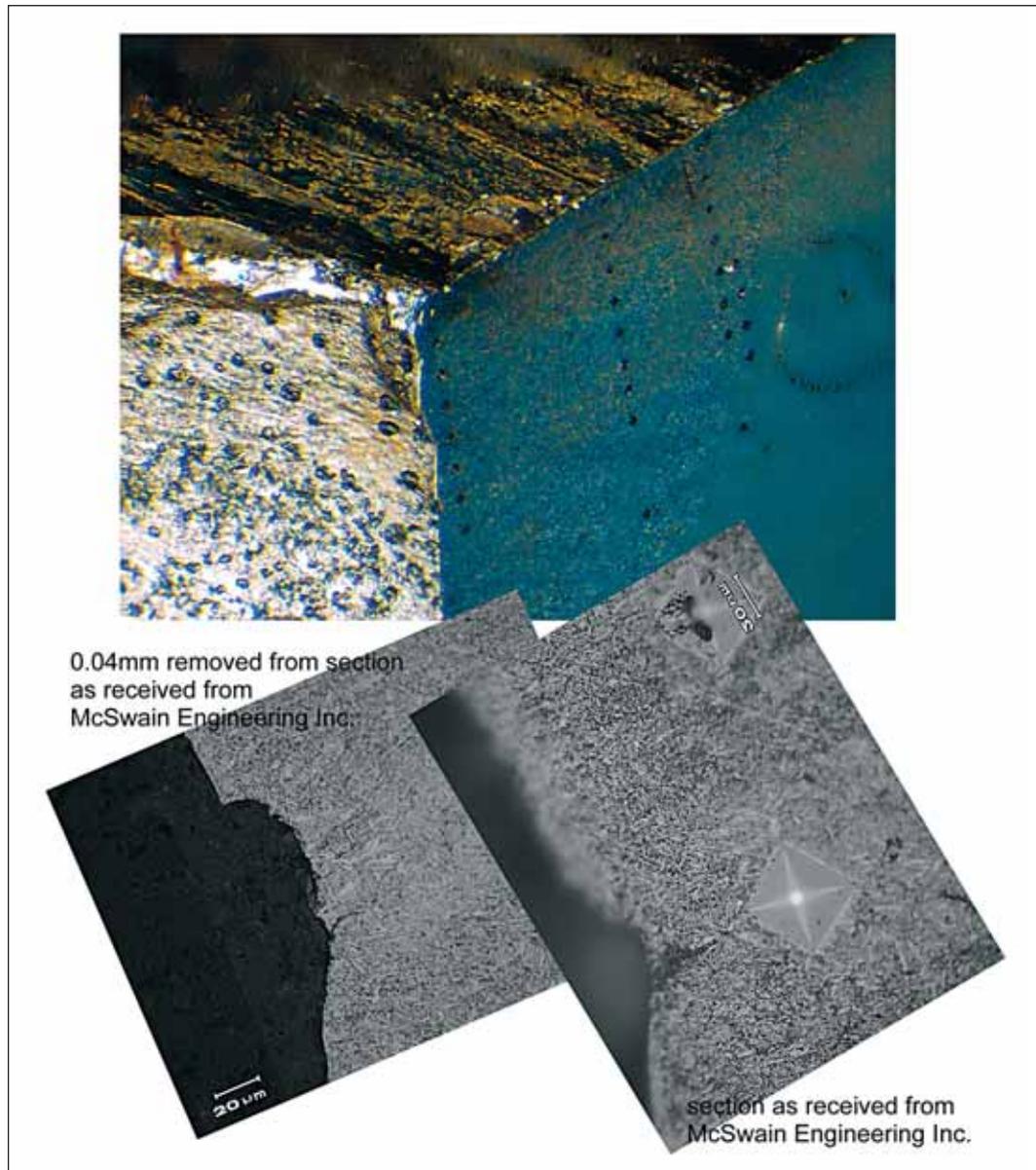
FIGURE 38:

The journal side of the fracture after a section of the smeared metal was broken away in the laboratory. The circumferential location of the fatigue initiation site is arrowed. It is clear that this region has been affected by the heat generated during the process of metal deformation and smearing



Characterisation of the step feature extending from the site of fatigue crack initiation

FIGURE 39:
Fatigue initiation site, crankarm side of the fracture



Note: the pitting evident on the fatigue fracture surface was created during the removal of the section by McSwain Engineering Inc.

Serial metallographic polishing used to examine the volume of steel surrounding the site of fatigue initiation revealed that no unusual non-metallic inclusion was present. Sectioning did reveal the presence of cracking extending over a short distance, perpendicular to the plane of fatigue cracking, from the bottom of the step feature on the crankarm side of the fracture. The path of this cracking followed microstructural features.

FIGURE 40:
Metallographic section through the end of the step feature prepared by McSwain Engineering Inc. The plane of the fatigue fracture is from top to bottom in the micrograph

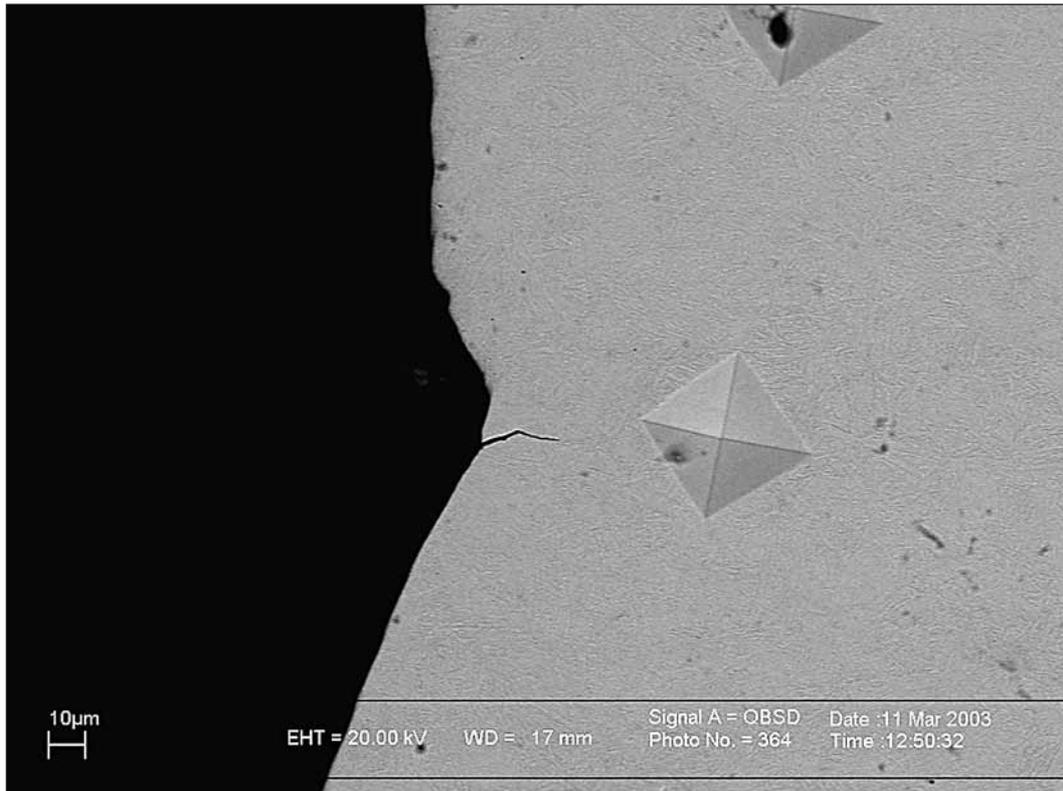


FIGURE 41:
Metallographic section prepared by ATSB, 0.04mm removed from McSwain section



The features of the step feature on the crankarm side of the fracture were examined more closely in a scanning electron microscope; see figs. 42, 43, 44.

FIGURE 42:
Sectioned fracture surface, as received from McSwain Engineering Inc

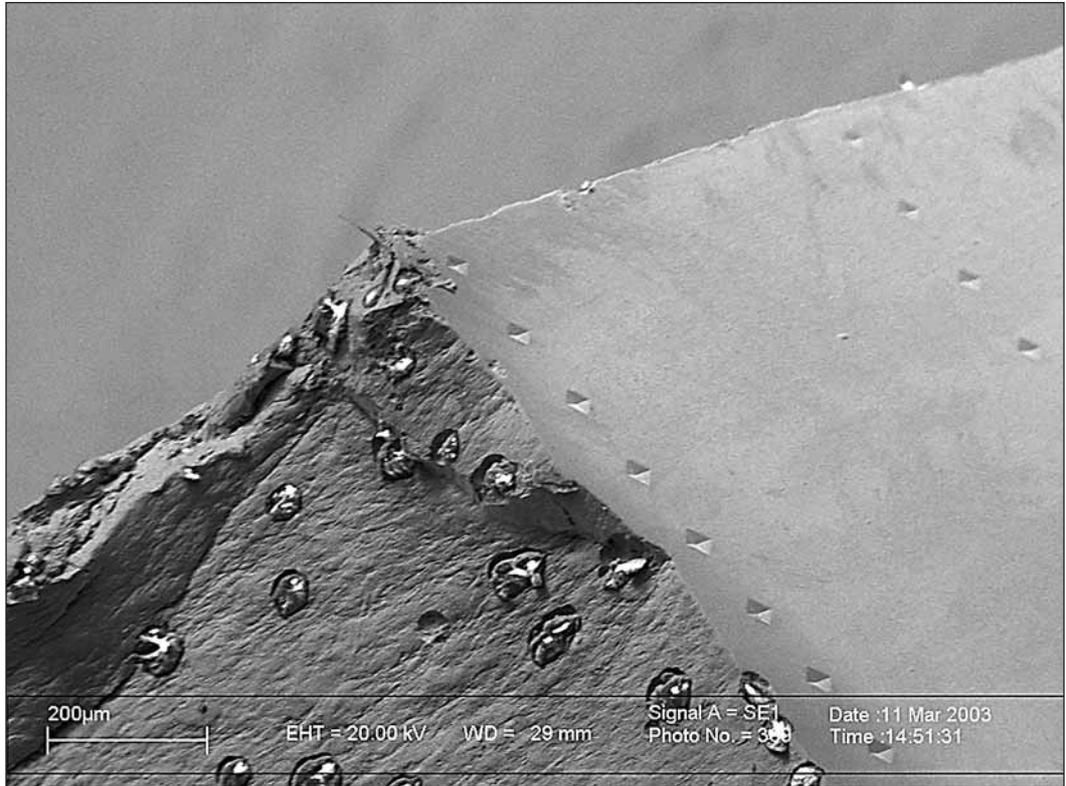
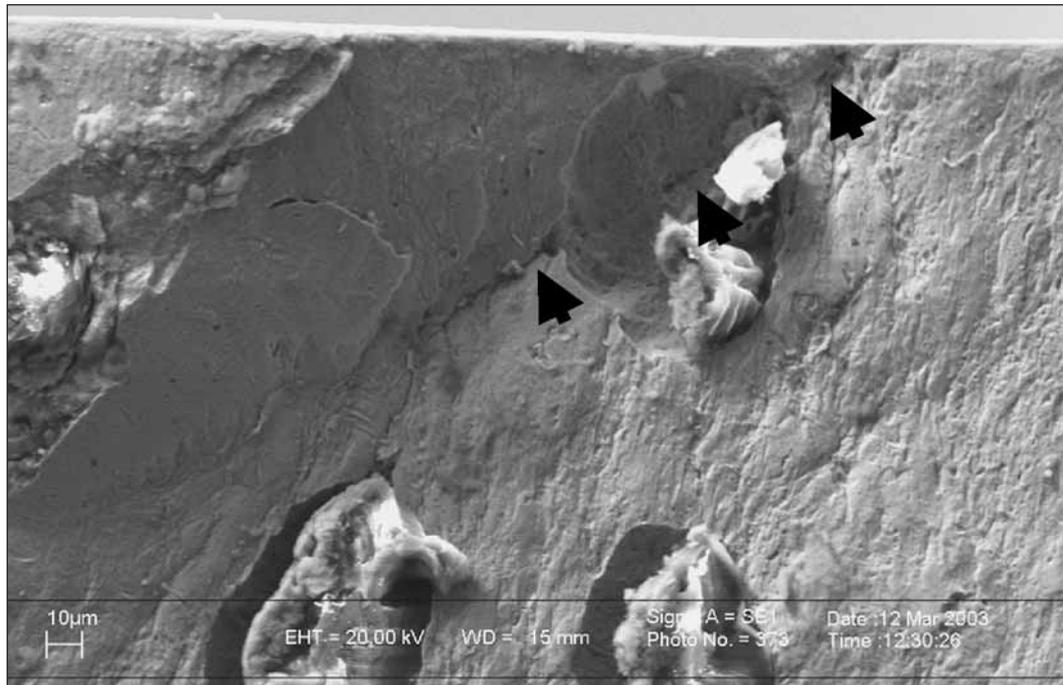


FIGURE 43:
The pits evident on the fracture surface were created by the sectioning process employed by McSwain Engineering Inc. The glowing residue in the pits is plastic material used to encapsulate the section during metallographic polishing



FIGURE 44:

The end of the step feature. Evidence of the cracking extending perpendicular to the plane of fatigue cracking is arrowed



The journal side of the fracture had not been examined by serial polishing prior to the present examination. The step feature on the journal side of the fatigue fracture was examined by preparing a number of sections perpendicular to the step, starting with sectioning parallel with the journal surface.

It was very apparent that the fracture surface features in the vicinity of the fatigue initiation site, journal side of the fracture, had been subjected local deformation during the process of final fracture and journal torsional separation.

FIGURE 45:

The step feature on the journal side of the fatigue fracture

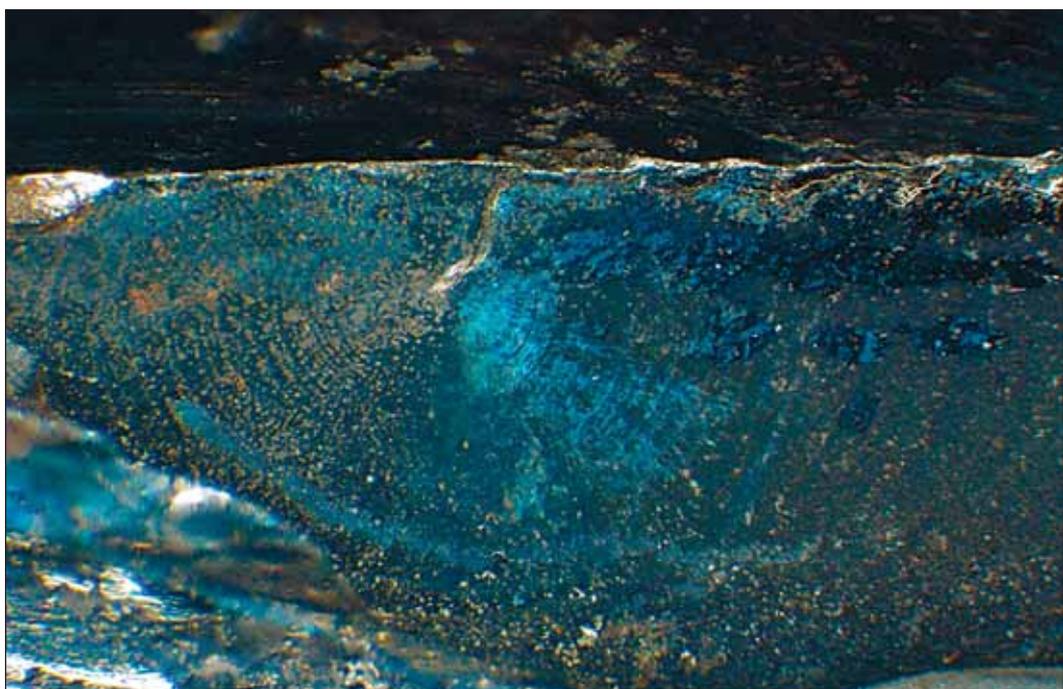


FIGURE 46:
The journal surface at the site of the step feature. The location of the step feature is arrowed

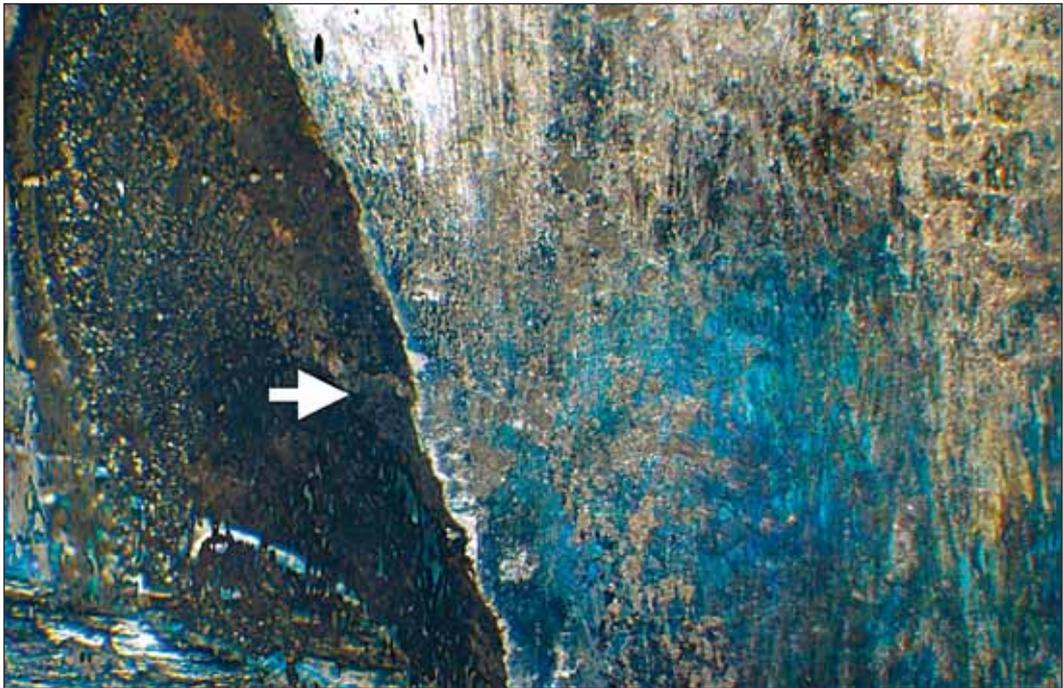
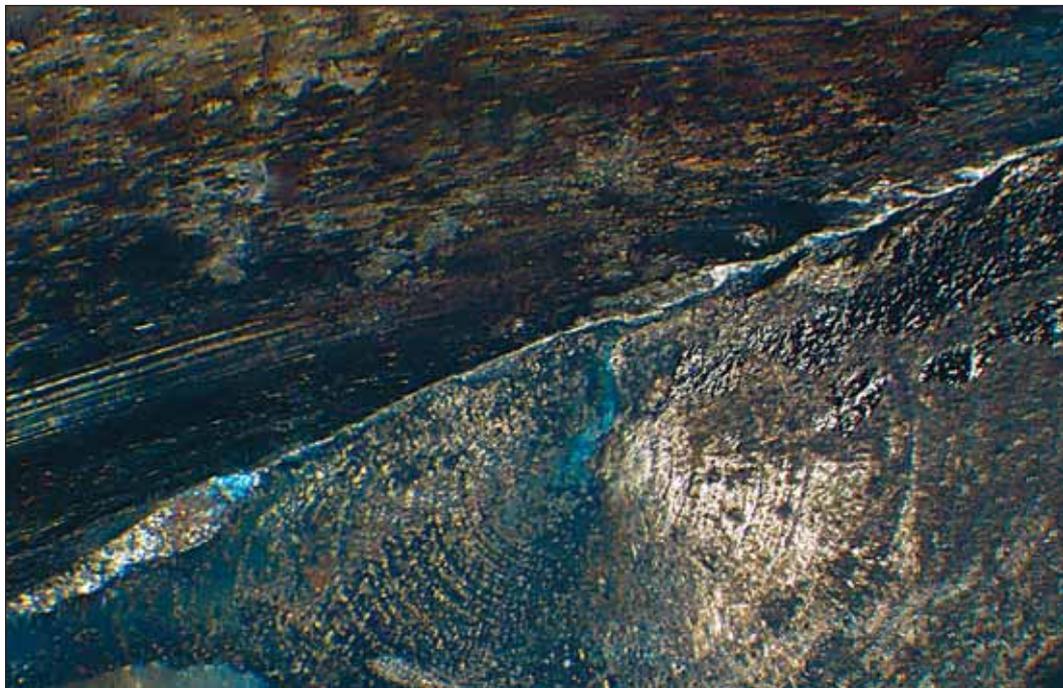


FIGURE 47:
Oblique view of the step feature, journal side of the fracture surface. The concentric fatigue progression markings on the fracture surface indicate that fatigue crack initiation occurred in the vicinity of the end of the step feature



Material was removed progressively by polishing in a series of planes parallel with the plane of the journal, see fig. 48.

FIGURE 48:
Serial sections through the step feature showing the overall nature of the feature

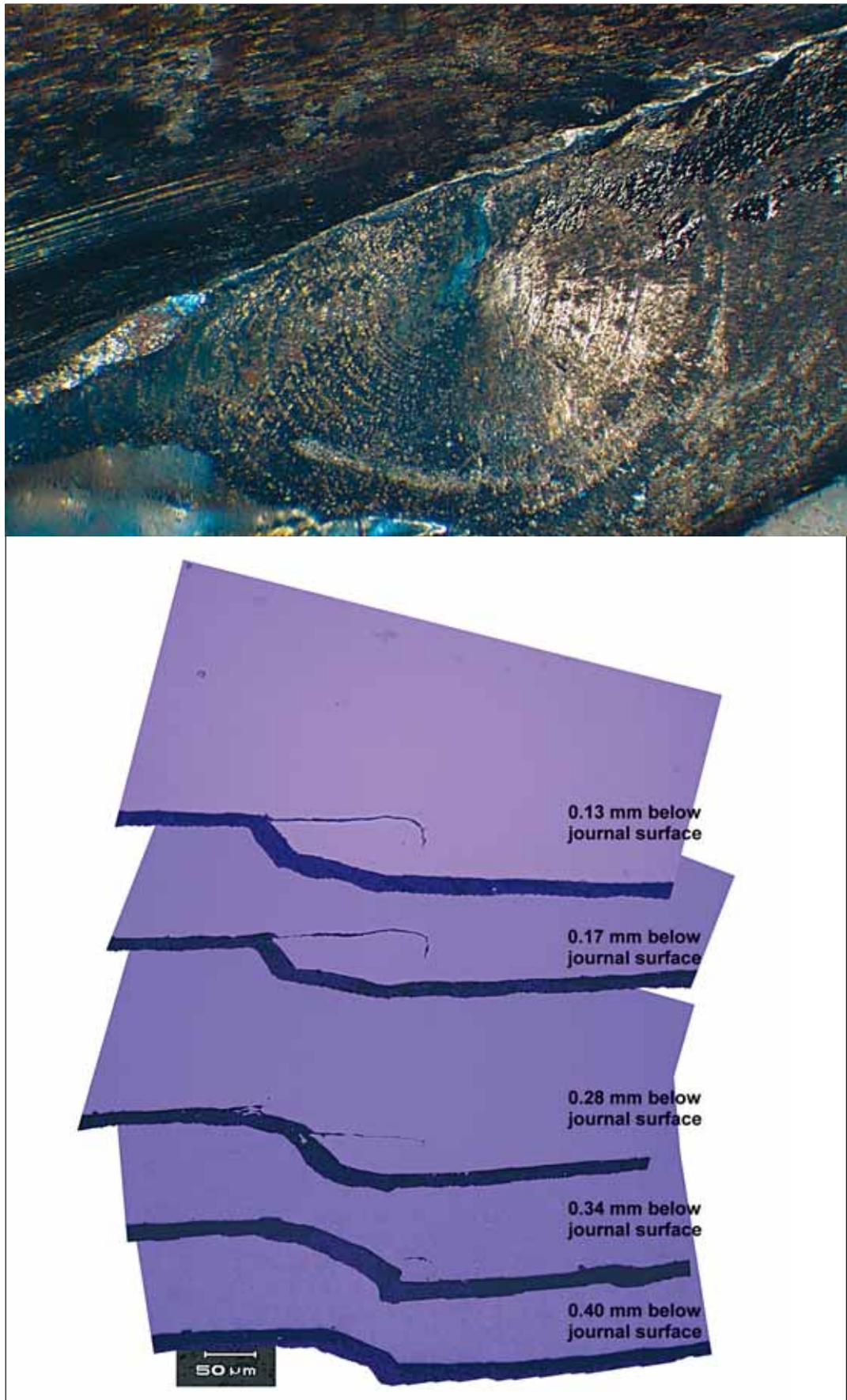
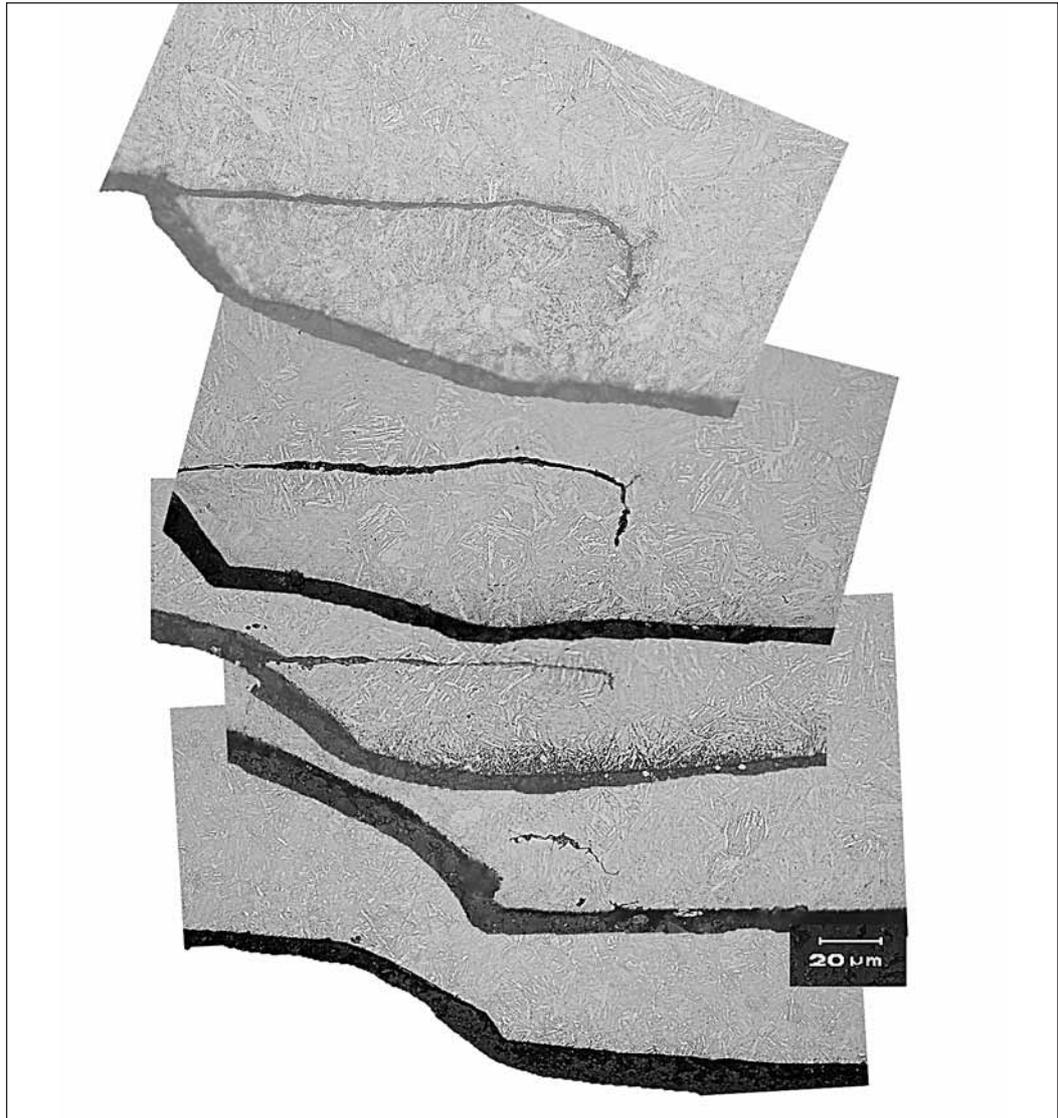


Figure 49:
Composite image showing the serial metallographic sections prepared from journal side of the fracture at higher magnification, etched in 1 per cent nital



Examination at higher magnification is shown in figs. 50–54

FIGURE 50:
Reflected light micrograph, 0.13 mm below the journal surface

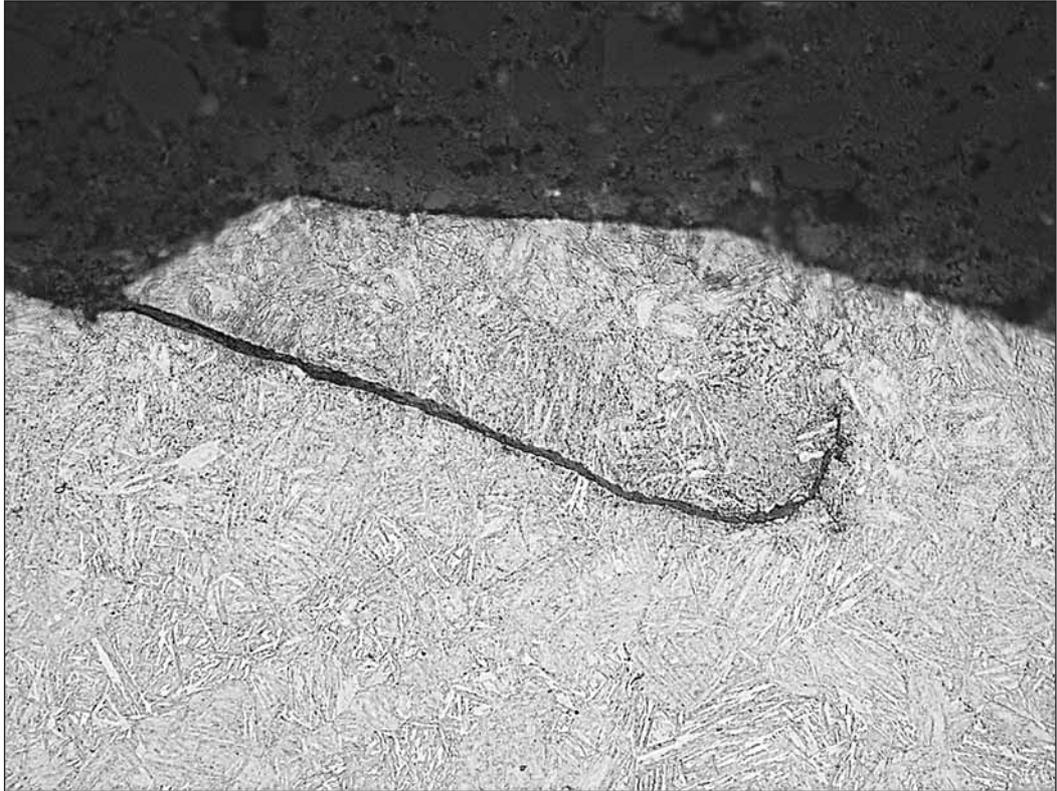


FIGURE 51:
Reflected light micrograph, 0.13mm below the journal surface

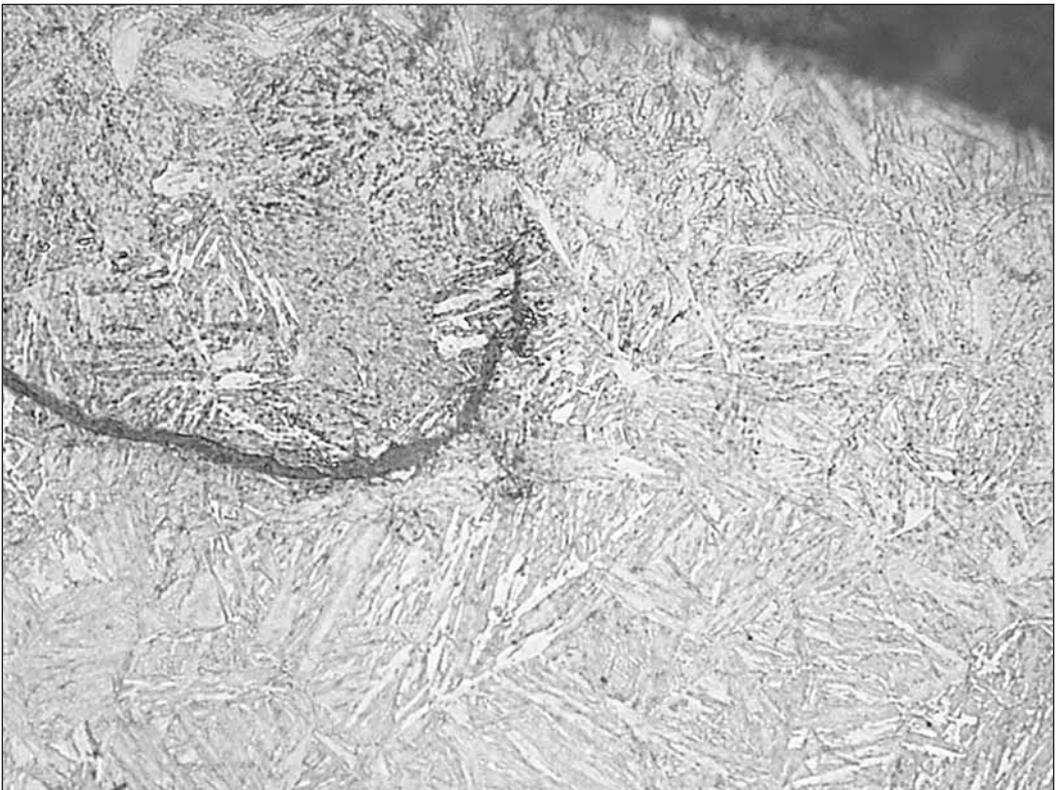


FIGURE 52:
Scanning electron micrograph, 0.17 mm below the journal surface

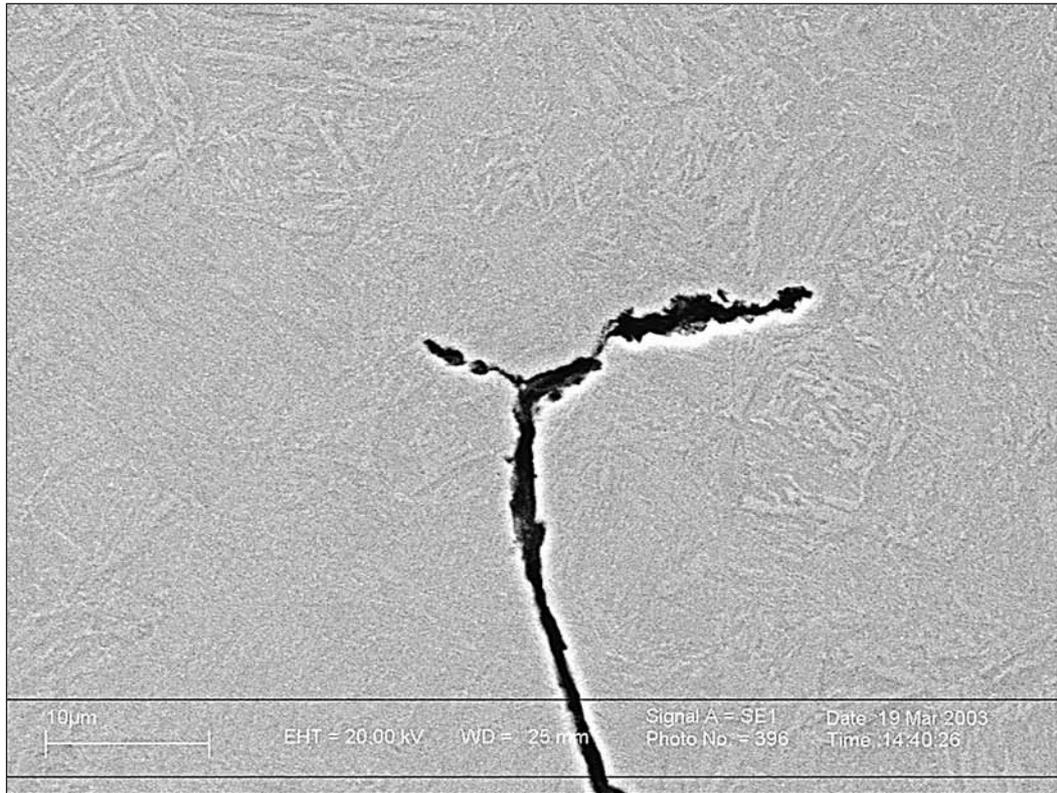


FIGURE 53:
Scanning electron micrograph, 0.28 mm below the journal surface

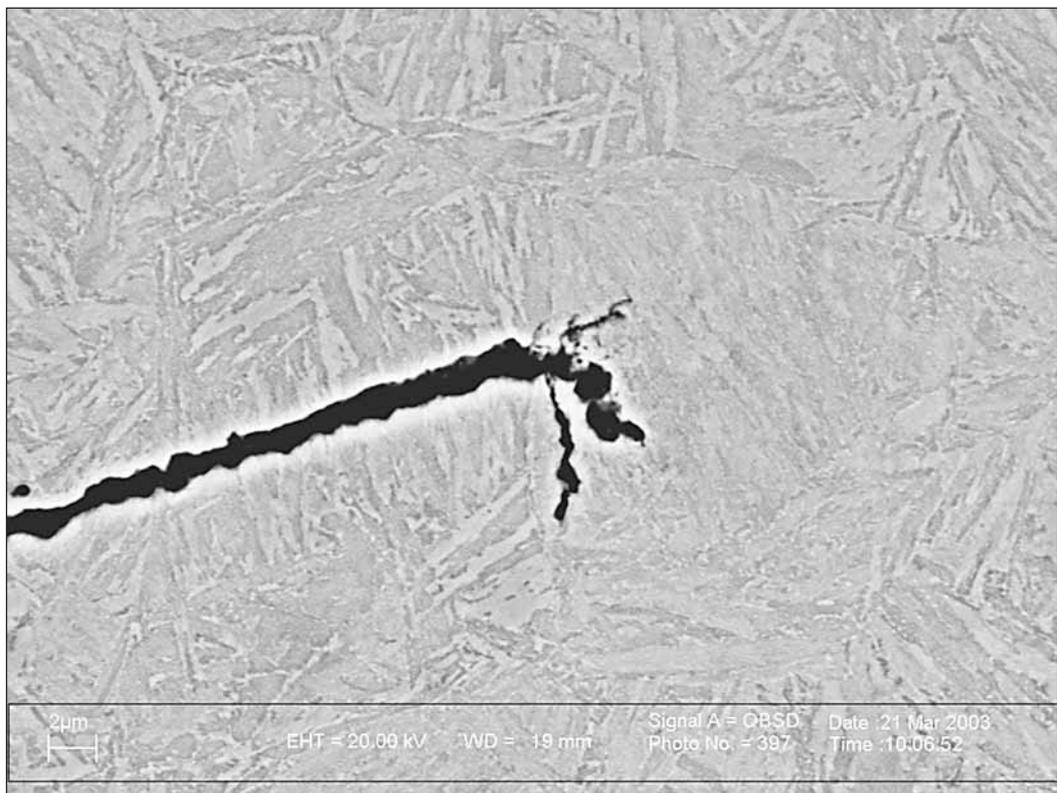


FIGURE 54:
Scanning electron micrograph, 0.34 mm below the journal surface



It is evident from the nature of the features under the step that the feature is not a simple lap. The lack of correspondence of microstructural features across the lap, the deformation evident in the microstructure in the vicinity of the lap and the small cracks extending from the curved portion of the lap all indicate that the lap is not the result of overlapping fatigue crack growth.

The complex nature of the lap features and cracks under the step indicate that some form of cracking was present prior to final fracture deformation and this cracking was oriented parallel with the axis of the journal and its path followed microstructural features.

If the step feature was simply the result of overlapping fatigue crack growth the complexity of the feature would not be present.

For the case of the growth of two parallel fatigue crack fronts, slightly displaced from each other, the stress fields around the crack tips interact as the two fronts approach each other. The local tensile stresses are no longer parallel to the applied stress and the cracks bend towards each other by tilting, and eventually intersect. The stress fields change progressively as the cracks grow so the fracture path is smooth and continuous.¹⁸

There is evidence in the serial sections taken from both sides of the fatigue fracture surface that indicates that a plane of cracking, oriented perpendicular to the fatigue fracture, parallel with the journal axis, and exhibiting a path determined by microstructural features was present in the vicinity of the site of fatigue crack initiation.

Cracks of this nature may be created by the localised thermal expansion of journal surfaces that have been hardened by nitriding.

¹⁸ Fractography Observing, Measuring and Interpreting Fracture Surface Topography, D Hull, Cambridge University Press 1999, p 84.

FIGURE 55:
Reflected light micrograph showing the nature of a thermal expansion crack in a nitrided surface

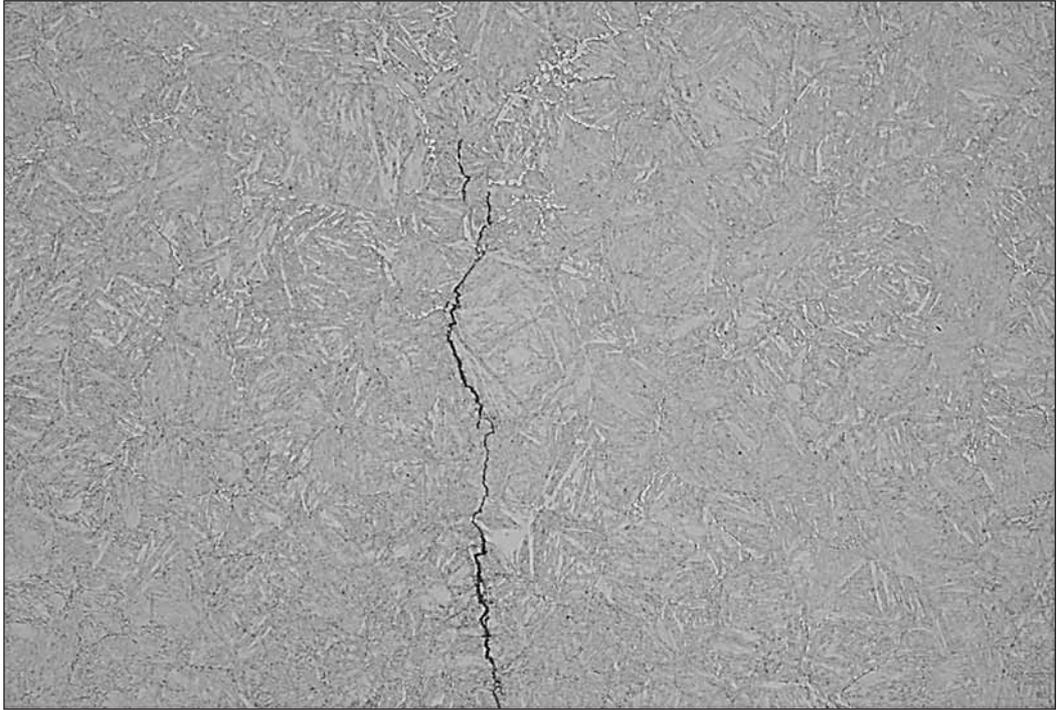
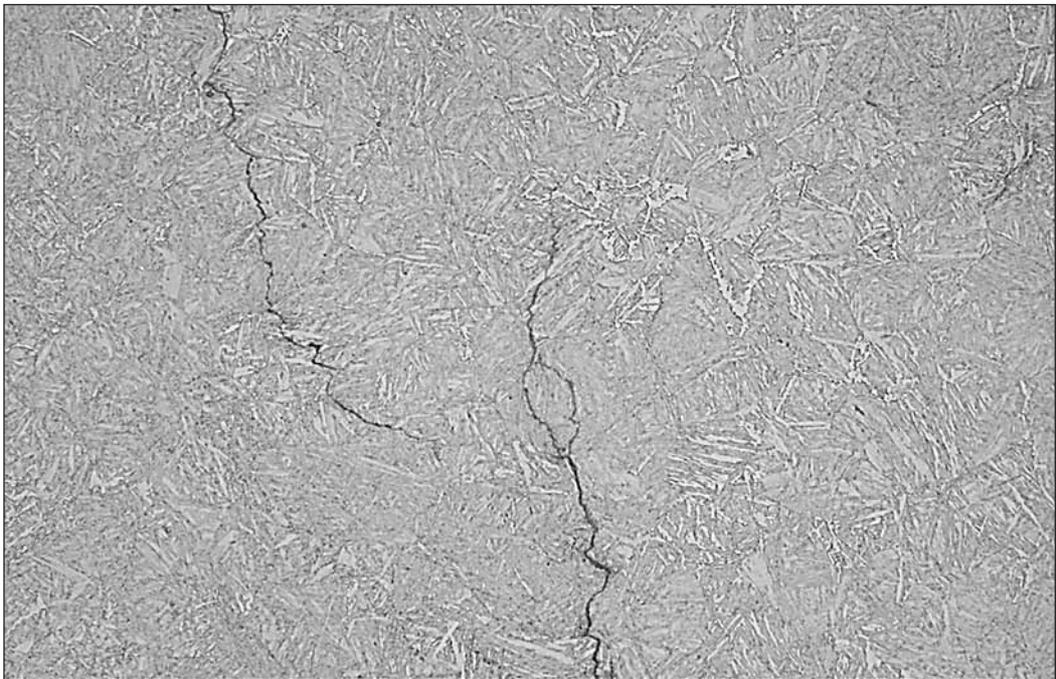


FIGURE 56:
Reflected light micrograph showing the crack path of a thermal expansion crack



Localised heating in the fillet radius of a surface hardened crankshaft journal may occur during grinding processes or during the unlubricated contact with other engine components during engine operation. The Textron Lycoming drawing notes for part number 13F27708 crankshafts state that no grinding is allowed on any connecting rod journal after nitriding.

The most likely engine component that could contact the connecting rod journal fillet near the transition from the journal to the fillet is the bearing insert. The range of axial movement of an insert to the point where the bolt clearance slot contacts the bolt guide surface will allow the bearing insert to contact the fillet radius in the location of the fatigue crack, see fig. 57.

FIGURE 57:

A composite image; showing the section through the step feature at the fatigue initiation site, a bearing insert correctly located in the big end housing (tang/lug intact), the maximum axial displacement of a bearing insert (coloured red) following a loss of retention force and deformation of the tang/lug. Note the deformation of the journal fillet radius at the site of the fatigue crack.



Examination of the crankarm side fillet radius of the No. 6 connecting rod journal revealed that a small region on the outer side of the crank had not been damaged extensively by the final fracture and separation processes. Examples of thermal expansion cracks in the journal surface created by bearing surface contact were found, see figs. 58–60. Bearing contact was established by the detection of the metals used in bearing construction, aluminium and tin, in the metal smeared on the journal surface in the region of the cracks.

FIGURE 58:

Scanning electron micrograph showing the smearing of bearing metal on the journal surface and the presence of small cracks aligned parallel with the axis of the journal. The as machined surface of the journal can be seen at the bottom of the micrograph



FIGURE 59:

Scanning electron micrograph showing the maximum length of the cracks



FIGURE 60:
Micrograph showing the location of energy dispersive Xray area scans figs. 61–65

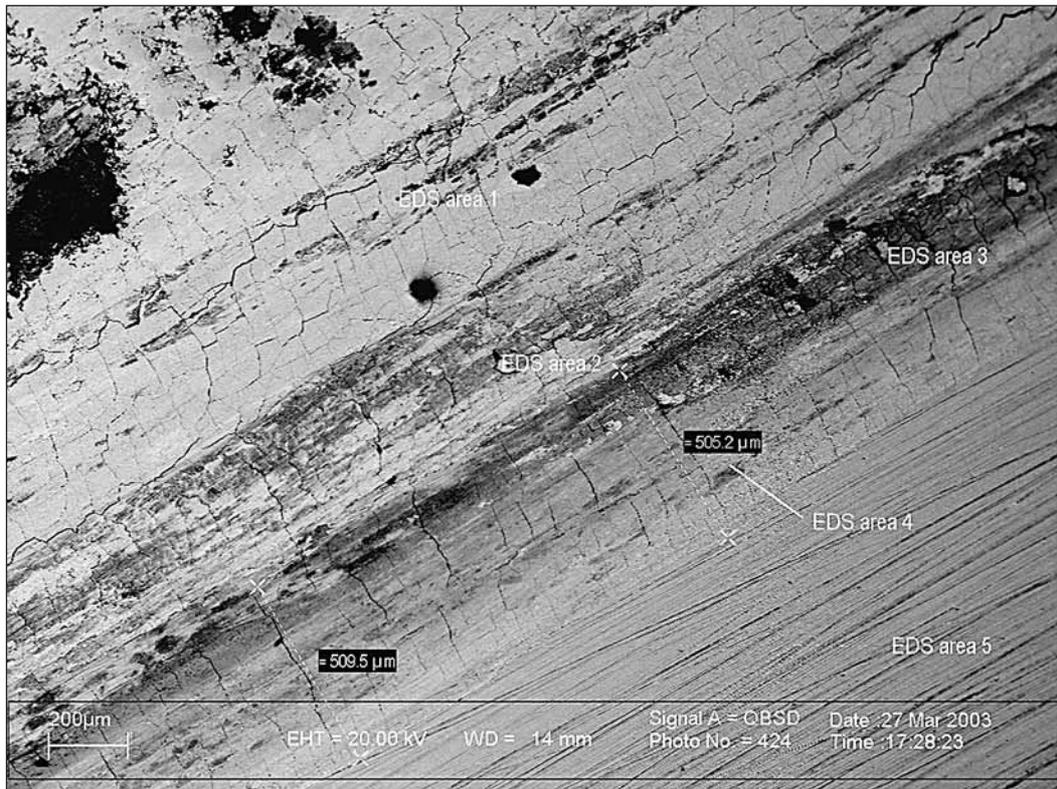


FIGURE 61:
Area marked EDS 1 in fig.60

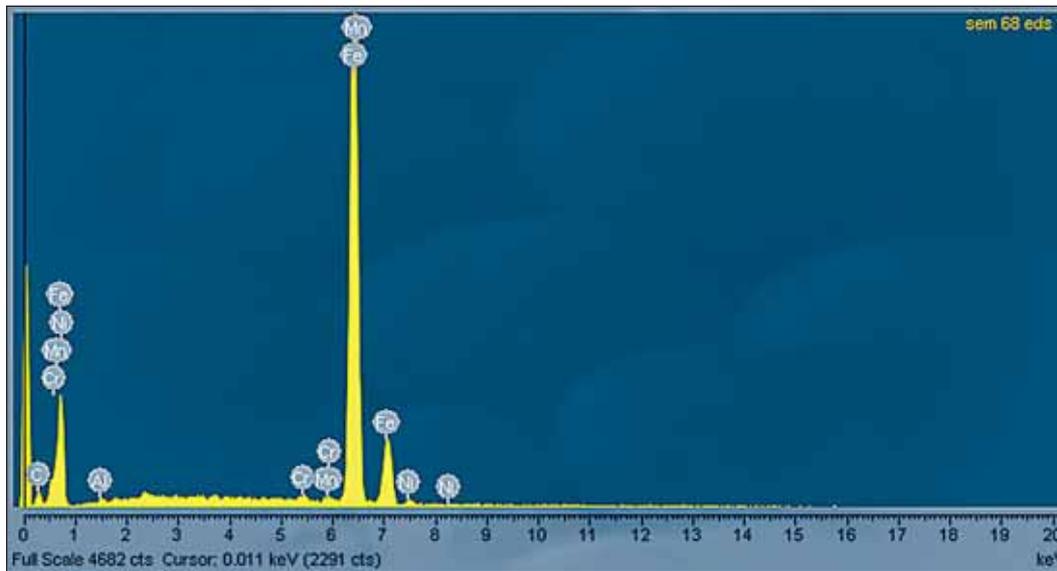


FIGURE 62:
Area marked EDS 2 in fig. 60

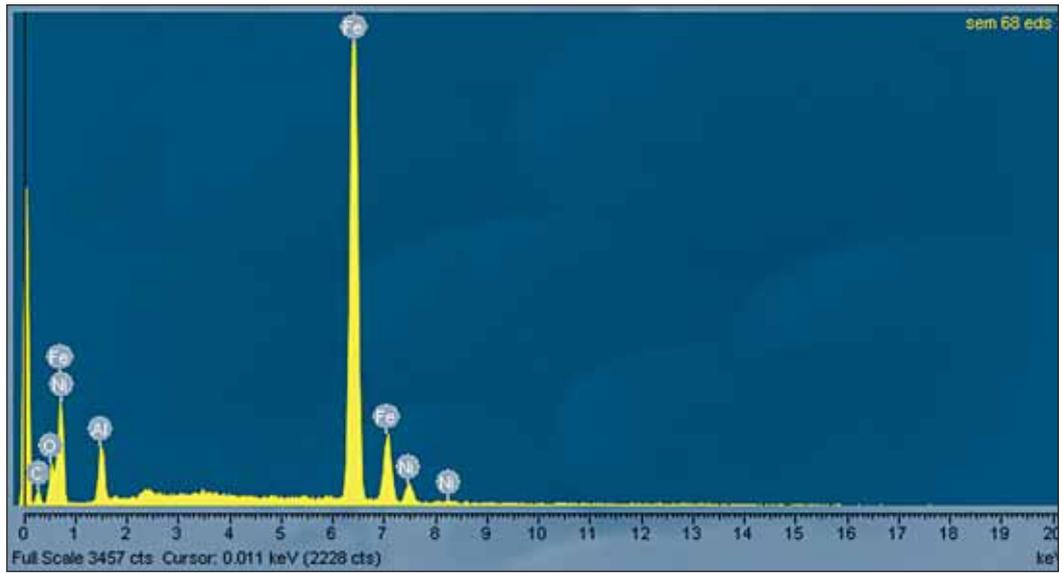


FIGURE 63:
Area marked EDS 3 in fig. 60

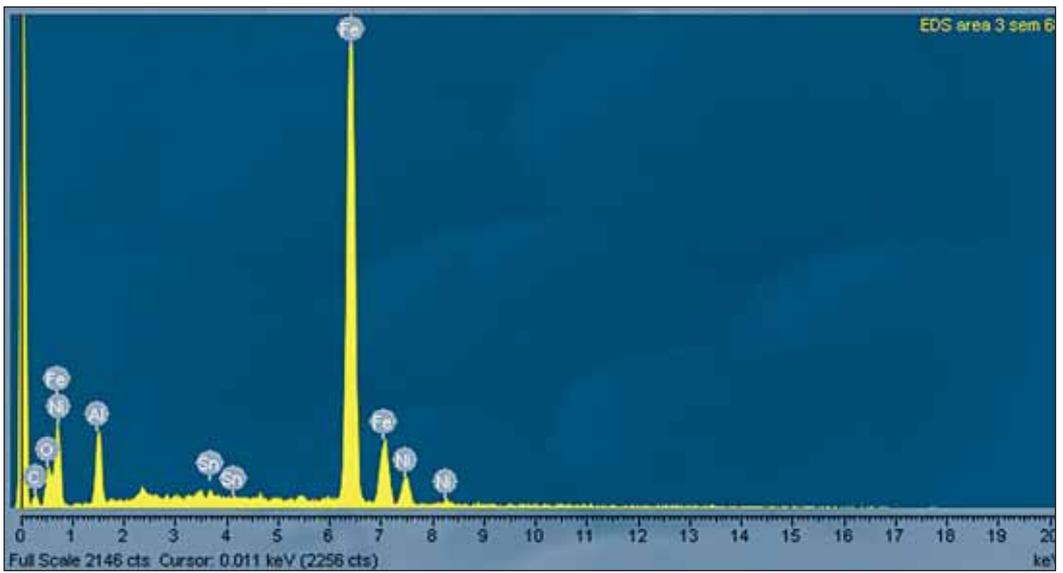


FIGURE 64:
Area marked EDS 4 in fig. 60

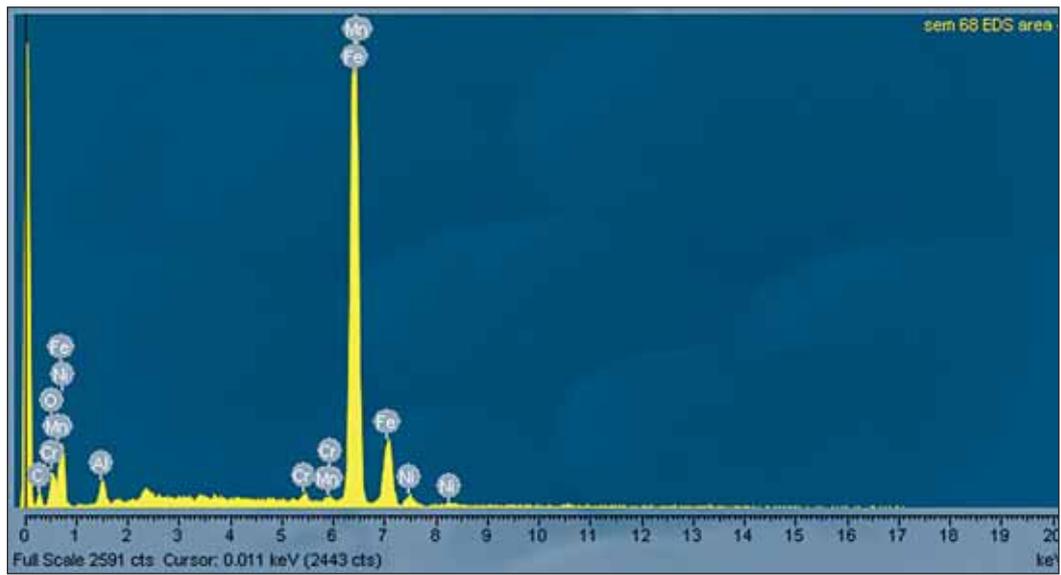
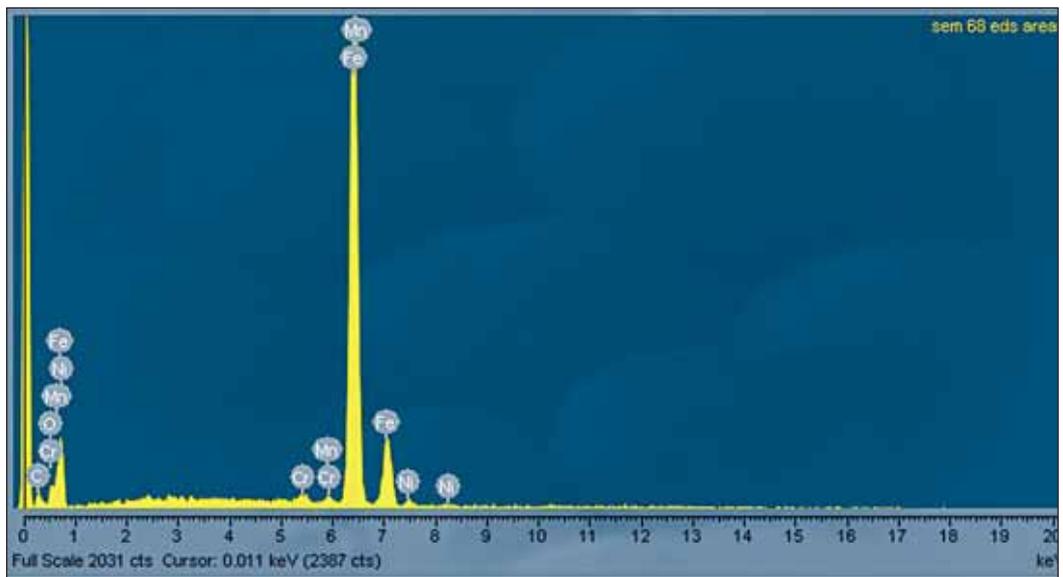


FIGURE 65:
Area marked EDS 5 in fig. 60



4. Conclusions

The chemical composition of crankshaft s/n V537912936 was within the limits specified in AMS 6414H with check test variation limits applied, with exception of two of the four carbon analyses. The results of carbon analysis show a higher degree of scatter than the other elements. The scatter range for carbon was 0.036 per cent. The use of different analysis techniques and four independent analyses indicates that this degree of scatter appears to be inherent in the analysis of carbon in steel. The two carbon analyses that exceeded the upper check test variation limit did so by 0.02 per cent, a value within the scatter range for the analyses conducted.

The strength of the crankshaft core as determined by hardness testing is consistent with strength levels achieved by a single stage nitriding process. The strength of the core is determined by the tempering temperature. If the nitriding temperature exceeds the tempering temperature the strength will be reduced. The strength of the steel is not affected by variations in carbon content within the range specified for the steel.

The nitrided surface hardened zone complies with the specified requirements for case depth and surface hardness.

The inclusion content of the steel is consistent with a steel treated with calcium and magnesium and produced by the vacuum arc remelted process. No inclusion stringers were observed. The maximum dimension of the inclusions observed was approximately 13 μm .

No inclusions of a size greater than normal, or of a type different from the normal inclusions, were identified in the volume of steel surrounding the site of fatigue crack initiation.

There was no evidence of a non-metallic inclusion being the site of fatigue crack initiation.

Pullout features created under impact loading are considered to be a feature of the fracture of steels containing very low levels of non-metallic inclusions. These features do not represent material flaws or sites of lower material strength. No evidence of this type of feature was found in the vicinity of the fatigue initiation site.

Evidence of cracking, aligned with the axis of the journal with a microstructurally influenced crack path, was found extending from the step feature on both sides of the fracture. Cracking of this nature is consistent with cracking created by the localised thermal expansion of surface hardened zones.

The fracture surface features at the site of fatigue crack initiation had been damaged during the processes of final fracture and torsional separation.

Attachment D: Screen shots showing operating conditions of Textron Lycoming TIO-540-J2B at various manifold pressure, RPM, and fuel flow settings as recorded at the engine test facility operated by Mr G Braly, Ada, Oklahoma, USA.

The screen shots (figures 1–4) were taken at the engine test facility operated by Mr G Braly at Ada, Oklahoma, USA. The shots depict the engine operating conditions both overall, and for individual cylinders, at various RPM, manifold pressure, and fuel flow settings. Each shot includes the following:

1. CGHP (left column) is gross corrected horsepower. The actual brake horsepower being produced by the engine is shown in the blue window at the top of column 2.
1. The digital value of CHT and EGT for each cylinder is shown in the lower section of the left column.
2. Columns 2 and 3 include six numbered individual windows, one for each cylinder. The key to the information for each cylinder is shown in the box at the top of column 2.
3. The top window in column 4 shows the history of manifold pressure, torque, fuel flow, and RPM.

The remaining five boxes on the display are trend lines for the parameters depicted on each box – SBDTC (spark before top dead centre), ThetaPP is the angle of crankshaft rotation after top centre which coincides with the peak combustion pressure, Peak PSI (peak combustion pressure), BHP comparison chart (brake horsepower output for each cylinder), CHT/EGT/TIT (EGT trend line left scale, CHT trend line right scale). They show how the parameter changes as engine operating conditions are varied. The lines in each box are colour coded to represent a cylinder as per the colour codes in the numbered windows for the individual cylinders. Those boxes show that there are significant differences in the performance characteristics of each cylinder.

The shots provide unequivocal evidence that:

1. The engine is capable of producing greater than its rated output of 350 bhp.
2. Figures 1 and 2 show that very small changes to RPM and MP produce significant changes to engine output. It is noteworthy that the differences in RPM and MP between those screenshots are well within the allowable engine adjustment tolerances.
3. Figures 3 and 4 show that the engine can produce significantly greater than 315 bhp at 2,400 RPM. Specifically, Figure 4 shows the engine operating at 2397 RPM and producing greater than its rated output of 350 bhp. The following exchange was taken from the transcript of evidence taken during the Coronial inquest. It was recorded on 28 October 2002 at Ada, Oklahoma, while Mr Braly was giving evidence during the operation of the engine in his test facility.

Question: Remember there is a potential scenario of the engine running at 2400 revs, substantially retarded throttle, and producing about 110 horsepower.

Mr Braly: Yes.

Question: Are we able to try and simulate that?

Mr Braly: Yes. Actually, there's another one, which is at 2400, and some maximum manifold pressure, so why don't we catch that one first and we'll go to the second

scenario. I believe its stable at that condition, basically wide open manifold pressure 2400 RPM, 37 gallons. Is that what somebody was asking? The screenshot is numbered 29 [Figure 3].

Question: What if we take the manifold pressure up further – what would happen?

Mr Braly: Those peak pressures are going to go higher, you are going to get some horsepower. Do you want me to do that?

Question: Please

Mr Braly: Extremely high mean effective pressures at this at low RPM and peak cylinder pressure is now pushing 1050. The induction air temperature is 170. The screenshot of that is 30 [Figure 4]. I'm not real happy to be staying here. Does anybody have any reason why they want me to stay here?

Question: Not unless you are willing to lean the mixture. What would be the effect of leaning the mixture – could you state what effect?

Question: What would happen if you leaned the mixture?

Mr Braly: The peak cylinder pressures would go through the roof, they would get very high, well past 1100. If the cylinder heads got above 400, which they would unless we cooled them, you would end up with some significant detonation if we didn't lose a spark plug first from the very high cylinder pressures.

The inferences drawn by the ATSB from this exchange include:

1. Mr Braly was not keen to continue operating the engine in the conditions depicted in Figure 4, apparently because of the potential to damage the engine.
2. Leaning the mixture from the conditions in Figure 4 would increase the power output above 359 bhp. The situation then would be that:
 - The engine would be operating in a condition of significant detonation,
 - Cylinder head temperature would rise above the limit unless some cooling was applied, and
 - Severe engine damage was likely.

Figure 1:
 Showing engine producing 350 bhp at 2575 RPM, 43.1 inches MP, and full rich mixture

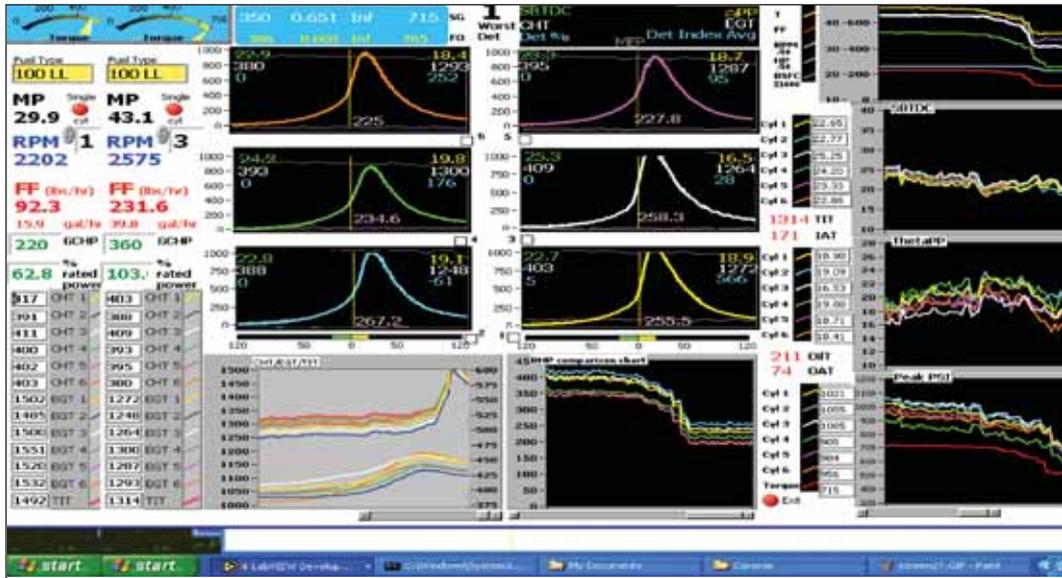


Figure 2:
 Showing engine producing 357 bhp at 2588 RPM, 43.3 inches MP, and full rich mixture. Note that very small changes in RPM and MP from those in Figure 1 resulted in a 2 percent power increase

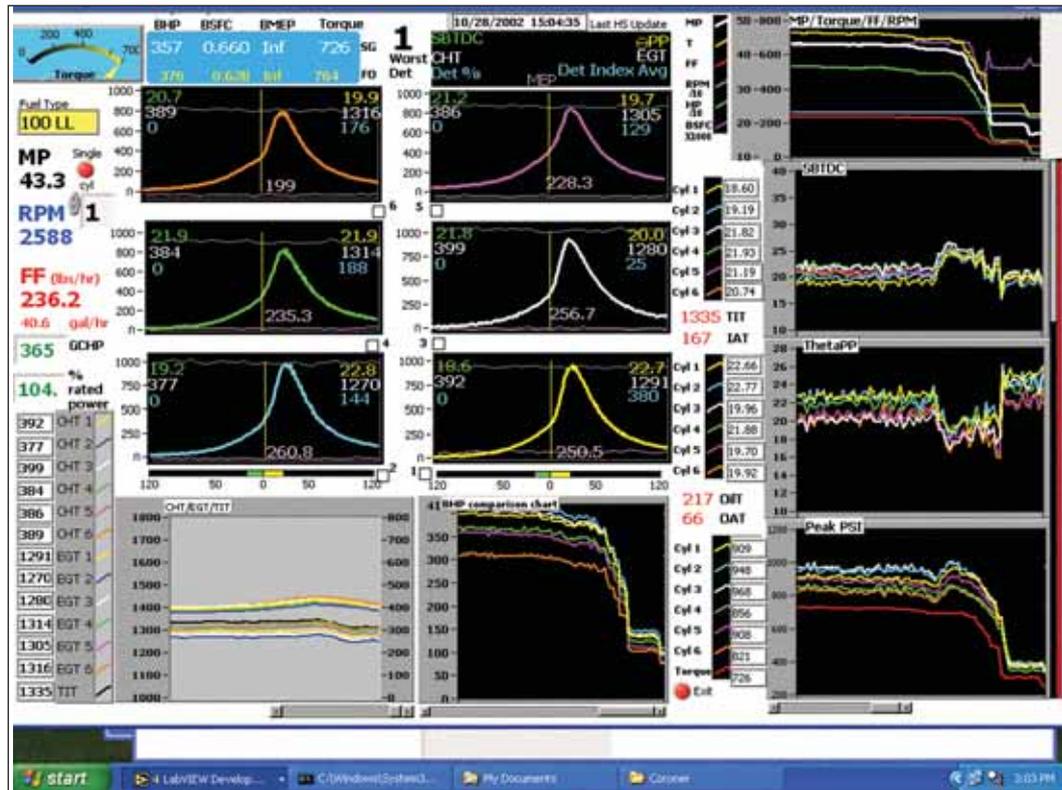


Figure 3:
Showing engine producing 333 bhp at 2403 RPM, 43.2 inches MP, and full rich mixture

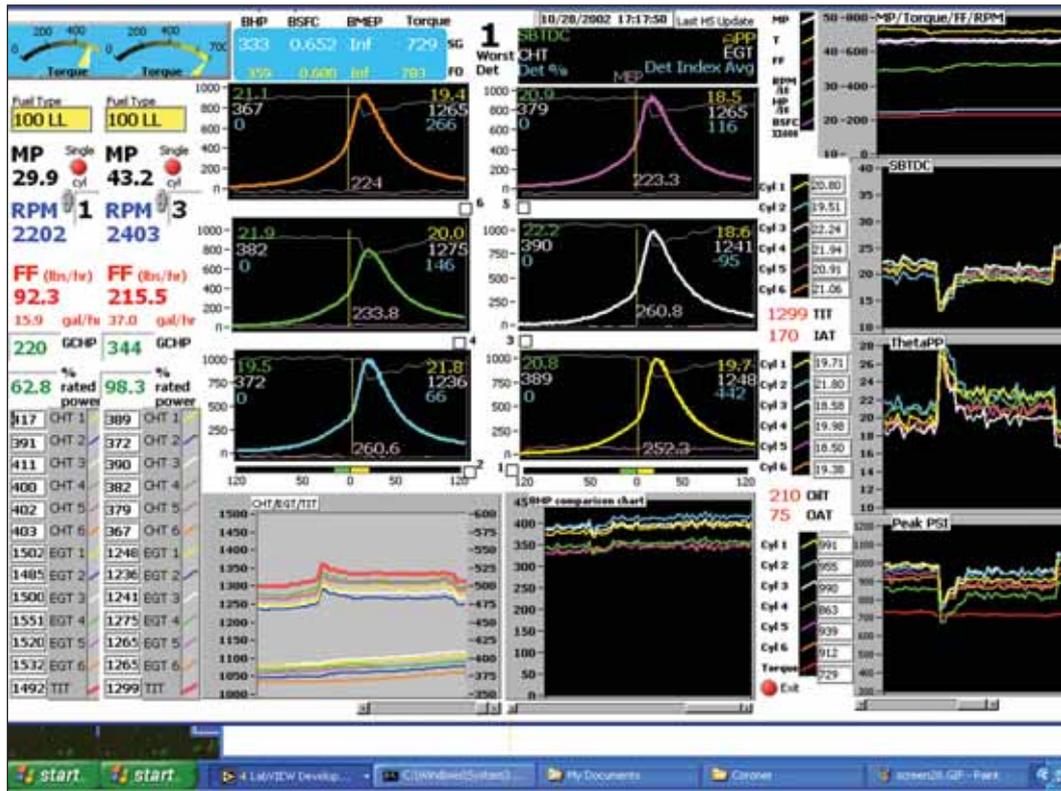
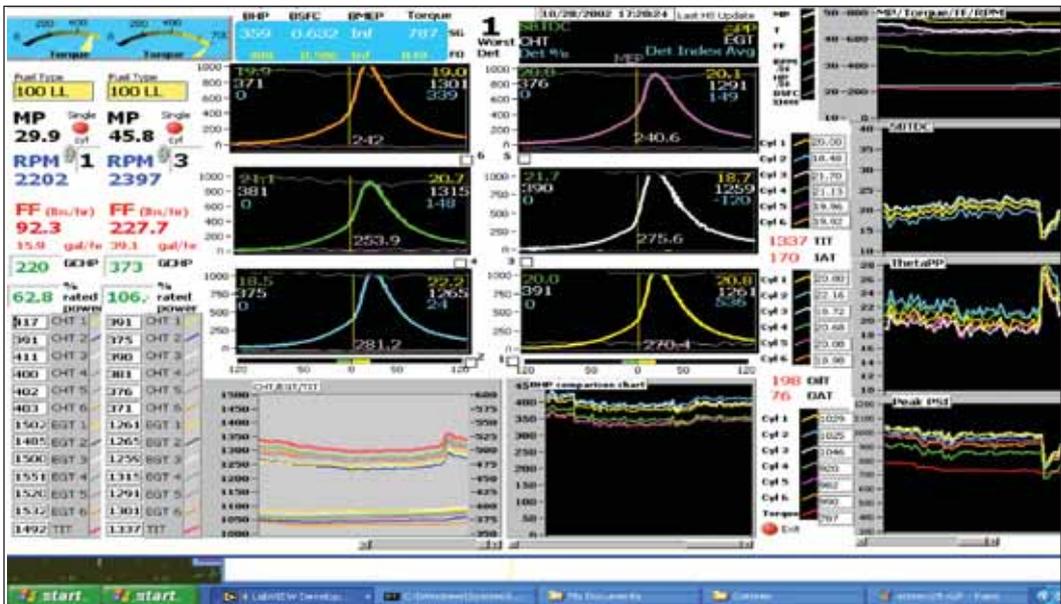


Figure 4:
Showing engine producing 359 bhp at 2397 RPM, 45.8 inches MP, and full rich mixture



Attachment E: ATSB explanation of engine overboost and operation of the turbocharger control system

There was considerable discussion during the course of the VH-MZK inquest regarding engine overboost and how it relates to the ATSB position in terms of aircraft performance and the damage to the right engine.

Definition of overboost

Overboost is defined as the operation of an engine at a manifold pressure higher than appropriate for the rotational speed of the engine.

The turbocharger control system

The Lycoming TIO-540-J turbocharger control system comprises three main components: the differential-pressure controller, the density controller, and the exhaust bypass valve assembly (wastegate).

Density controller

The density controller is designed to maintain the density of the air from the compressor at a level appropriate for full-power operation of the engine. The density controller is only active when the throttle is wide open. The density controller maintains density by controlling the position of the wastegate, which varies the amount of exhaust gas fed to the turbocharger turbine.

The density controller senses the *density* of the air between the compressor and the throttle valve.

Air density is determined by pressure and temperature. The density controller senses pressure using a diaphragm assembly, and temperature using a bellows which contains dry nitrogen. The density controller adjusts the wastegate by way of a metering valve which controls oil flow. When the preset maximum pressure (up to 46.5 inches manifold pressure at a compressor discharge temperature of 230 degrees F according to Lycoming Service Instruction 1187J) is reached, the metering valve opens, allowing oil to flow from the wastegate. The wastegate opens, which allows exhaust gas to bypass the turbocharger turbine. As the compressor discharge temperature increases, the air density between the compressor and the throttle valve decreases. Consequently, the density controller bellows expands, and the metering valve is adjusted to allow a higher manifold pressure so a constant air density can be maintained.

Differential-pressure controller

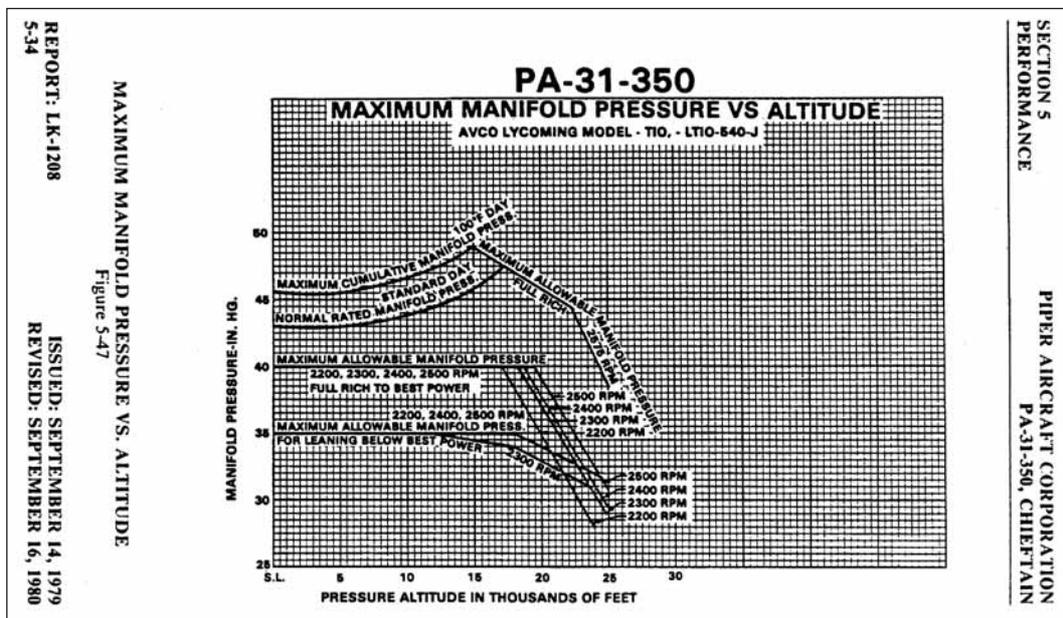
The differential-pressure controller operates at all throttle settings other than wide-open throttle. It senses the difference in pressure across the throttle valve and regulates the wastegate to control manifold pressure. The differential-pressure controller contains a diaphragm connected to an oil bleed valve. One side of the diaphragm senses air pressure before the throttle valve, and the other side of the diaphragm senses pressure after the throttle valve and before the cylinder inlet.

If the differential-pressure controller were not used, the density controller would attempt to position the exhaust bypass valve so that the air density at the injector entrance would always be that required for maximum power.

System operation

Although systems with controllers generally protect against overboost provided the engine is operated at normal combinations of RPM and manifold pressure (see fig 5-47 below), it is still possible to overboost a turbocharged engine. Any sudden straight-arming of the throttles, particularly on cold engines, can cause an overboost condition during which the manifold pressure could exceed the red line (49"). But overboost can also take place even though 49 inches manifold pressure has not been exceeded. This occurs during combinations of lower RPM and high manifold pressure. An example of this has been observed when the pilot has descended with a low RPM, then on final approach executed a go-around without first advancing the RPM. Thus he could be pulling maximum manifold pressure (to red line) at low RPM. This would produce a definite overboost condition, with resulting heavy detonation and undesirable compressor surge.

Figure 5-47: From the Piper POH (Report LK-1208)



As demonstrated in figure 5-47 above, the normal rated manifold pressure for the Lycoming TIO-540-J engine is 43 inches at sea level on a standard day with the engine operating at 2575 RPM and full rich mixture. The maximum manifold pressure allowed for engine operation at 2200, 2300, 2400 or 2500 RPM with mixtures between full rich and best power is 40 inches.

The engine would be overboosting if the manifold pressure was greater than 40 inches at 2200, 2300, 2400 or 2500 RPM even with a full rich mixture. It is significant that the chart shows the 40 inches manifold pressure limit as a straight line, indicating an artificial limit, as opposed to the line for normal rated manifold pressure that shows manifold pressure varying with altitude.

Lycoming Service Instruction No. 1187J, Table 1 specifies that a correctly maintained density controller for a TIO-540-J2B engine may be set to a maximum of 46.5 inches manifold pressure.

The TIO-540 series Lycoming Operator's Manual, figure 3-36 Sea Level and Altitude Performance – TIO-540-J,-N series – Sheet 1 of 3 chart includes data for operation up to

46 inches manifold pressure when the engine is operated at 2575 RPM. The chart indicates that at 2575 RPM, 46 inches manifold pressure is equivalent to 375 horsepower.

The TIO-540 series Lycoming Operator's Manual, figure 3-37 Sea Level and Altitude Performance – TIO-540-J,-N series - Sheet 2 of 3 chart includes data for operation up to 40 inches manifold pressure when the engine is operated at 2400 RPM. The chart suggests that Lycoming do not recommend operations at manifold pressures greater than 40 inches with a rotational speed of 2400 RPM.

A print out of engine test stand data provided by Mr Braly indicates that his TIO-540 engine was producing 357 brake horsepower (104 per cent rated power based on a gross corrected horsepower of 365) at 43.3 inches of manifold pressure and 2588 RPM (see Attachment D, fig 2). Mr Braly did not indicate that the engine was being overstressed when operated at this configuration and power setting.

Mr Braly supplied the Coroner with data from a Piper Chieftain test flight. Photographs of the instrument panel indicate that the aircraft was travelling at 148 kts true airspeed with one engine inoperative and the operative engine set to 2400 RPM and 40 inches manifold pressure. Despite the lighter weight and performance enhancements of Mr Braly's aircraft compared with MZK, the speed attained by his aircraft indicates the Piper and Lycoming documentation is conservative.

Normal rated power for the TIO-540-J2B engine is 350 horsepower at 43 inches manifold pressure and 2575 RPM. However, it is clear from Mr Braly's demonstration that increases in manifold pressure, RPM and a mixture set at best power will all result in the engine outputting greater than rated power. It is also clear that the manifold pressure is not physically limited to 40 inches if the engine RPM is lower than 2575. Because the propeller is more efficient at 2400 RPM, manifold pressure settings above 40 inches can produce sufficient horsepower to propel the aircraft to true airspeeds greater than the maximum proposed by Piper.

As indicated in a Lycoming Flyer article, an aircraft engine may be overboosting when operating at low RPM and high manifold pressure, which will lead to heavy detonation and engine overheating, of which a melted piston is one of the well documented results.

Proper functioning of the turbocharger control system depends on three main factors:

- Proper adjustment of the system by maintenance personnel,
- Normal functioning of the system during flight, and
- Proper operation of the engine by the pilot.

Maintenance adjustment for MZK

Evidence during the inquest by the Maintenance Controller for Whyalla Airlines indicated that the density controller was properly adjusted. Records indicate that maintenance action was carried out on the turbocharger density controller, but no record was made of the actual compressor discharge temperatures obtained, the adjustments made, the environmental conditions prevalent, or the maximum manifold pressure set.

The density controller can be adjusted, but it must be done under controlled conditions with ample stabilisation time. Since this unit regulates wide-open-throttle manifold pressure only, adjustments should not be made to correct any part-throttle discrepancies. The controller should be adjusted by authorised personnel and must be adjusted to the curve found in the engine operation manual (Kroes et al, p 99).

The TIO-540-J series turbocharger density controller is a sensitive device and is required to be set on a newly installed engine and at 125 hourly intervals (AD/LYC/95).

‘Accuracy of the manifold pressure [gauge] should be established prior to any readjustment of the density controller’ (SI 1187J p1). ‘Turning the adjustment screw 1/16 turn will change the manifold pressure approximately 2 inches; therefore care must be exercised to turn the screw in very small increments until the correct adjustment is obtained.’ ‘On LTIO/TIO-540-J2B engines, the adjustment is made in the same manner except a cover plug is not incorporated with the density controller; simply remove the lockwire from the adjusting fitting, and by means of a small wrench, turn the square head of the fitting clockwise or counter clockwise to accomplish the adjustment. Be very careful when reinstalling safety wire to avoid turning the adjusting fitting’ (SI 1187J p6).

System functioning during flight

Since the wastegate contains O-rings, seals, springs and a piston there is a certain amount of friction which may result in slightly different valve positions for the same oil pressure, dependent on whether the pressure is increasing or decreasing at the time the setting was made (Kroes et al, p 99). A wastegate position that differs from that selected may result in a manifold pressure higher or lower than selected. Any mechanical system can malfunction. Confirmation that the turbocharger systems in the MZK engines were functioning normally was prevented by saltwater corrosion damage. However, there was no evidence that the turbocharger system on either engine was not functioning correctly.

Engine operation by the pilot

The engine manufacturer issues operating instructions that set out engine operating procedures and limitations. These limitations are incorporated into aircraft manufacturer’s Pilot Operating Handbooks that are applicable to an engine installation in a particular aircraft. Changes in aircraft design or in-service operational experience may lead to changes in Pilot Operating Handbook procedures over time. Significant changes may require a new version of a POH for particular models of an aircraft type.

One of the purposes of these instructions is to ensure engine reliability by preventing damage that could result if limitations were exceeded. The correct relationship between the mixture, propeller, and throttle controls must be maintained to avoid possible damage. It is clear that the engine controls can be manipulated to obtain a manifold pressure greater than 40 inches at 2400 RPM. Such settings take advantage of greater propeller efficiency at the lower RPM, but run the risk of detonation and engine damage.

Other than propeller RPM information from the recorded audio data, the aircraft performance information as recorded by radar, and the damaged engines themselves, there is no further information available regarding the operation of the engines during the flight.

References

Aircraft Powerplants, Kroes, Wild, Bent, McKinley, 6th edition.

Textron Lycoming Service Instruction 1187J

Textron Lycoming Flyer Key Reprints. The Pilot and Turbocharging

Piper Aircraft Corporation Pilot Operating Handbook LK-1208 Piper PA-31-350 Chieftain 14 September 1979.

Textron Lycoming TIO-540 series Operator’s Manual

Civil Aviation Safety Authority Airworthiness Directive AD/LYC/95 Turbocharger Density Controller Adjustment. 2 February 1995.

Attachment F: Explanation of maximum single-engine speed achievable by VH-MZK

A detailed explanation of the ATSB position regarding the maximum single engine speed achievable by MZK follows.

The definitions for terms used in the explanation are as follows:

- Indicated airspeed – speed indicated on the cockpit airspeed indicator.
- Calibrated airspeed – indicated airspeed corrected for airspeed indicator system errors.
- True airspeed – calibrated airspeed corrected for pressure and temperature.
- Groundspeed – speed across the ground, true airspeed adjusted for wind, speed derived from radar data.

Factors affecting true airspeed

Aircraft true airspeed is dependent primarily on thrust and drag. Increase thrust and aircraft speed will increase, similarly reduce thrust and aircraft speed will reduce. Likewise reduce drag and aircraft speed will increase, and increase drag and aircraft speed will reduce. Some of the factors affecting thrust and drag are listed as follows:

Aircraft

- Drag increases as aircraft weight increases.
- An aircraft with cowl flaps closed has less drag than the same aircraft with cowl flaps open.
- An aircraft with flaps retracted has less drag than the same aircraft with flaps extended.
- An aircraft fitted with vortex generators has less drag at lower speeds than the same aircraft without vortex generators. Similarly an aircraft fitted with vortex generators has more drag at higher speeds than the same aircraft without vortex generators.
- An aircraft with landing gear retracted has less drag than the same aircraft with landing gear extended.
- A clean aircraft has less drag than a dirty aircraft.
- An aircraft with a paint job in excellent condition has less drag than the same aircraft with a paint job in poor condition.
- An aircraft in balanced flight has less drag than an aircraft in unbalanced flight.

Environment

- Temperatures above international standard atmospheric (ISA) temperature decrease air density and consequently decrease drag but reduce propeller efficiency and therefore reduce thrust. Temperatures below ISA temperature increase air density and consequently increase drag but increase propeller efficiency and therefore increase thrust.

Propeller

- At normal operational RPM, a lower propeller rotation speed increases propeller efficiency and therefore increases thrust for a given level of input horsepower. Similarly, a high propeller rotation speed reduces propeller efficiency and therefore decreases thrust for a given level of input horsepower.
- Propeller blades in good condition will deliver more thrust per input horsepower than propeller blades in poor condition.

Engine

- An increase in manifold pressure results in an increase in engine horsepower which results in an increase in thrust. Conversely, a decrease in manifold pressure results in a decrease in horsepower.
- An increase in engine RPM results in an increase in engine horsepower.
- An EGT of about 125°F rich of peak corresponds to the fuel/air mixture setting for 'best power'. Adjustment of the mixture away from this setting will result in less engine power. A full rich mixture setting is richer than the best power setting.

Groundspeed recorded by radar

ATSB analysis of radar data indicated that the groundspeed of MZK between 1847:15 and top of descent averaged 167 kts. The fluctuations in the groundspeed between 1837 and 1847 were influenced by poor data from one of the two radar sensors tracking the aircraft. However, the good data also shows fluctuations in groundspeed during this period, which contrast with the groundspeed data from other Chieftain aircraft operating on the same and similar routes in the periods shortly before, and after, the accident flight. If the general variation and reduction in groundspeed were related to radar tracking limitations, similar variations would have been expected on the radar data for these other aircraft.

One of the radar sensors provided intermittent data during this period. Continuous data from the other radar sensor showed the groundspeed to have been steady at around 167 kts.

Wind strength

A tailwind component increases aircraft groundspeed while a headwind component decreases aircraft groundspeed.

The ATSB asked the Bureau of Meteorology (BoM) to provide a report on the weather conditions that existed on the night of the accident. Their initial advice indicated that the wind on the night at 6,000 ft was a direct tailwind of 20 kts, indicating that between 1847:15 and top of descent, MZK maintained an average true airspeed of 147 kts.

Later, more detailed advice from the BoM after the publication of ATSB Report 200002157 indicated the wind was stable at 15–20 kts from between 150 and 170 degrees.

The ATSB draft report assumed a tailwind wind strength of 13 kts. However, this was not sourced from the BoM. One of the pilots involved in the search reported that the wind below the cloudbase (approximately 4,200 ft) was up to 10 knots. The BoM stated that a temperature inversion existed at about 4,000 ft, and therefore the winds below 4,000 ft were likely to have been different from those at 6,000 ft.

It is not possible to determine precisely what the wind speed and direction was on the night of the accident. However, the BoM estimate of 15 to 20 knots from between 150 and 170 degrees at 6,000 ft is the best available. ATSB analysis of the radar data of the accident flight and other flights on the night of the accident by MZK and other Chieftain aircraft on similar routes supported the BoM's assessment of the wind speed and direction.

Aircraft performance

Piper, the aircraft manufacturer, provided the ATSB with an aerodynamic performance graph (a drag polar) which indicated that on one engine, a Chieftain aircraft at 6,000 ft required 312 thrust horsepower to achieve 147 kts true airspeed. Engine brake horsepower is calculated by dividing thrust horsepower by propeller efficiency. Propeller efficiency data also provided by Piper indicated that for the propeller to produce 312 thrust horsepower, the engine must provide 375 brake horsepower. As highlighted in ATSB Report 200002157, the Lycoming Operators Manual for the engine indicated that 2575 RPM and 46 inches manifold pressure would provide about 375 brake horsepower. By comparison, to achieve 312 thrust horsepower at 2400 RPM, because of higher propeller efficiency at that RPM, only 359 brake horsepower engine output is required.

The thrust horsepower required to achieve 147 kts true airspeed would be less if the aircraft configuration resulted in less drag, for example, if the cowl flap on the operating engine was closed.

Maximum engine power

Normal rated maximum power for the Piper Chieftain engine is 350 brake horsepower at 43 inches manifold pressure and 2575 RPM.

During the inquest, the coroner observed a TIO-540-J series engine in an engine test facility producing 357 brake horsepower (104 per cent rated power based on a gross corrected horsepower of 365) at 43.3" manifold pressure and 2588 RPM (see Attachment D, fig 3). There was no indication from the test facility operator, Mr Braly, that the engine was being overstressed when operated in this configuration and power setting. Clearly, an engine can output greater than rated power. Further increase is possible if the mixture is adjusted from full rich to the 'best power' position. However, setting the mixture at the best power position while the engine is operating at maximum manifold pressure and RPM will establish the conditions for detonation and result in significant damage to the engine.

The Coroner also observed the engine producing 359 brake horsepower (106 per cent rated power based on a gross corrected horsepower of 373) at 2397 RPM, 45.8 inches manifold pressure (see Attachment D, fig 4).

The ATSB position is that, after the left engine failed at about 1847, the pilot responded by increasing the power setting on the right engine. No data or other information was available regarding which engine controls the pilot manipulated, or the positions that he placed them in. However, the nature of damage to the right engine indicated that it had experienced severe detonation, implying operation at high power. It was while the right engine was being operated at high power that it overheated, resulting in the damage to the No. 6 piston and the inability of the engine to produce sufficient power for the aircraft to maintain a normal rate of descent.

It is impossible to establish with absolute certainty the maximum single engine true airspeed that was achievable without operating an engine outside the normal limits and

running significant risk of engine damage/destruction. Clearly, that option was not practicable. The realistic option was to utilise the engine and aircraft performance data provided by Textron Lycoming and Piper. The ATSB position was based on that information which clearly indicated that 147 kts true airspeed was achievable by the aircraft on one engine (ATSB Report 200002157, p 18). In fact, the data indicated that the achievable speed may be greater than 152 kts.

Operation at 2400 RPM

The ATSB's analysis of the recorded audio information identified 2200 propeller RPM at 1833:54 (shortly after top of climb) and 2400 RPM at 1855:43 (shortly before top of descent). Those readings were instantaneous 'snapshots' at those specific times. There is no information available regarding the RPM at other times. 2400 RPM was not a normal setting for the cruise or descent phases of the flight. It is not possible to state when 2400 RPM was selected by the pilot, other than it was at some time after initially setting the normal cruise setting as identified at 1833:54. There was no information regarding the other engine control settings.

The propeller is more efficient at 2400 RPM than 2575 RPM, even though the engine is capable of greater brake horsepower output at the higher RPM. For example, according to data provided by Piper, the propeller efficiency at 6,000 ft, 147 kts TAS, and 2400 RPM is 1.5 percent greater than at 2575 RPM at the same speed and altitude. The engine manufacturer does not provide engine power output data for manifold pressures greater than 40" at rotational speeds equal to or less than 2500 RPM, even though the manifold pressure can be increased beyond 40 inches at less than 2500 RPM. There is a high risk of detonation at manifold settings above 40 inches with the rotational speed less than 2575 RPM.

Engine power output

The rated maximum power output of the Lycoming L/TIO-540-J2B engine is 350 brake horsepower. However, as shown in Attachments E and D, it is possible for the engine to produce greater than rated output when operated at certain combinations of manifold pressure, RPM and mixture, and depending on whether maintenance adjustments to the engine were at the high or low end of the allowable tolerances.

