Inquiry 11-203: passenger ferry *Jet Raider*,
catastrophic engine failure, Hauraki Gulf, 27 August 2011

Final Report

Marine inquiry 11-203
passenger ferry *Jet Raider*, catastrophic engine failure,
Hauraki Gulf, 27 August 2011

Approved for publication: December 2013

Transport Accident Investigation Commission

About the Transport Accident Investigation Commission

The Transport Accident Investigation Commission (Commission) is an independent Crown entity responsible for inquiring into maritime, aviation and rail accidents and incidents for New Zealand, and co-ordinating and co-operating with other accident investigation organisations overseas. The principal purpose of its inquiries is to determine the circumstances and causes of occurrences with a view to avoiding similar occurrences in the future. Its purpose is not to ascribe blame to any person or agency or to pursue (or to assist an agency to pursue) criminal, civil or regulatory action against a person or agency. The Commission carries out its purpose by informing members of the transport sector, both domestically and internationally, of the lessons that can be learnt from transport accidents and incidents.

Commissioners

Chief Commissioner	John Marshall, QC
Deputy Chief Commissioner	Helen Cull, QC
Commissioner	Howard Broad, CNZM

Key Commission personnel

Chief Executive	Lois Hutchinson
Chief Investigator of Accidents	Captain Tim Burfoot
Investigator in Charge	Captain Iain Hill

Email	inquiries@taic.org.nz
Web	www.taic.org.nz
Telephone	+ 64 4 473 3112 (24 hrs) or 0800 188 926
Fax	+ 64 4 499 1510
Address	Level 16, 80 The Terrace, PO Box 10 323, Wellington 6143, New Zealand

Important notes

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Information derived from interviews during the Commission's inquiry into the occurrence is not cited in this final report. Documents that would normally be accessible to industry participants only and not discoverable under the Official Information Act 1980 have been referenced as footnotes only. Other documents referred to during the Commission's inquiry that are publicly available are cited.

Photographs, diagrams, pictures

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Jet Raider August 2011

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Abbreviations

CO_2	carbon dioxide
Commission	Transport Accident Investigation Commission
Fullers	Fullers Group Limited

Data summary

Vessel particulars

Name:	*Jet Raider*
Type:	Restricted Limit Passenger
Limits:	inshore: Auckland, Barrier enclosed: all areas within the above limits
Classification:	New Zealand Safe Ship Management
Length:	37.0 metres
Breadth:	7.5 metres
Depth (minimum moulded):	1.8 metres
Built:	1991 by Wavemaster International Proprietary Limited, in Henderson, Western Australia
Propulsion:	2 MWM Deutz TBD 604B V12 turbo-charged, intercooled, 4-stroke diesel engines producing 1260 kilowatts at 1800 revolutions per minute, each driving a KaMeWa 56S water jet unit with steering, forward and reverse thrust through a ZF BU 465 non-reversing reduction gearbox
Service speed:	21 knots
Owner: Operator:	Souter Holdings Limited Fullers Group Limited
Port of registry:	Auckland
Minimum crew:	between 2 and 6 dependent on passenger loadings

Date and time	27 August 2011 at about 1130[1]
Location	Hauraki Gulf
Persons involved	crew – 5 passengers – 316
Injuries	nil
Damage	starboard engine constructive total loss

[1] Times in this report are in New Zealand standard time (co-ordinated universal time +12 hours) and are expressed in the 24-hour mode.

1. Executive summary

1.1. On 27 August 2011 the *Jet Raider* was making a trip from Auckland to Waiheke Island in the Hauraki Gulf with 5 crew and 316 passengers on board. At about 11:20 the starboard engine failed catastrophically when 2 engine connecting rods broke free of the crankshaft and were ejected through the engine casing.

1.2. The escaping mixture of fuel and exhaust gases, and possibly steam resulting from damage to the cooling water system, set off the fire alarms and gave the crew the appearance on the closed-circuit television that a fire had occurred. The crew shut down the engines, sealed the engine compartment and released the fixed engine room carbon dioxide (CO_2) fire-suppression system. Meanwhile the skipper raised the alarm and anchored the ferry in the Motuihe Channel.

1.3. The passengers were transferred to another company ferry that had been following close behind. Nobody was injured, but the starboard engine was a total constructive loss.

1.4. The investigation found that no fire had occurred, but a momentary flash-off caused by the ignition of a vaporised fuel and exhaust gas mixture from the damaged engine might have occurred.

1.5. The engine failure was caused by the overload failure of the bolts clamping the big ends of number 4 connecting rods to the crankshaft. Owing to the damage sustained to engine components it was not possible to determine what initiated the sequence of engine component failures. A number of possibilities are discussed.

1.6. There was no evidence of poor maintenance procedures contributing to the catastrophic engine failure. However, the *Jet Raider* was being used as a standby vessel to support the main passenger fleet. Consequently it had a low annual number of operating hours. The engine manufacturer had recommended a shorter interval between replacements of some engine components for this type of operation. Fullers Group Limited (Fullers) was not following that recommendation, but it could not be determined whether that contributed to this failure because the engine manufacturer could not explain the rationale behind its recommendation.

1.7. Two safety issues were identified:

- transferring passengers to another vessel as a form of abandoning ship was the usual method employed by ferry operators in the Hauraki Gulf because of the high probability of another passenger vessel being in the vicinity. However, this method was not considered during emergency response training, and no thought had been given to small modifications in ferry design that could reduce the risk to passengers during such an event

- when the fixed engine room CO_2 fire-suppression system was used, only half of the required CO_2 gas was released to the engine room. Part of the reason was a lack of clear placarding to highlight the differences in procedures between mono-hull ferries with single engine rooms and catamaran-style ferries with split engine rooms.

1.8. Neither of these safety issues affected the outcome of this accident, but recommendations have been made to prevent their affecting outcomes under different circumstances in future.

1.9. Key lessons that can be taken from this inquiry are:

- training for emergency responses must cover the procedures for using mandatory lifesaving equipment, but should also be extended to cover other common scenarios, such as using a ship-to-ship transfer of passengers when abandoning ship

- instruction placards for critical systems such as fixed engine room CO_2 fire-suppression systems should be clear and concise to avoid operators misinterpreting them at times of high or stressful workload.

2. Conduct of the inquiry

2.1. On 27 August 2011 at about 1210, the Transport Accident Investigation Commission (Commission) learnt from Maritime New Zealand that an accident had occurred earlier that day to the passenger ferry *Jet Raider* as it was on passage from Auckland to Waiheke Island with 316 persons on board.

2.2. The circumstances were that the vessel experienced what was thought to have been an engine room fire in the vicinity of the starboard engine. After initial inspection the engine room was shut down and the fire suppression system activated. The passengers were transferred to other passenger ferries in the vicinity. Fire service personnel were taken out to the *Jet Raider* but any fire had been extinguished. The *Jet Raider* was towed back to Auckland.

2.3. The Commission immediately opened an inquiry into the occurrence under section 13(1) of the Transport Accident Investigation Commission Act 1990, and appointed an investigator in charge.

2.4. On 27 August 2011 an investigator from the Commission travelled from Wellington to Auckland. On arrival the investigator was briefed by staff from the operating company and conducted an inspection of the engine room.

2.5. During the next 2 days the investigator interviewed witnesses who had been involved in the events leading up to the accident and others involved in the operation and maintenance of the vessel. Relevant data was also sourced from the operating company's documentation.

2.6. The investigator returned to Auckland on 13 September and 19 September to be present for the engine strip-down and to gather further evidence and discuss the engine failure.

2.7. The Commission engaged the New Zealand Defence Technology Agency to establish the nature of the engine failure.

2.8. On 24 October 2013 the Commission approved a draft final report to be circulated to interested persons for comment.

2.9. Submissions on the draft final report were received from 6 interested persons. On 17 December 2013 the Commission reviewed all the submissions, and changes to the draft final report were made where appropriate.

2.10. The Commission approved the final report for publication on 17 December 2013.

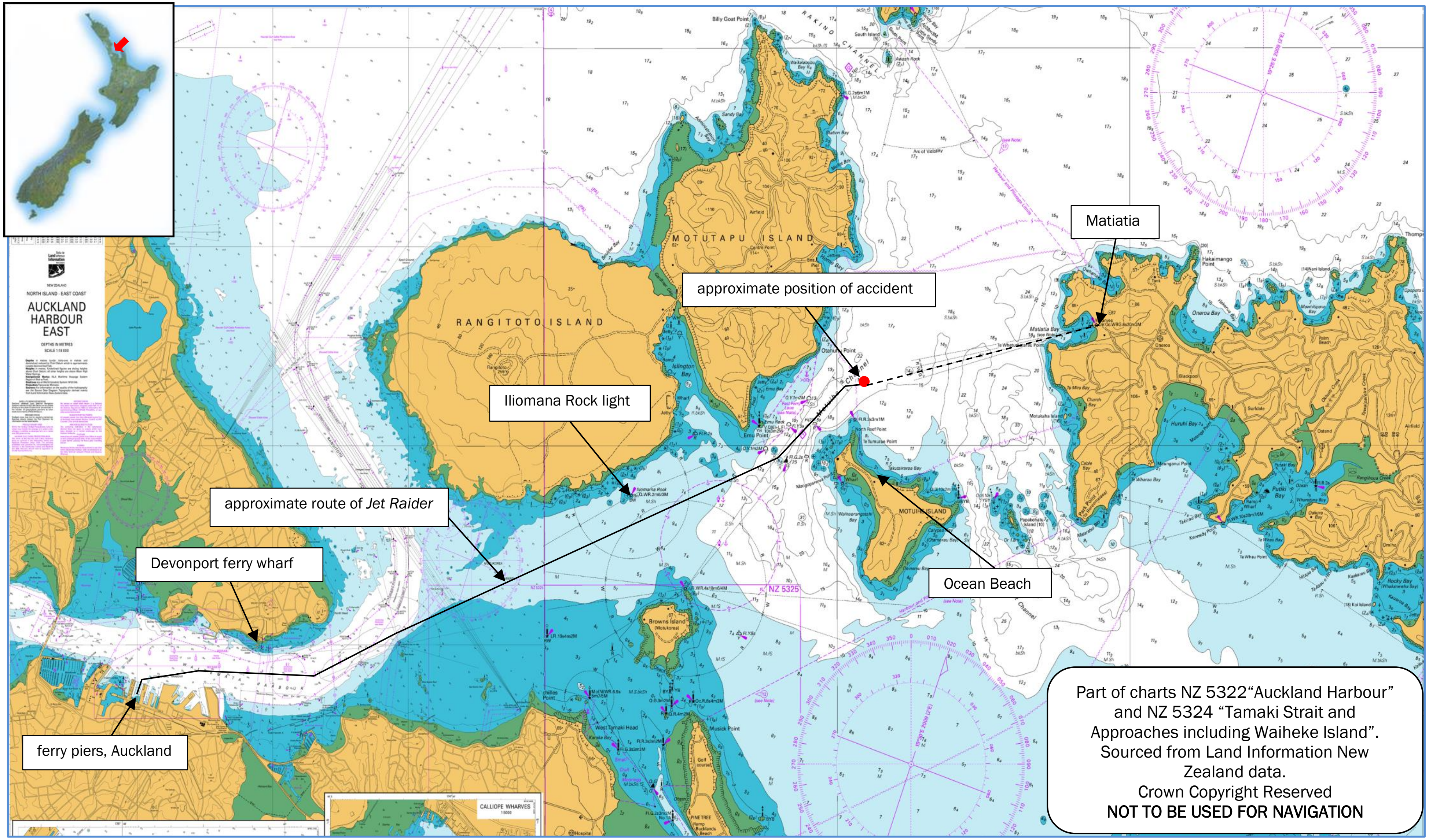

Figure 1
Chart of the general area showing the *Jet Raider*'s route

3. Factual information

3.1. Narrative

3.1.1. At about 07:30 on 27 August 2011, the *Jet Raider* was tied up alongside Queens Wharf in Auckland. The master, engineer and services crew prepared the vessel and moved it to berth 2D to embark passengers. At about 09:00 the *Jet Raider* sailed for a return trip to Waiheke Island. The trip was uneventful, and all engine checks were recorded as normal.

3.1.2. Back at Auckland the crew began embarking passengers and loading cargo for another return trip to Waiheke Island.

3.1.3. The *Jet Raider* departed Auckland on schedule at about 11:00 with 316 passengers on board. At about 11:20, as the vessel passed Iliomana Rock Light, the engineer went to the engine room to check the equipment and operating parameters of the engines; all was again noted as being "normal". The engineer then returned to the navigating bridge to assist in keeping a lookout. The engineer had just sat down when there was a loud bang and the vessel shuddered. Engine room alarms started sounding.

3.1.4. The engineer looked at the engine room closed-circuit television monitor and he saw what looked like a ball of fire and smoke emitting from the starboard engine. The master also looked at the closed-circuit television monitor. He then reduced the power on both engines to idle.

3.1.5. The engineer then made his way to the engine room, but when he reached the lower middle cabin he saw that the after deck was full of smoke. He returned to the navigating bridge and started to go through the emergency shut-down procedures for the starboard engine. The skipper shut down the engine while the engineer proceeded to the lower middle cabin. From there he released the starboard fire dampers and operated the fuel tank emergency shut-off valves. He and the services supervisor then went to the controls for the fixed fire-fighting gas suppression system at the stern of the after deck.

3.1.6. The master made an announcement to the passengers. He then contacted the Fullers ferry *Starflyte* that was following close behind the *Jet Raider* and requested it to stand by in case a passenger evacuation was necessary. The two café hands proceeded to the foredeck to let go the anchor.

3.1.7. The engineer fired the starboard fixed fire-fighting gas suppression system[2] into the engine room. By this time the *Starflyte* had manoeuvred alongside the *Jet Raider's* port side gate aft.

3.1.8. By now the vessel was anchored and the engine room sealed off, with one of the 2 engine room fire-suppression systems activated to smother any fire. The master decided to transfer the passengers and cargo to the *Starflyte.*

3.1.9. The engineer and the services supervisor made fast the *Starflyte* to the port side of the *Jet Raider*; one of the café hands remained on the forecastle to monitor the anchor; and the second café hand started to guide the passengers towards the stern of the vessel ready for evacuation. The passengers, their luggage and the cargo were then transferred across to the *Starflyte*.

3.1.10. At 11:44 the master notified Auckland Maritime Radio of the situation, declaring that at that time he did not require any assistance. He also contacted the Royal New Zealand Coastguard, the New Zealand Police and the New Zealand Fire Service. He then contacted the Fullers duty manager to advise them that tug assistance would be required to return to Auckland.

3.1.11. One of the New Zealand Police maritime launches ferried Fire Service personnel to the *Jet Raider*. They confirmed that any fire had been extinguished, after which the crew ventilated the engine room while waiting for the tug to tow the vessel back to Auckland ferry terminal.

[2] There were 2 systems, labelled port and starboard.

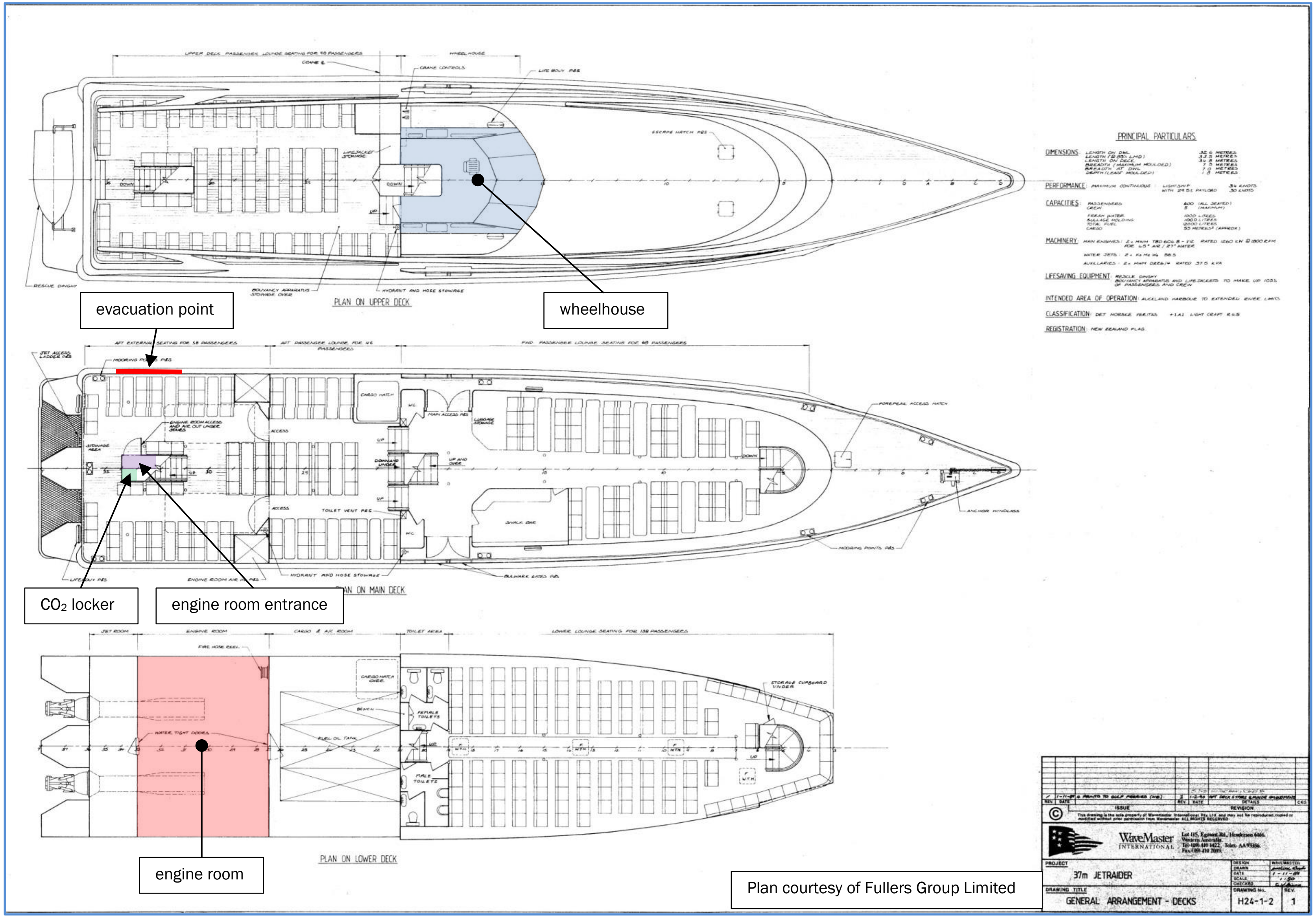

Figure 2
Plan layout of the *Jet Raider*

3.2. Vessel information and post-accident inspection

3.2.1. The *Jet Raider* was a mono-hulled ferry built in 1991 by Wavemaster International Proprietary Limited, of Henderson, Western Australia. It had an overall length of 37.0 metres, a breadth of 7.5 metres and a gross tonnage of 227.

3.2.2. The *Jet Raider* was owned by Souter Holdings Limited and operated by Fullers. It was certificated to carry 360 passengers in the enclosed and inshore water limits. It required between 2 and 5 crew, dependent on passenger loadings. The *Jet Raider* was operated under safe ship management administered by Dunsford Marine Limited. The safe ship management certificate had been issued on 14 June 2010 and was valid, subject to periodic audits and inspections, until 30 May 2014.

3.2.3. Propulsion was provided by 2 MWM Deutz TBD 604B V12 turbo-charged diesel engines, each producing a power of 1260 kilowatts at 1800 revolutions per minute. Each engine drove a KaMeWa 56S water-jet unit through a ZF BU 465 non-reversing gearbox.

3.2.4. The fuel, lubricating oil and cooling water pumps were directly connected through gearing to the MWM Deutz TBD 604B V12 engine. The speed and flow rate of these pumps were directly dependent on the speed at which the engine was operating.

3.2.5. The *Jet Raider* was not in daily service with Fullers at the time but was used more as a replacement vessel for the rest of the fleet, or when extra capacity was needed. As such its running hours were less than those of the other vessels within the fleet.

3.2.6. The initial inspection of the engine room revealed no evidence of fire. Instead the starboard engine was found to have suffered a catastrophic failure. One of the starboard engine's crankcase covers had blown off and was punctured. A connecting rod[3] was found on the engine room floor plates with other engine debris. The oil filler cap for the starboard engine was missing. A freshwater cooling pipe had been severed and damage was noted on other nearby equipment.

3.2.7. An inspection into the crankcase of the engine through the missing door showed that at least 2 connecting rods and their associated balance weights were missing and damage had occurred to the crankshaft journal[4] to which the connecting rods had been connected.

3.2.8. The starboard engine was removed from the *Jet Raider* and transported to Fullers' maintenance facility for further investigation and dismantling. When the engine was removed from the vessel it was found that one of the missing connecting rods had exited the crankcase through the bottom of the engine sump. The connecting rod had struck the vessel's hull and one of the hull frames. The hull was gouged and the frame bent. The weld securing the hull to the frame was fractured (see Figure 3).

3.2.9. The starboard engine was dismantled and the following components were removed and sent to the Defence Technology Agency for inspection and testing:

- 2 connecting rods from the number 4 cylinder set
- parts of the associated connecting rod bolts
- bearing caps and bearing shells.

3.2.10. The Commission engaged the Defence Technology Agency to produce a report into the failure (see Appendix 2 for the full report).

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[3] The main rod connecting each piston to the crankshaft.

[4] The offset cylindrical section of the crankshaft, to which the connecting rods were attached by the big-end bearing assembly.

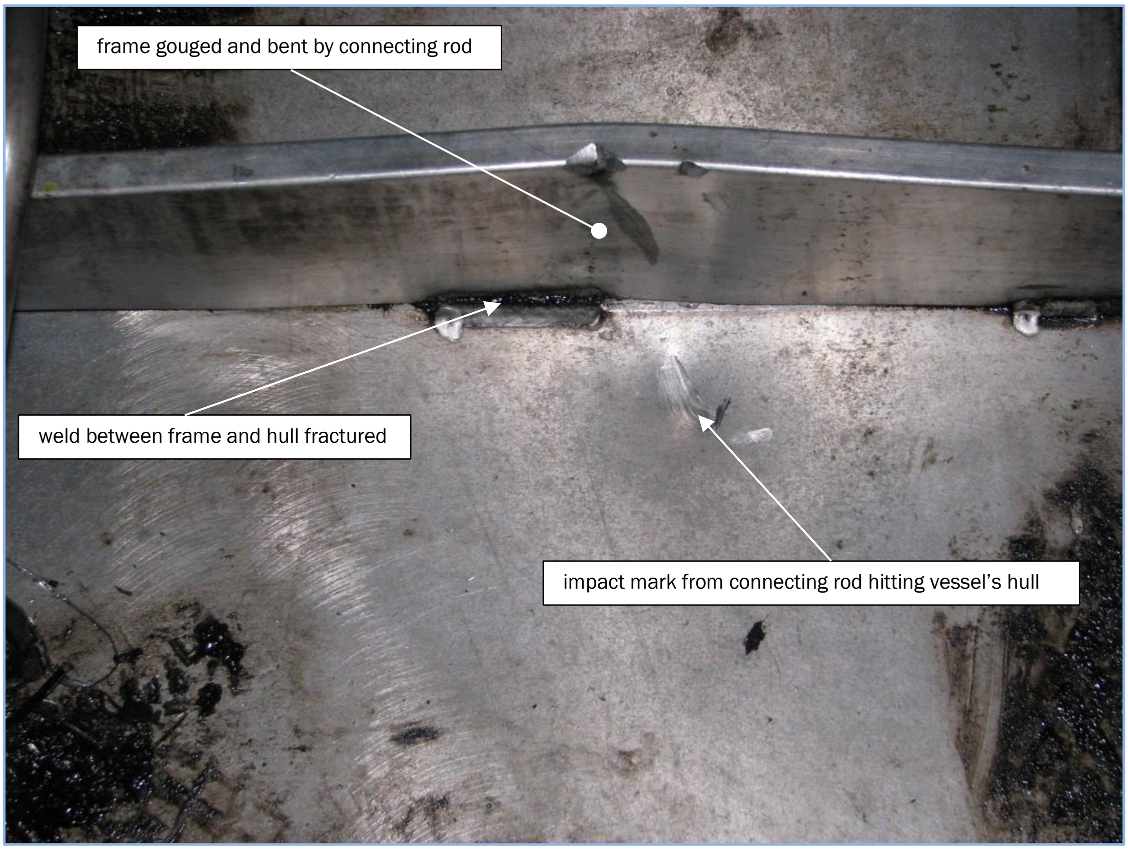

Figure 3
Damage caused to hull and frame by connecting rod exiting through engine sump

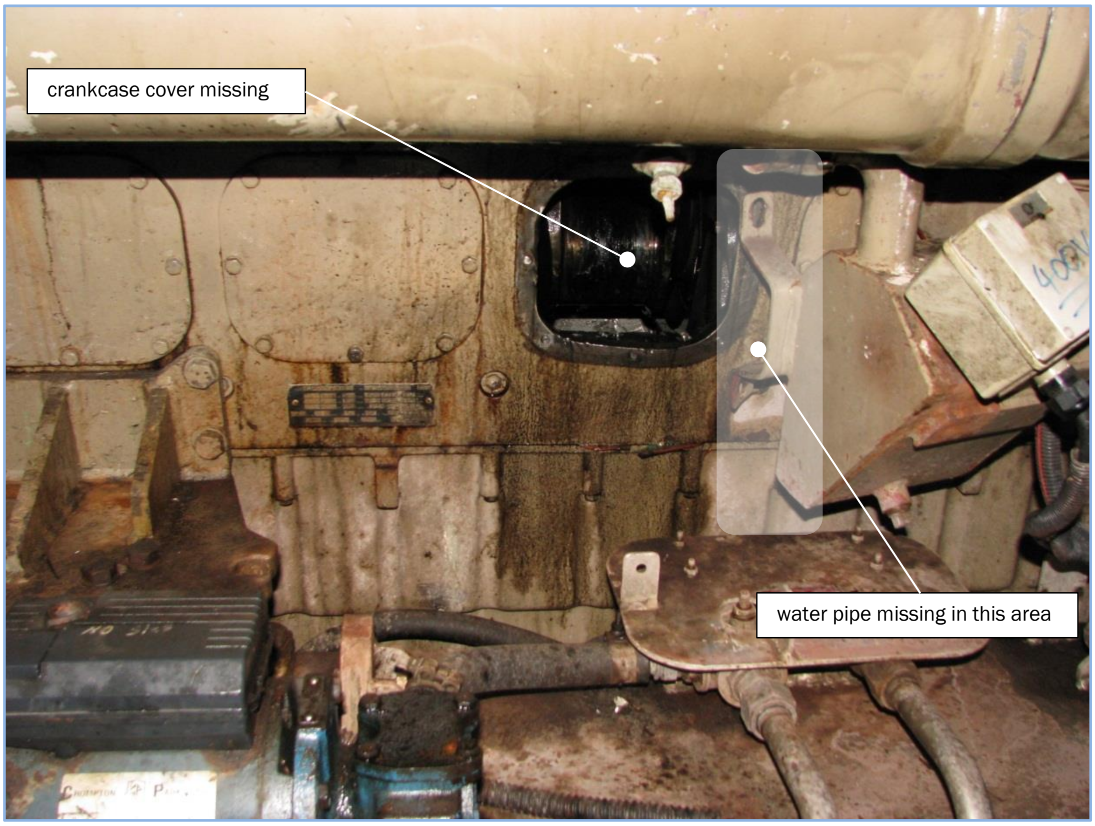

Figure 4
Starboard engine showing missing crankcase cover

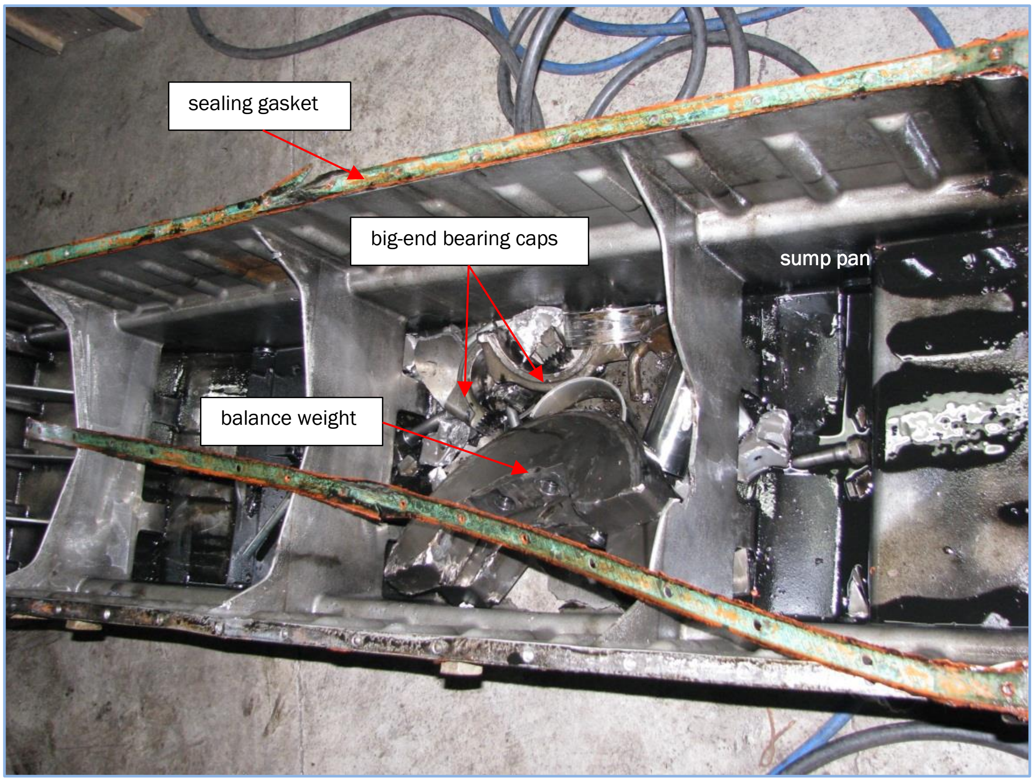

Figure 5
Engine debris found in sump after lifting main engine block away

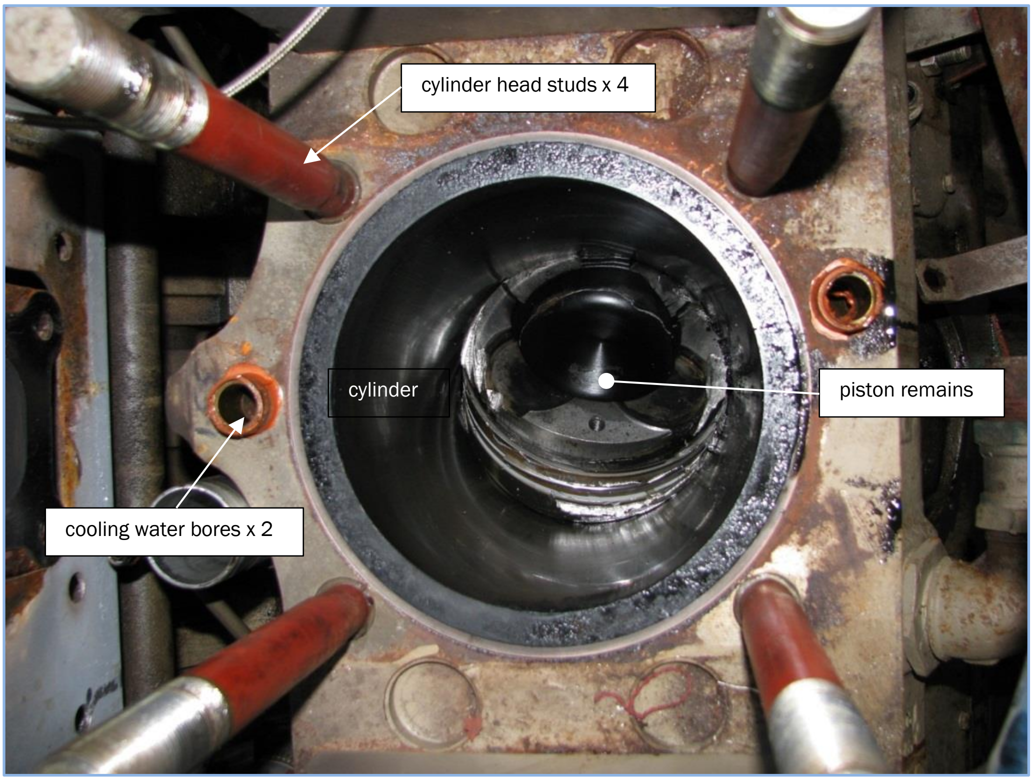

Figure 6
Remains of piston in number 4 cylinder, bank "A"

3.3. Personnel information

3.3.1. The master had been employed by Fullers for about 20 years, initially in a part-time role but after about 3 years he became a full-time employee. At the time of the incident he worked on a part-time contract as and when required. He had driven most of the vessels in the Fullers fleet he currently met the company's competency requirements on the *Quickcat*, *Superflyte* and *Jet Raider*.

3.3.2. The engineer had been employed by Fullers since 1999. He held an Inshore Launch Master's certificate of competency and a Marine Engineer's Certificate of competency class 5. The engineer had been taken off his normal shift to cover the *Jet Raider* sailings on 27 August.

3.3.3. The services supervisor had been employed by Fullers for about 5 years. During her employment with Fullers the services supervisor had held various positions on board the vessels. She currently met the company's competency requirements on the *Quickcat*, *Superflyte* and *Jet Raider*.

3.3.4. Both café hands had been recently employed by Fullers and had completed its basic induction and training regime.

3.4. On-board practices

3.4.1. The crew on board the *Jet Raider* were all appropriately trained and their qualifications were current. The master and crew had been trained to a level commensurate with their positions on board, with the more senior staff being more highly trained. New crew entrants underwent induction training as contained in the Crew Induction Training Manual[5].

3.4.2. Induction training for new entrants included, but was not limited to: vessel safe ship management systems, lookout duties, lifesaving appliances' positions and use, fire-fighting appliances' position and use, and emergency drills. Emergency drills included a fire drill, anchoring drill, man-overboard drill, abandon-ship drill and evacuation and crowd control.

3.4.3. The *Jet Raider*'s safety plan allotted certain jobs to the crew during emergencies; Table 1 shows the allotted jobs for both fire and abandon-ship emergencies.

3.4.4. The abandon-ship drill required the crew to prepare the vessel's lifesaving appliances and launch them on the instruction of the master (see Appendix 1), then to abandon the vessel, into the water, on the master's instruction.

Table 1: Allotted duties as per the *Jet Raider*'s safety plan

Crew member	Fire	Abandon ship
Master	In command	In command
Engineer	Assess situation and use appropriate extinguishers	Don own lifejacket. Prepare floating apparatus on cabin top
Service supervisor	Assist engineer as required	Don own lifejacket. Prepare floating apparatus on cabin top
On-board services (café) crew 1	Notify master of situation and relay messages	Don own lifejacket. Assist in lowering rescue boat. Aid passengers donning lifejackets. Direct them to the stern of the vessel
On-board services (café) crew 2	Assist and calm passengers	Don own lifejacket. Check all toilets. Assist passengers with lifejackets

[5] Fullers Group Limited, Operations Manual, part 7, Crew Induction Training Manual.

3.4.5. Fullers' Emergency Response Plan[6] stated in paragraph 2.7, "Support for staff at the scene" that:

> **During a vessel based incident**
> A vessel standing by the vessel in distress provides mental support to the passengers and crew. Updates on the situation can be made from the vessel standing by; crew can be transferred to assist with the emergency; and passengers may be evacuated to the vessel. It is important to get a vessel there as a support mechanism in the first instance; a vessel in close support can keep you updated as the incident progresses.

3.4.6. Fullers' engine room logbook required that the on-board engineer follow the following routines:

a. At commencement of each shift refer to previous log and requisition entries

b. Carry hours and Lube Oil forward daily

c. Engine readings taken at least 25 minutes after engine has been running at full power

d. Engineer to take all gauge readings from the engine room

e. Use all clock digits

f. Engine room inspections and readings minimum of once per hour

g. Alternate genset and battery banks daily (i.e. odd and even calendar days

h. Full explanation and diagnosis of problems entered in comments

i. Record all completed maintenance

An inspection of the *Jet Raider*'s engine room logbooks showed that the engineer had completed the logbook at about 10:20, with all readings within the "normal" range, and that at about 11:20 he had carried out a visual inspection of the engine room and had not noted anything of interest.

[6] Fullers Group Limited, Operations Manual, part 3, Fullers Emergency Response Plan, May 2011.

4. Analysis

4.1. Introduction

4.1.1. Catastrophic engine failure can have serious consequences. Crew in the engine room at the time are at risk of injury from flying debris, and in some circumstances it can result in a fire if the lubricating or fuel oil systems are damaged and oil sprays onto hot surfaces.

4.1.2. In this case the engine room was normally unmanned, with most engine monitoring done remotely using gauges and closed-circuit television. The likelihood of injury occurring was therefore low.

4.1.3. Also, in this case, no fire occurred. The initial indications of fire were likely caused by steam from the cooling water system that was damaged by flying debris, and escaping exhaust gases and unburned fuel from the damaged engine. It is possible that there was a momentary "flash-off" of this gaseous mixture.

4.1.4. The initiating cause of catastrophic engine failure is often difficult to determine due to the resulting damage. It can be difficult to distinguish damage that might have initiated the event from damage caused by the resulting failure sequence. This failure is one such case.

4.1.5. The following analysis discusses the potential causes of the engine failure. Two safety issues are also discussed:

- the maintenance regime that Fullers followed did not correspond to Wärtsilä's (the engine manufacturer's) recommended maintenance programme, but also Wärtsilä would not explain the rationale behind its recommended maintenance programme

- the system of transferring passengers to another vessel as a means of evacuation was not documented or practised during evacuation drills.

4.2. Possible failure sequence

4.2.1. The failure of an engine connecting rod assembly is one common cause of catastrophic engine failure. The connecting rods in this case failed when the connecting rod bolts clamping the big-end of the connecting rod to the crankshaft failed in overload.

4.2.2. In his submission on the draft final report, one interested person from the operator identified several failure mechanisms that could have initiated or contributed to the engine failure, such as stretch in the connecting rod bolts and stress cracks developing in and around a piston assembly. None of these factors could be excluded, but due to the severity of the total damage sustained in the catastrophic failure it is difficult to determine if any of these factors directly contributed to the failure.

4.2.3. Similarly, the Defence Technology Agency report into the failure (see Appendix 2 for the full report) outlined 2 possible failure sequences based on the available evidence, but its investigation was unable to identify positively which factor initiated the failure sequence.

4.2.4. For each of the 2 possible failure sequences the outcome was the same – there was an increase in the clearances in the big-end bearings where the connecting rods were connected to the crankshaft. This increase in clearances causes minor shock loading within the bearings, which can lead to failure of the connecting rod bolts. The failure of the connecting rod bolts allows the big-end of the connecting rods to open and the connecting rod is thrown off the rotating crankshaft with considerable force. The resultant massive imbalance in the engine can cause other components to fail as well. One possible scenario is where clamping force on the bearings is lost due to a loosening of the connecting rod bolts. The other is where the bearings become worn. The result in either case was increased clearances within the bearing assembly.

4.2.5. A loss of clamping force itself can cause the bearing to wear prematurely, so factors from both scenarios can overlap to contribute to the same outcome, making it difficult to determine which occurred first.

4.2.6. A loss of clamping force by the upper connecting rod bolt would allow fretting[7] at the upper multi-v joint between the connecting rod and the connecting rod cap.

4.2.7. A loss of clamping force can be caused by under-torqueing[8] the connecting rod bolt during maintenance. Conversely, over-torqueing a connecting rod bolt can weaken the bolt, causing it to fail at lower forces. However, failure due to either type of maintenance error usually shows up earlier in the engine life. In this case the engine had run for more than 6000 hours since being rebuilt (when the bolts would have been last torqued).

4.2.8. The white metal surfaces of the big-end bearings for the Number 4 pistons were severely worn, and overheating had caused the white metal surfaces to extrude out of the immediate bearing area. This type of damage could have initiated the connecting rod failure, or equally it could have been a result of the failure.

4.2.9. If the big-end bearings had been worn prior to failure this would have resulted in increased clearances within the connecting rod assembly, which as mentioned can lead to minor shock loading of the bearing, possibly leading to connecting rod bolt failure.

4.2.10. Other factors that can lead to bearing wear include:

- bearing cavitation
- corrosive wear
- a previous overheating incident
- fuel dilution
- contamination of the lubricating oil
- lubricating oil starvation.

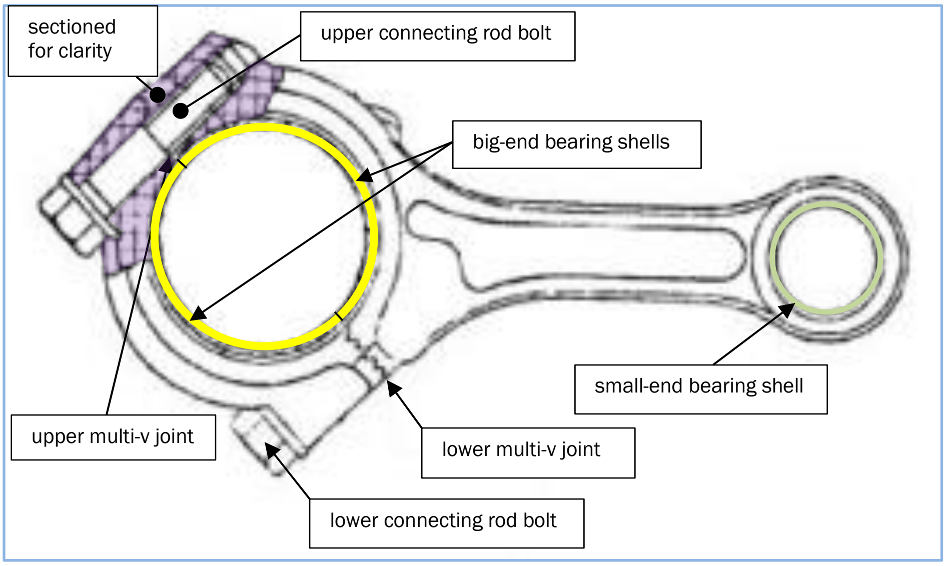

Figure 7
Diagram of a connecting rod

[7] A wear process that occurs at the contact area between two components when they are subject to small amplitude relative motion due to forces such as vibration.
[8] Tightening the bolts to a set rotational force.

4.2.11. Cavitation, corrosive wear or a previous overheating of the number 4 big-end bearings could not be ruled out because any evidence was masked by damage sustained during the failure sequence.

4.2.12. The damaged Number 4A piston showed possible piston scuff marks[9] on one side (see Figure 8). Piston scuffing is usually caused by either a lack of lubrication between moving metal parts or a lack of cooling. Localised heating can cause engine parts to weld together momentarily before breaking free. This momentary welding can put excessive strain on the connecting rod bolts, leading to their eventual failure. However, considerable damage to both the cylinder liner and piston made it difficult to determine whether the scuff marks had been present before the engine failure or whether they were incurred when the engine failed.

Lubrication and cooling

4.2.13. Engine cooling is achieved by both cooling water circulating through the engine and cooling by the lubricating oil. A reduction in flow of either can result in an overheating of the engine, or localised overheating.

4.2.14. Apart from the big-end bearings for Number 4 pistons, the components in the rest of the engine were relatively undamaged and in good condition, meaning that the engine as a whole had not been starved of lubricating oil.

4.2.15. Fullers used systematic monitoring of engine lubricating oil as part of its engine monitoring and maintenance programme. The previous lubricating oil test reports for the failed engine had not shown any evidence of fuel dilution or other abnormal contamination of the lubricating oil, so oil quality did not appear to be an issue.

4.2.16. Both the lube oil and cooling water pumps on the Deutz MWM engine were mechanically driven directly off the engine. This meant that the flow each produced was proportional to the engine revolutions. A rapid decrease in engine revolutions results in a corresponding sudden decrease in the flow of cooling water and lubrication oil. If the engine has been running at high revolutions and high temperatures, the sudden decrease in cooling water and lubricating oil flow can result in localised overheating. The consequence of this engine feature can be mitigated by avoiding large, sudden changes in engine speed, which is not always possible when operating short-range ferry operations with multiple pick-up points, in heavily congested waters.

4.2.17. There had been another catastrophic engine failure involving the same engine type on a passenger ferry operating in Fiji[10]. In that case a connecting rod from Number 4 piston failed and exited through the crankcase door in a similar way to this engine. The other bearings were all seized on to the crankshaft.

4.2.18. An engineer with expert knowledge of the Deutz MWM engine conducted an investigation into the cause of the failure. The engineer concluded that the B4 cylinder liner and the B4 piston had failed due to localised heating. He was of the opinion that the lubricating oil cooling jet on the underside of the piston head had been operating correctly; however, so much damage had occurred he was unable to confirm this.

4.2.19. It could be coincidental that the same pistons and connecting rod assembly (Number 4) failed on the same engine type, or it could be that local overheating associated with fluctuations in cooling water and lubricating oil pressures first manifests itself within the Number 4 piston assembly on this engine type. The scuff marks found on the Number 4 pistons of both engines would support this possibility. Regardless of whether this was the case, operators of engines with direct engine-driven cooling water and lubricating oil pumps should consider modifying their operations and driving styles to mitigate any such risk.

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[9] Scuffing is the process by which metals weld themselves together and then break loose. It is also known as “micro seizure” or “adhesive wear”. Scuffing is likely to occur when 2 moving metallic parts lose lubrication between them. In this case the scuffing is between either the piston or piston rings and the walls of the cylinder.

[10] Passenger ferry Ocean Dreaming – December 2011.

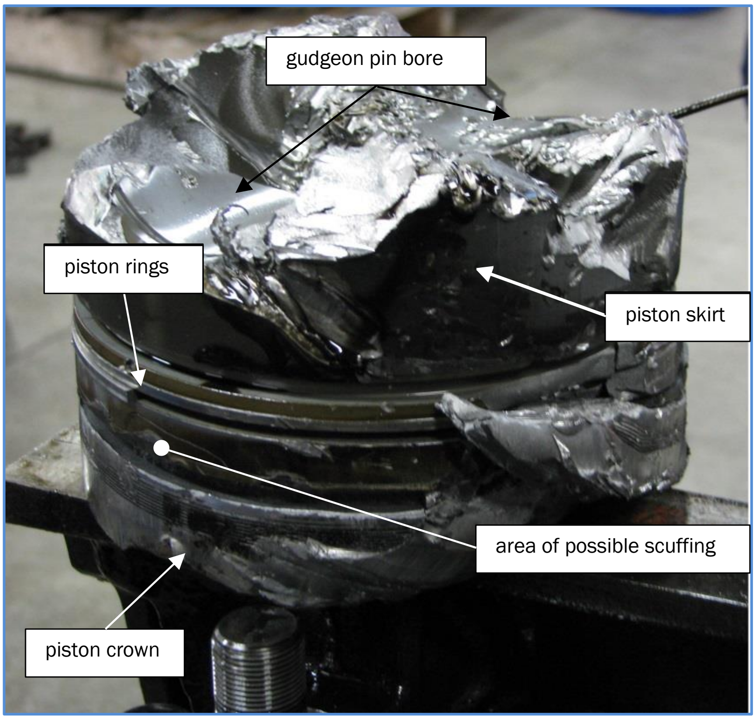


Figure 8
Number 4A piston after removal from cylinder

Findings

1. The engine catastrophically failed when the bolts securing 2 connecting rods to the number 4 journal failed in overload.

2. The severity of the damage to engine components meant it was not possible to say what the root cause of the failure was. However, similarities in the failure of this and another engine of the same type indicate that localised overheating caused by fluctuating lubricating oil and cooling water pressures due to engine-handling technique could not be excluded.

4.3. Maintenance

4.3.1. The service and technical support functions for the Deutz MWM marine product range had been transferred to another manufacturer of marine diesel engines (Wärtsilä) in 2005. Fullers carried out the maintenance of the engines itself using Wärtsilä's specified maintenance schedule.

4.3.2. Wärtsilä set its recommended engine maintenance into specific engine performance groups, depending on the type of operation and the typical engine running hours achieved each year (see Table 3 in Appendix 2). When the *Jet Raider* was in daily service with Fullers, its yearly hours would have placed it in Wärtsilä's maintenance group "A", which was for vessels in continual operation for more than 4000 hours per year. Fullers followed schedule A for the maintenance of all Deutz engines in its fleet, but it had extended the 16 000-hour replacement programme to 24 000 hours on the basis of its engine lubricating oil monitoring programme used to enhance the monitoring of engine performance.

4.3.3. When Fullers took the *Jet Raider* out of daily service it fell broadly into maintenance group C, for vessels in restricted operation up to 2000 hours per year. Running hours alone was not the only factor to consider when deciding which maintenance plan to follow. The time for which the engine was operating at or above 80% power was another consideration. Taking both into account it was possible that the *Jet Raider* fell somewhere in between groups A and C.

4.3.4. Engine maintenance for vessels that fell into group C was more rigorous than that for vessels in group A. For example, the Wärtsilä renewal interval for the big- and small-end bearings under group A was 16 000 hours. This was reduced to 6000 hours for engines under group C (see the table on page 5 of Appendix 2). The reason for Wärtsilä reducing the interval for replacement of the bearings is unclear. Fullers had previously asked Wärtsilä for the reason, but Wärtsilä had not responded. In its submission on the draft final report, Wärtsilä said that it thought the maintenance schedule may have originated when the engines were delivered from MWM/Deutz Far East in Singapore. As far as Wärtsilä was concerned, the Fullers maintenance schedule was adequate, providing the connecting rod bolts were exchanged after every removal. The asset manager for Fullers Group Limited confirmed that the connecting rod bolts were changed every time the bolts were removed as a matter of policy.

4.3.5. Fullers took regular samples of engine lubricating oil and sent them to an independent oil analysis company. The company would provide a report on each sample, which would also comment on any trend in oil condition for the same engine. It was then up to Fullers to use that information and decide what maintenance action to take.

4.3.6. Lubricating oil analysis is carried out to optimise the life of oil, rather than change it unnecessarily. It can also be used to monitor the wear rates of engine components by detecting and quantifying wear metal[11] levels within the oil over set time intervals. In this way abnormal wear in a component can be detected before it fails, possibly catastrophically (see Appendix 3). The most recent lubricating oil analysis performed on the starboard engine had been one month before it failed.

4.3.7. An examination of the oil analysis reports prior to the accident on board the *Jet Raider* showed higher levels of contaminant elements and wear elements in the starboard (failed) engine than in the comparative samples for the port engine (as noted in the Defence Technology Agency report). These were, however, within the limits for what the oil analyses described as "normal condition".

4.3.8. The report from the oil analysis company noted that the Fullers fleet in general had consistently higher levels of chromium in the lubricating oil than the "global population" of Deutz engines under its oil analysis programme. The oil analysis company, however, cautioned against taking any of the figures in isolation. The figures should be considered in conjunction with other wear triggers and establish whether the figures are a one-off level or indicative of a developing trend.

4.3.9. The lubrication oil analysis for the starboard engine did not, in isolation, show that failure was inevitable. However, the higher levels of contaminant and wear elements than for the port engine could have alerted Fullers to monitor more closely the performance of the starboard engine.

4.3.10. The starboard engine on the *Jet Raider* had undergone a major strip-down, overhaul and re-build in May 2007. All replacement rotating/moving parts had been sourced from the original equipment manufacturer (OEM). Since the major overhaul the engine had run for about 6000 hours. The next major overhaul was scheduled for about 24 000 hours. The 6000 hours it took for the engine to fail corresponded with the time in which the bearings would have been replaced if Wärtsilä's group C engine maintenance schedule had been followed.

4.3.11. Without knowing the exact reason for Wärtsilä or the original engine manufacturer specifying a 6000-hour interval between big- and little-end bearing replacements, it is difficult to say whether Fullers not following the manufacturer's recommended maintenance schedule was a factor contributing to the engine failure. However, in its submission on the draft final report Wärtsilä said that it was not likely that any engine component failed due to it being left in service longer than the maintenance schedule allowed.

[11] Traces of the types of metal that typically wear during the service life of an engine.

Findings

3. The starboard engine on the *Jet Raider* failed after running for 6000 hours since it had last been overhauled. The engine manufacturer recommended that the interval between overhauls be reduced from 16 000 to 6000 running hours for vessels operating similarly to the *Jet Raider*, but the manufacturer's reasons for this were unclear.

4. Fullers' lubricating oil analysis programme had not detected that the *Jet Raider*'s starboard engine condition was deteriorating in comparison with the port engine's, but the lubricating oil was still within "normal" parameters.

5. It could not be established whether the timing or quality of maintenance contributed in any way to the engine failure. However, Wärtsilä thought it unlikely that any component failed due to it being left in service longer than recommended in the maintenance schedule.

4.4. Emergency response

4.4.1. The crew response to the accident was well thought out and followed the emergency response plan. The master organised his crew to reassure passengers and he anchored his disabled vessel. No 2 emergencies are ever the same, which means there will often be new lessons to take from each case.

4.4.2. In this case there were 2 safety issues identified:

- the procedure for releasing the engine room fixed CO_2 fire-suppression system
- the procedure for abandoning ship when another vessel is involved.

Fixed fire-suppression system

4.4.3. Most of the fleet operated by Fullers comprised catamaran-style vessels, where the engines were housed separately in each hull. The fixed CO_2 fire-suppression system was divided into 2 sections – one for each hull (port and starboard). Setting off either section would release the exact initial number of CO_2 bottles required to extinguish a fire in that space.

4.4.4. The *Jet Raider* was a mono-hull vessel, where both engines were housed in one engine-room space. There were 2 CO_2 bottles, labelled port and starboard. A fire in the engine room required both bottles to be released into the engine room. However, the engineer only fired the starboard CO_2 bottle into the engine room because he associated the failure of the starboard engine with that of the catamaran configuration, forgetting that both engines were in fact in the same space. This type of error is not uncommon when people are required to switch between different operations. It creates a risk of their applying a procedure that would normally be correct, but for a different situation.

4.4.5. The risk of this type of error occurring is heightened when people are placed in stressful situations, such as responding to an emergency. A common example of such an error is when car drivers switch to vehicles that have the indicator switch on the opposite control column to which they are used to. In terms of the study of human factors, this is known as "negative transfer error" (D.J. Woltz, 2000).

4.4.6. If the engine failure had caused a sustained fire in the engine room, releasing only one of the 2 required CO_2 cylinders may not have been sufficient to extinguish the fire. This safety issue could be resolved by placing a clear placard at the control station for the fixed CO_2 fire-suppression system, alerting the operator that both bottles are required to extinguish a fire in the engine room.

Abandoning ship

4.4.7. The *Jet Raider* was fitted with a combination of survival craft, buoyant apparatuses', (mainly life-rafts) and personal flotation devices in accordance with Maritime Rules. The devices were provided for the worst-case situation, where passengers and crew had little time to abandon ship and take to the water. The abandon-ship procedures were designed around evacuating passengers and crew into life-rafts. The crew routinely conducted abandon-ship and life-raft drills.

4.4.8. Most of the Fullers vessels operated in enclosed or inshore limits, and in areas frequently plied by other ferries and recreational vessels. In the previous 10 years there had been a number of incidents and accidents involving passenger ferries in the Auckland area, and on almost every occasion the passengers had not needed to enter life-rafts. Instead they had been transferred to other vessels in the vicinity.

4.4.9. Fullers' emergency response plan called for another company vessel to be in close proximity to provide support and back-up crew and possibly receive passengers in case a vessel had to be abandoned. With the number of vessels that Fullers operated, it was highly likely that during a situation there would be another company vessel nearby. Fullers would also have been one of 2 operators on the Hauraki Gulf with the capability to accept a large number of passengers from a stricken vessel.

4.4.10. In this case the *Starflyte* was close behind the *Jet Raider* and was soon close by. When the master of the *Jet Raider* made the decision to transfer his passengers to the *Starflyte*, the weather was benign and the transfer was made easily and efficiently. If the weather, (especially the sea state) had been worse, the operation would have been more difficult and less safe.

4.4.11. Although passenger transfer was the more likely method for abandoning ship in the congested Hauraki Gulf, the crews did not practise transferring passengers from one vessel to another, nor did they practise bringing one vessel alongside another. The vessels in the Fullers fleet had subtly different heights of rubbing strips, and access and egress points. There would be merit in introducing this into the training schedule, and also merit in considering subtle design changes to better facilitate ship-to-ship passenger transfers.

Findings

6. The emergency response to the engine failure was well thought out and well executed. However, only half of the fixed CO_2 fire-suppression system was released into the engine room, which might not have extinguished a sustained fire if one had occurred.

7. A clear placard should be placed at the control station for the fixed CO_2 fire-suppression systems on all passenger ferries, alerting them to the exact number of CO_2 bottles needed to extinguish a fire in each of the protected compartments.

8. When an accident or incident occurs that requires a passenger ferry operating in Auckland's congested Hauraki Gulf to abandon ship, it is highly likely that this will be achieved by a ship-to-ship transfer of passengers and crew. This scenario should be included in emergency response training and drills, and passenger ferries from all companies operating in the same area should be designed to minimise the risks of such an operation.

5. Findings

5.1. The engine catastrophically failed when the bolts securing 2 connecting rods to the number 4 journal failed in overload.

5.2. The severity of the damage to engine components meant it was not possible to say what the root cause of the failure was. However, similarities in the failure of this and another engine of the same type indicate that localised overheating caused by fluctuating lubricating oil and cooling water pressures due to engine-handling technique could not be excluded.

5.3. The starboard engine on the *Jet Raider* failed after running for 6000 hours since it had last been overhauled. The engine manufacturer recommended that the interval between overhauls be reduced from 16 000 to 6000 running hours for vessels operating similarly to the *Jet Raider*, but the manufacturer's reasons for this were unclear.

5.4. Fullers' lubricating oil analysis programme had not detected that the *Jet Raider*'s starboard engine condition was deteriorating in comparison with the port engine's, but the lubricating oil was still within "normal" parameters.

5.5. It could not be established whether the timing or quality of maintenance contributed in any way to the engine failure. However, Wärtsilä thought it unlikely that any component failed due to it being left in service longer than recommended in the maintenance schedule.

5.6. The emergency response to the engine failure was well thought out and well executed. However, only half of the fixed CO_2 fire-suppression system was released into the engine room, which might not have extinguished a sustained fire if one had occurred.

5.7. A clear placard should be placed at the control station for the fixed CO_2 fire-suppression systems on all passenger ferries, alerting them to the exact number of CO_2 bottles needed to extinguish a fire in each of the protected compartments.

5.8. When an accident or incident occurs that requires a passenger ferry operating in Auckland's congested Hauraki Gulf to abandon ship, it is highly likely that this will be achieved by a ship-to-ship transfer of passengers and crew. This scenario should be included in emergency response training and drills, and passenger ferries from all companies operating in the same area should be designed to minimise the risks of such an operation.

6. Safety actions

General

6.1. The Commission classifies safety actions by 2 types:

(a) safety actions taken by the regulator or an operator to address safety issues identified by the Commission during an inquiry that would otherwise result in the Commission issuing a recommendation

(b) safety actions taken by the regulator or an operator to address other safety issues that would not normally result in the Commission issuing a recommendation.

Safety actions addressing safety issues identified during an inquiry

6.2. On 3 December 2013 the Marine Manager of Fullers Group Limited submitted to the Commission that:

> To this date Fullers Group Ltd has identified signage in line with this recommendation (signage wording attached) this signage has been ordered and will be installed once delivered. Anticipated completion date, 13 December 2013.
>
> To this date to facilitate vessel to vessel transfer recommendation to the Auckland Council Harbour Masters Office, Fullers Group Ltd has produced a Transfer Protocol (attached), purchased several large fenders and is presently determining a drill schedule to commence in the New Year. Anticipated (to drill stage) completion date, March 2014.

7. Recommendations

General

7.1. The Commission may issue, or give notice of, recommendations to any person or organisation that it considers the most appropriate to address the identified safety issues, depending on whether these safety issues are applicable to a single operator only or to the wider transport sector. In this case, recommendations have been issued to Fullers, with notice of these recommendations given to Maritime New Zealand.

7.2. In the interests of transport safety it is important that these recommendations are implemented without delay to help prevent similar accidents or incidents occurring in the future.

Recommendations

Recommendation 1

7.3. Most of the Fullers vessels operate in enclosed or inshore limits, and in areas frequently plied by other ferries and recreational vessels. In the past 10 years there have been a number of incidents and accidents involving passenger ferries in the Auckland area, and on almost every occasion the passengers have not needed to enter life-rafts. Instead they have been transferred to other vessels in the vicinity.

Although passenger transfer is the more likely method for abandoning ship in the congested Hauraki Gulf, the crews do not practise transferring passengers from one vessel to another, nor do they practise bringing one vessel alongside another. The vessels in Fullers' fleet have subtly different heights of rubbing strips, and access and egress points. There would be merit in introducing this into the training schedule, and also merit in considering subtle design changes to better facilitate ship-to-ship passenger transfers.

On 16 December 2013 the Commission recommended to the Chief Executive of Auckland Council that he co-ordinates the ferry companies that operate large passenger ferries on the major Hauraki Gulf routes to adopt ferry design features and training programmes aimed at minimising the risk of a ship-to-ship transfer of passengers when the need arises to abandon a passenger ferry. (027/13)

> In response to this recommendation, Auckland Council agrees to coordinate the ferry companies that operate large passenger ferries on the major Hauraki Gulf routes to adopt ferry design features and training programmes aimed at minimising the risk of a ship to ship transfer of passengers when the need arises to abandon a passenger ferry.
>
> Whilst the Council will work with the ferry operators in this regard, the Council has limited regulatory power to require ferry owners to comply. Maritime New Zealand is the regulatory body who have the necessary power to compel commercial operators to adopt the required design features. Maritime New Zealand has existing Maritime Rules which prescribe the regulations concerning the construction of vessels and the training of crew members.
>
> The large passenger ferries are of varying ages and designs and it may not be economically viable to redesign some members of the existing fleet; however thought regarding passenger transfer should be considered during the design of future new builds.
>
> Auckland Council will undertake to implement the recommendation so far as it is able to do so by 30 June 2014.

8. Key lessons

8.1. Training for emergency responses must cover the procedures for using mandatory lifesaving equipment, but should also be extended to cover other common scenarios, such as using a ship-to-ship transfer of passengers when abandoning ship.

8.2. Instruction placards for critical systems such as fixed engine room CO_2 fire-suppression systems should be clear and concise to avoid operators misinterpreting them at times of high or stressful workload.

9. Citations

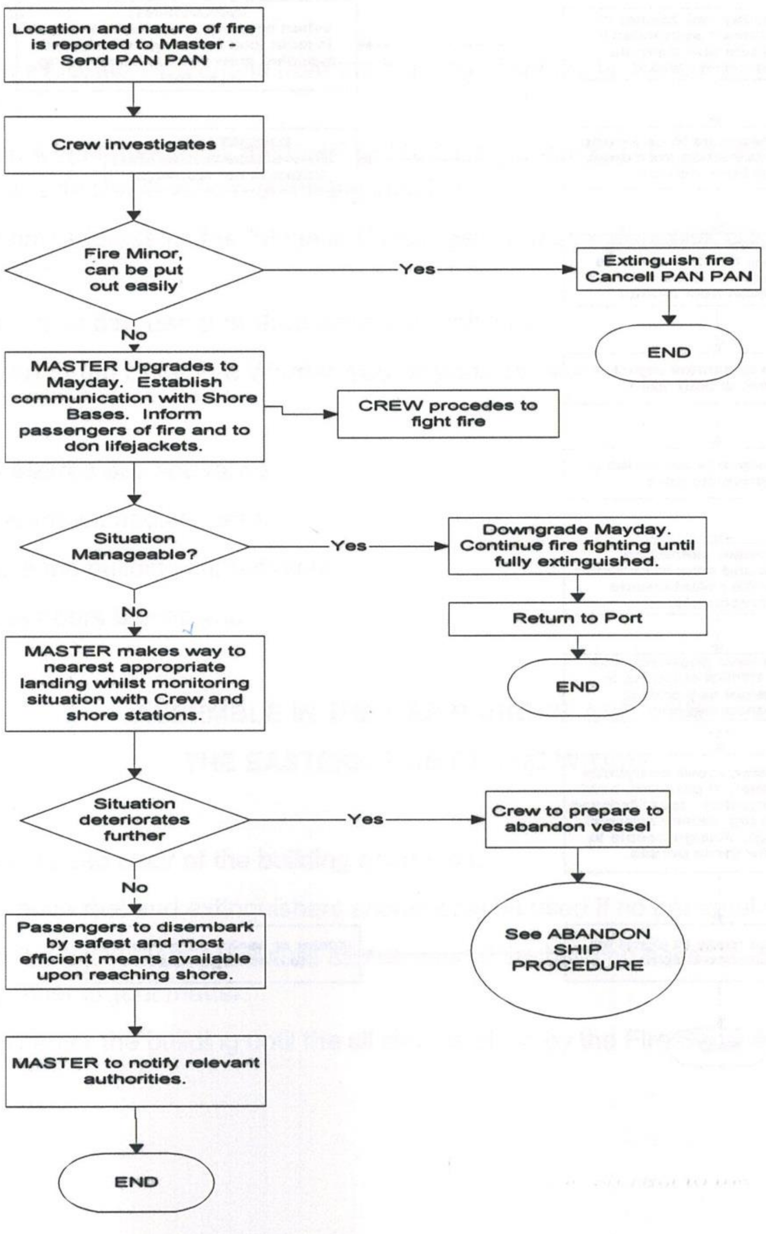
D.J. Woltz, M. G. (2000). Negative transfer errors in sequential cognitive skills: strong-but wrong sequence application. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 26(3), 601-635.

Appendix 1: Fullers Group Limited – Emergency response plan fire-control and abandon-ship procedures

Appendix B - Vessel Incident Procedures (contd.)

09/05/11

FIRE CONTROL PROCEDURE



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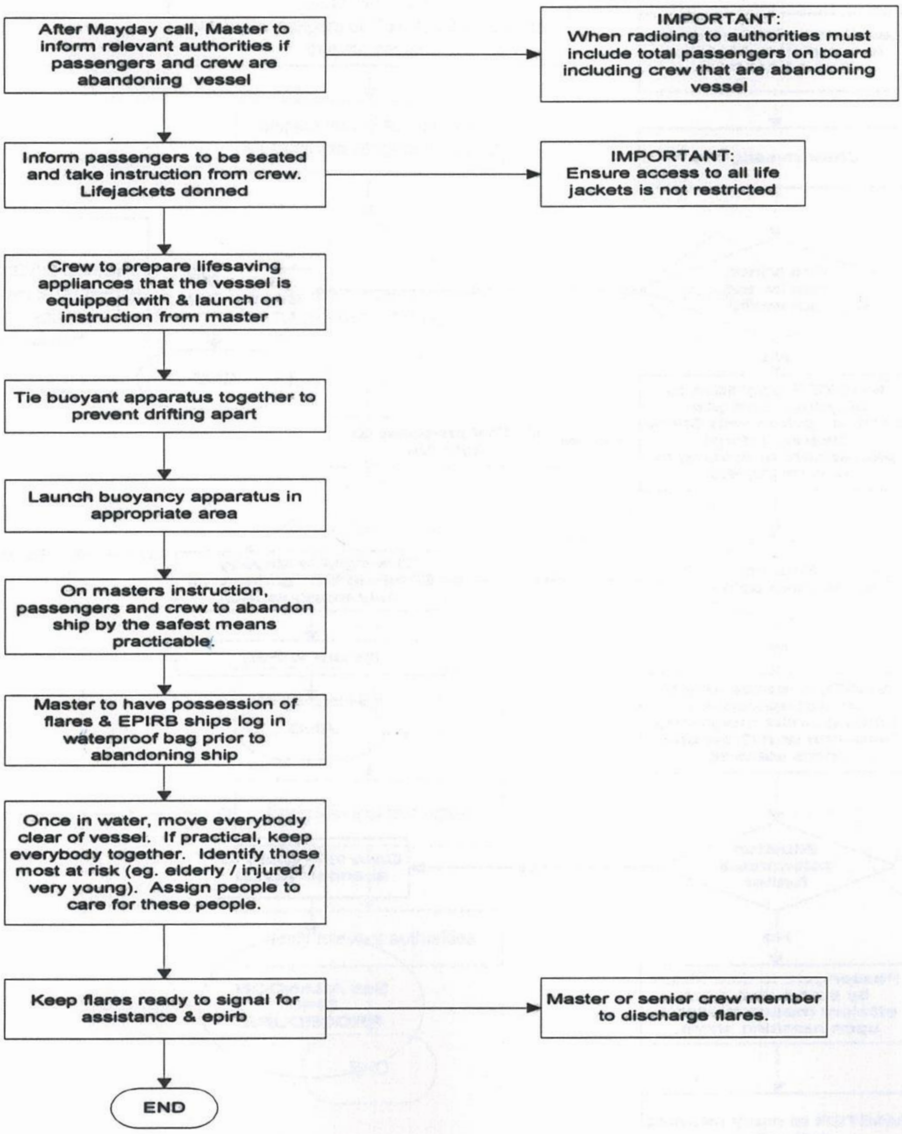
Appendix B - Vessel Incident Procedures (contd.)

09/05/11

ABANDON SHIP PROCEDURE



Emergency Response Plan 21

Appendix 2: Defence Technology Agency report

Defence Technology Agency
NZ Defence Force
Private Bag 32901
Auckland Naval Base
AUCKLAND

Ph (09) 445-5902 Fax (09) 445-5890

DTA

DEFENCE TECHNOLOGY AGENCY
Applied Vehicle Systems Group

Date: 12 September 2012 Page 1 of 9

TECHNICAL MEMORANDUM C1217

Subject: **Jet Raider Deutz MWM Starboard Main Engine Failure**

File Ref: 3739/5 Contact Ph No: (09) 445-5823
Project No: GEN3 141

Work Requested: To provide technical support to the engine failure investigation.

Task Reference: TAIC Memo dated 7 September 2011

Report To: Iain Hill
Transport Accident Investigation Commission
PO Box 10323, Wellington 6143

Introduction

1. On 27th August 2011 the Jet Raider, operated by Fullers Group Ltd, suffered a catastrophic failure of its starboard main engine. The engine is a Deutz MWM TBD 604 BV12, developing approximately 1200kW of power, with the serial number 7477261. The engine had done approximately 7,000 operating hours since overhaul in 2007. The Transport Accident Investigation Commission (TAIC) opened an inquiry into the incident to assess why the failure occurred. DTA was requested to provide initial specialist metallurgical and fractographic services and advice in support of the TAIC investigation [Task Reference].

2. DTA personnel viewed the engine and components during the initial engine strip on September 14th and again on September 20th 2011 at the Fullers workshop in Grey Lynn, Auckland. Additionally, DTA took possession of some components for more detailed laboratory examination.

3. This report summarises observations of critical damage associated with the cause of the failure and outlines a failure sequence which may have occurred.

Examination

4. The following (Table 1) is a summary of the visible evidence that is considered to have occurred prior to the catastrophic failure. No instrumental or detailed metallurgical analyses have been performed. Each piece of evidence has been logged with respect to the relevant conrod. The location of the conrods (cylinders A4 or B4) has not been determined.

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Conrod S/N 400	Conrod S/N 438
Conrod bolt failures	
Upper bolt: Unusual failure surface over approx ¼ of surface. Remaining ¾ failed in plastic elongation (Figure 1). Fretting damage on pilot surface (Figure 2).	Upper bolt: Tensile plastic elongation and failure.
Lower bolt: Tensile plastic elongation and failure.	Lower bolt: Tensile plastic elongation and failure.
Rod cap to underside of conrod bolt interface	
Upper bolt: Significant but small amount of fretting damage plus small burr on conrod cap from edge of bolt head.	Upper bolt: Initiation of fretting – almost insignificant.
Lower bolt: Significant but small amount of fretting. Less than upper bolt.	Lower bolt: Initiation of fretting – almost insignificant.
Conrod – rod cap joint: damage to flanks of locating multi-‘V’ set	
Upper: Significant fretting on both flanks of Vs.	Upper: Initiation of fretting. No serious surface loss.
Lower: Some fretting on both flanks of some Vs. More toward outer edges, plus serious fretting on last V tooth. Significant bending outward of last V tooth.	Lower: No fretting. Significant bending outward of last V tooth.
Big end bearing shell locating pin	
Partially sheared off. Likely to have been present up to the final failure sequence.	Sheared off timing unclear.
Bearing shells: Unable to unambiguously determine which bearing shell came from which conrod half	
White metal bearing surface appears to be absent. Resulting significant heat damage and metal-to-metal contact of bearing shell backing with crank shaft. Severe wear of crankshaft and bearing shell. Significant extrusion of shells under rotating loading action while hot, although the temperatures have not been determined.	

Table 1. Summary of visible evidence.

5. Overall, both the subject conrods have relatively little pre-catastrophic failure damage. The predominance of the pre-catastrophic failure damage is restricted to the bearing shells and the crankshaft. The relatively good condition of other engine systems and components indicates that the engine, as a whole, has not been starved of oil.

6. Conrod S/N 400 has the most significant heat damage, and has the most fretting damage at the big end bearing cap multi-V jointing interfaces, indicating this one was in a more advanced state of damage prior to final catastrophic failure. The fracture surface of the upper fastening conrod bolt on conrod S/N 400 has an unusual appearance. Examination of one half of the fracture by scanning

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electron microscopy revealed that the 'ridged' portion of the fracture was covered in oxidation products, largely obscuring fractographic details. However, a number of facets exhibited a dimpled appearance consistent with ductile overload (figure 3). The true nature of this part of the fracture has not been determined, but its appearance may have been influenced by elevated temperature and stress state. For both conrods, the upper bolts appear to have failed first, resulting in the conrod caps hinging open about the lower joint with the resulting bending damage to the outer Vs at the conrod – cap joint.

7. Results of tensile testing of the upper bolt ex conrod S/N 400 and two bolts supplied by Fullers for comparison are given in Table 2. Results indicated that all three had similar tensile properties and by and large met the requirements for P/N DZ12304262 [E]. The results do not indicate any deficiency in tensile properties.

	Tensile Strength, Rm (N/mm2)	**Proof Strength, Rp0.2 (N/mm2)**	**Elongation after Fracture, A (%)**
Sample Bolt (DTA 1217/7)	1105 (note 1)	1087	10.0 (note 3)
Sample Bolt (DTA 1217/8)	1059	1015	14.0 (note 3)
Upper bolt ex conrod S/N 400	1071	1069 (note 2)	16.0
Specification (Reference E)	1000-1100	Minimum 900	-

Note 1. At face value this result exceeds the specified maximum value. However, the result is within the margin of error of the test method at the specified value.
Note 2. Yield and strength previously exceeded during engine failure.
Note 3. Failed adjacent to gauge mark.

Table 2. Results of tensile testing

Discussion

8. Based on the pre-catastrophic failure evidence summarised above, a possible sequence of failure is outlined below. This failure sequence does not specifically identify or discuss the initiating cause of the loss of clamping force of the conrod bolts. This is discussed in later paragraphs. The probable failure sequence is numbered for clarity although the actual sequence may not have occurred exactly as laid out. It is likely that many of the stages listed below overlapped at least partially. This sequence would account for the damage observed.

8.1 Loss of clamping force by upper conrod bolt on conrod S/N 400.
8.2 This allowed fretting at the upper multi-V joint between the conrod and conrod cap.
8.3 It is considered probable that the fretting allowed minor shock loading due to the slackness of the joint and this probably contributed to further loosening of the upper conrod bolt and increased fretting.

Note: The tensile loads induced in the conrod can be large as the piston crosses top dead centre (TDC) during transition from the exhaust to the inlet stroke. As the piston crosses TDC the tensile loads induced in high speed engines can exceed the compressive loads induced by the power stroke [D]. During the transition from tensile to compressive loading on the conrod any excessive bearing clearance can result in a shock or impulse load.

8.4 The clearances in the upper conrod multi-V joint increase to the degree that the lower conrod bolt deforms and allows fretting of the lower joint.
8.5 The loss of restraint at one or both ends of the bearing cap will have increased the clearances and reduced the thickness and integrity of the hydrodynamic oil film until breakdown of the hydrodynamic oil film occurred allowing metal to metal contact and accelerating wear of the white metal bearing and further increased clearances.
8.6 This will have resulted in a significant increase in localised heat, the total loss of the white metal and an acceleration of the metal on metal damage and contact of the bearing shell backing with the crankshaft.
8.7 Severe wear and heating of crankshaft and bearing shells. The metal portion of the bearing shells began to heat, wear and extrude out of the immediate bearing area, impinging on the adjacent bearing and precipitating the failure of the neighbouring S/N 438 conrod bearing.
8.8 S/N 438 conrod bearing suffers breakdown of the hydrodynamic oil film and allowing metal to metal contact and a similar accelerated wear pattern to the S/N 400 bearing shell.
8.9 It is probable that the loss of appropriate lubrication and increased clearances allowed minor shock loading of the joint and contributed to deformation of the upper conrod bolt on the S/N 438.
8.10 Initiation of fretting at the S/N 438 conrod upper multi-V joint.
8.11 The hammering – minor shock loadings due to increasing clearances will have eventually forced the failure of the upper conrod bolt on conrod S/N 400.
8.12 This will have led to the opening of the conrod, overload and failure of the lower conrod bolt and the hinging action that damaged the outermost V of the lower conrod joint.
8.13 The failure of the S/N 400 conrod and associated components forced the failure of the adjacent S/N 438 conrod.

9. An alternative to that above may commence, not with loss of conrod bolt tension, but with bearing wear, resulting in increased clearance and shock loading of the bearing as described in 8.3. In this case, loss of bolt tension may well have occurred later in the failure sequence. Any evidence that may support this theory will be subtle and will have been destroyed by subsequent damage.

10. In either scenario, the root cause of failure initiation is unclear. Possible root causes may include, but not be restricted to, fuel dilution, a previous overheating incident, insufficient bearing crush (although this is considered unlikely given the number of hours since overhaul), dirt or contamination of lubricating oil, bearing cavitation and corrosive wear. Any possible evidence of cavitation, corrosive wear, overheating or insufficient bearing crush on the relevant bearings has been lost during the failure process. No further comment can therefore be made regarding the possible implication of these factors on the failure. Significant under-torque or significant over-torque of the conrod bolts is not considered likely as engineering experience indicates that this type of error is likely to shown up earlier in engine life.

11. Oil samples are taken from both main engines of the Jet Raider approximately every 600 hours at the time of the scheduled oil change. Analytical results from the last two sample intervals (January and July 2011) for both engines have been made available to DTA [A, B]. Fuel dilution, which can reduce oil lubricating properties, is not apparent on the test reports.

12. Compared with the reported results for the July 2011 sample and the January and July samples for the port engine, the analyses of the January 23rd 2011 oil sample for the starboard (subject) engine indicated considerably higher levels of contaminant elements potassium and silicon (possible ingress of contaminants), and wear elements lead, tin, iron, copper and aluminium. The levels, whilst still low,

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may have been an increase over 'normal' levels. These results may, therefore, have provided some indication of a potential problem, but a more detailed examination of reported results would be required to confirm this.

13. It is commendable that routine oil analyses are undertaken. However, it is important that the results are interpreted correctly and corrective action implemented in a timely manner, and that any form of condition monitoring programme be tailored and optimised for whatever mode of failure is being guarded against. An oil analysis programme that tests one sample, taken at the time of routine oil change, will always be of very limited value.

14. It is also interesting to note that the big and small end bearing renewal interval, as specified in reference C, is 16,000 hours for Performance Group A and G engines, but is reduced to only 6,000 hours for Performance Group C engines. Fullers are understood to follow the Group A and G schedule as defined in Table 3. It is acknowledged that this table should not be interpreted without more detail, however it is noted that the subject engine has done approximately 7,000 hours since 2007, an approximate annual average of 1,750 hours, possibly more in keeping with Performance Group C. It is recommended that maintenance requirements for this engine in the current application be reviewed.

WÄRTSILÄ

Explanation

Application	Marine propulsion engines			Marine Genset
Performance group	A	B	C	G
Area of application & examples	Continuous operation; unrestricted in time (work boats, tug boats, pusher tugs, supply boats, ferries, harbour boats)	Continuous operation (fast passenger ships and ferries)	Operation restricted in time (police, customs and fast patrol boats, sport fishing boats, commercial yachts)	Continuous operation; unrestricted in time
Standard reference conditions	ICFN	ICFN	IFN	ICXN
Marine conditions	MCFN	MCFN	MFN	MCXN
Typical operating time per year	> 4000 h	3000 h	2000 h	> 4000 h
Operating time period over the 90% of the maximum power	> 80%	max. 80%	max. 20%	> 80%

Table 3. Wartsila Performance Groups (reproduced from reference C).

Conclusions

15. It has not been possible to establish the root cause of failure initiation.

16. Evidence of pre-catastrophic failure damage is indicative of a probable failure sequence centred around loss of integrity of a big end bearing assembly.

Recommendations

17. It is recommended that historic oil analysis reports be examined in order to determine if the failure could have been anticipated. Analyses may be able to be optimised to the detection of this failure mode.

18. It is also recommended that scheduled maintenance activities and overhaul intervals be reviewed to ensure they are appropriate.

References

A. Signum Report Number 31129126 dated 5 August 2011
B. Signum Report Number 31129127 dated 5 August 2011
C. Wartsila Maintenance Schedules/Maintenance Parts D620 (as supplied to DTA by TAIC).
D. Google Books: Design of Machine Elements, 2nd Edition, K Ganesh Babu & K Srithar, Published by Tata McGraw Hill, 2010.
E. Email from Kevin O'Rourke to Iain Hill dated 19 December 2011.

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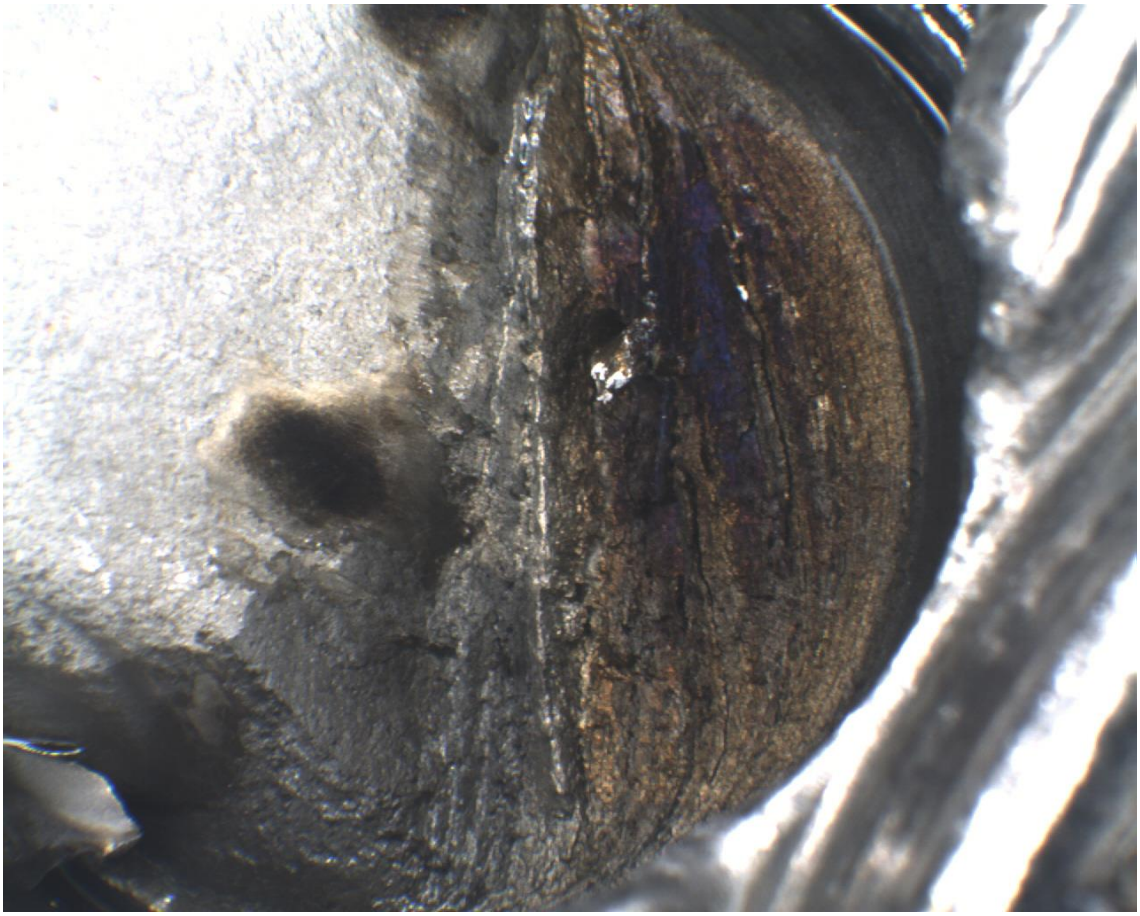

Figure 1. Fracture surface of upper conrod bolt ex conrod S/N 400.

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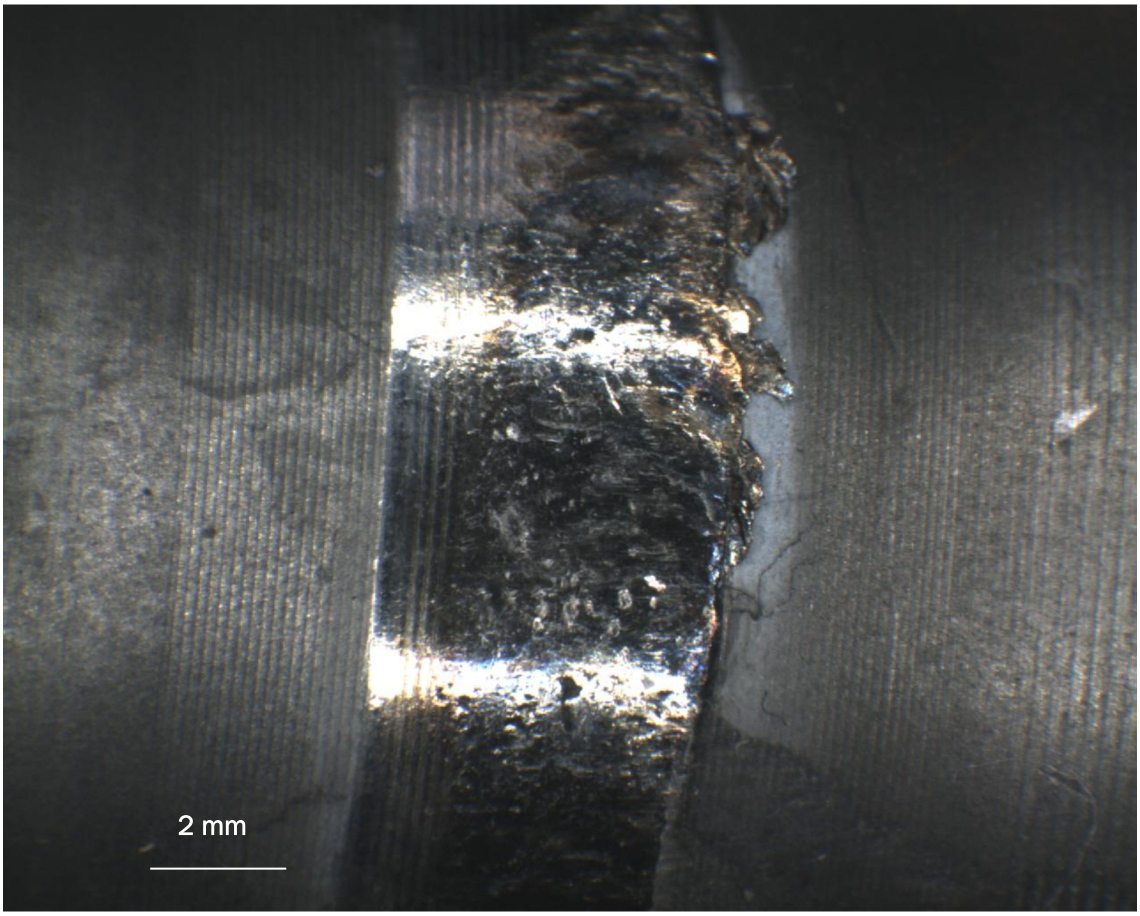

Figure 2. Fretting damage to the upper conrod bolt ex Conrod S/N 400.

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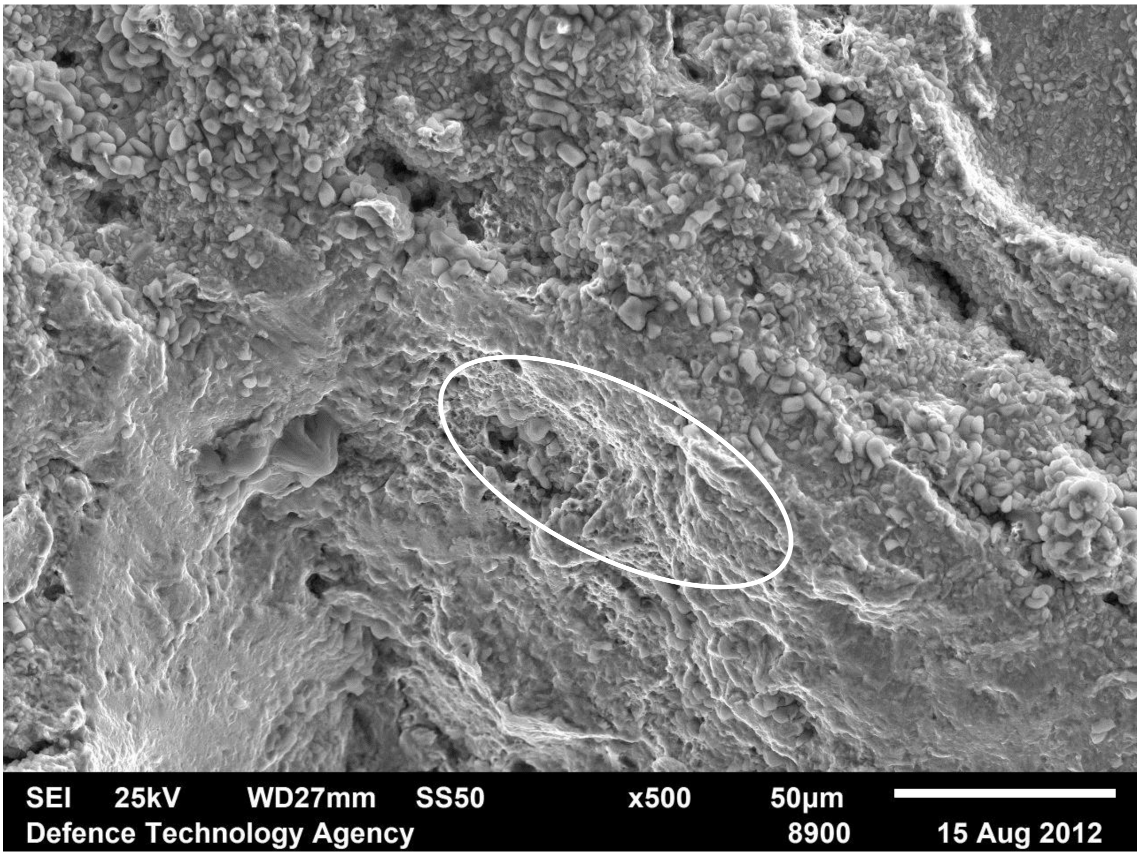

Figure 3. Scanning electron fractograph exhibiting evidence consistent with ductile overload within the ridged portion of the upper conrod bolt ex Conrod S/N 400 shown in figure 1.

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Appendix 3: Oil analysis, condition-monitoring fundamentals

Signum Oil Analysis
Condition-Monitoring Fundamentals

SIGNUM
OIL ANALYSIS

Table of Contents

Signum Oil Analysis

Condition-Monitoring Fundamentals

In today's industry, condition-based maintenance practices have gained widespread acceptance. Key industry leaders increasingly realises that oil analysis is a critical component in any equipment monitoring program.

A successful oil analysis program can:

- Ensure equipment reliability
- Reduce maintenance costs
- Lower the total lifetime cost of equipment ownership

Signum Oil Analysis simplifies the lubrication monitoring process while producing the reliable results that help guide maintenance professionals to the best decisions for their operations.

Signum Oil Analysis provides informative reports on the condition of lubricants and equipment backed by the unmatched flexibility, expertise, and quality assurance of ExxonMobil.

Flexibility

Perform many tasks more efficiently with Signum Oil Analysis online capabilities.

Expertise

Through global Original Equipment Manufacturer (OEM) relationships and hands-on lubrication experience, ExxonMobil supports your maintenance activities.

Quality

Make decisions with confidence by leveraging the quality assurance offered by ExxonMobil.

Steps to Establish and Maintain a Successful Oil Analysis Program

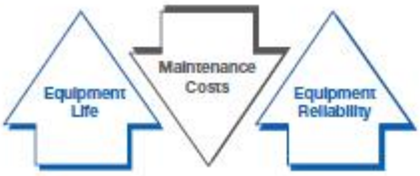
1. Establish Goals and Metrics
2. Obtain Management Commitment
3. Train and Educate Personnel
4. Identify Equipment and Sample Frequencies
5. Implement the Program
6. Respond to the Analysis Results
7. Measure Program Results Versus Goals and Metrics
8. Review and Modify Program
9. Document Savings

Points to Consider - Oil Analysis

Oil analysis is an effective condition-monitoring tool. Additional equipment monitoring practices (inspections, vibration, operator logs, etc.) can be implemented to further enhance the value of your overall maintenance program.

Establishing a Successful Oil Analysis Program

Oil analysis is most effective as a trending tool to monitor equipment and lubricant conditions over time. An analysis of a timeline of data provides insight to help maximise equipment life and reliability while reducing maintenance costs. Success begins when you commit the resources necessary to execute an oil analysis program.



What and When to Sample

Oil analysis is most effective as a diagnostic tool when samples are taken from the appropriate equipment at established scheduled intervals.

1. **Determine What to Sample** – Consider the five general factors listed below when you select equipment for the program and set sample frequency. Additionally, refer to your OEM manual for guidance on specific equipment and recommended sample frequency.

How Frequent? Weekly, Monthly, Quarterly, Semi-Anually, Anually, Never

Fluid Environment Severity	Fluid Age Factor	Machine Age Factor	Target Results	Economic Impact of Failure
• High dirt / dust environment • High loads / pressures / speeds • High temperatures • Shock, vibration, duty cycle • Chemical contamination	• Hr / mi / km since last change • Oxidation, contamination • Mineral,p remium, synthetic oil	• Hr / mi / km since last overhaul • Rated life expectancy • Make and model number	• Above control limits • Within control limits	• Safety risk • Mission criticality • Repair cost • Downtime cost • Lost production

2. **Determine Sample Frequency** – The goal of sample frequency is to achieve a regular pattern of sampling. This establishes a credible historical trend of machine performance.

- Follow OEM-recommended sample intervals for your equipment.
- In the absence of OEM guidelines, refer to the table below for general guidance in establishing initial sample frequency.

Off-Highway Equipment

Sample Point	Frequency
Diesel Engine	250 hours
Wheel Motor	250 hours
Differential/Gear	500 hours
Hydraulic System	500 hours
Transmission	500 hours
Final Drive	1000 hours

On-Highway Equipment

Sample Point	Frequency
Diesel Engine	25,000 km or 15,000 miles
Transmission	40,000 km or 25,000 miles

Industrial/Plant Equipment

Sample Point	Frequency
Landfill Gas Engine	250 hours
Generator Engine	500 hours
Natural Gas Engine	500 hours
Paper Machine Lube System	Monthly
Turbine	Monthly
Compressor	3 months
Gear Drive	3 months
Hydraulic System	3 months

HOW TO : Login to Signum Oil Analysis

1. Login at: http://www.exxonmobil.com/online or your local Lubes Country Website.
2. Enter your User Name and Password.

3. From the Signum Community Homepage click on the Signum logo to access your account.
4. **You are now in the Signum Oil Analysis application.**

SIGNUM OIL ANALYSIS

Selecting a Signum Service

Advanced Levels of Analysis

Signum Oil Analysis provides you with analysis options based on the Sample Point's application, adding a new dimension to your equipment or maintenance practices. The result? Signum Oil Analysis provides you with the insight you need to make important decisions about your equipment and your business.

The Sample Point data you provide during online registration is used to determine your Signum Service analysis options and to interpret your equipment's sample results. Signum uses the equipment manufacturer, model, and other operating parameters to provide you an overall assessment based on your application:

- **ExtendedS ervice** – Performs additional tests to support an Optimised Drain Interval (ODI) program and helps detect premature component wear for optimal engine and power-train performance.
- **ContaminationC ontrol** – Performs tests to monitor system cleanliness and measures lubrication performance to improve reliability. This service is specifically designed for circulation, compressor, gear drive, hydraulic, and turbine applications.
- **Precision Hydraulic Analysis** – Delivers high precision hydraulic system analysis to provide you with an assessment of equipment, contamination, and lubricant conditions. Helps you maximise equipment life and reliability while reducing maintenance costs.
- **ContinuedS ervice** – Performs testing to help improve reliability and detect problems before they result in costly downtime or expensive repairs. This service is designed for turbine applications and heat transfer systems. A one litre sample is required for tests on these systems.

HOW TO: Register Sample Points

Complete the following steps to register Sample Point data.

1. Click the **Sample Points** screen tab.
2. Click the **Sample Point – Edit** view tab.
3. Click the **New** button to add a Sample Point or Click the **Edit** button to modify an existing Sample Point.*
4. Add or modify basic Sample Point data.
5. Click the **Next** button.
6. Enter the specific details for the Sample Point.
   - Select Analysis – Signum Service
   - Create Unique Sample Routes
   - Establish Sample Frequency
   - Record Equipment Comments
7. Click the **Save** button to complete your registration.

Alternate Navigation

From the **Account** screen, drill down on the **Account hyperlink** and access the **Sample Point** view tab.

(*) *Contact your local Mobil representative if you are unable to perform this function.*

Taking a Representative Sample

Start with a representative sample to obtain accurate analysis results. For best results:

1. Establish a Sampling Schedule

- Set-up a sampling schedule.
- Take samples at a consistent interval and location.
- Sample as close to operating temperature as safely possible.

2. Follow Good Housekeeping Techniques

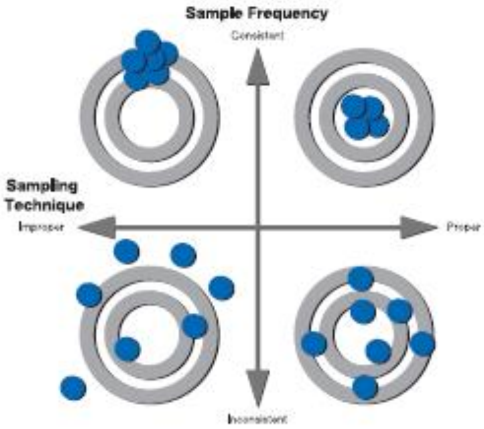
- Inspect work environment for safe operating conditions.
- Clean the area around the Sample Point.
- Use only approved sample bottles.

3. Record Sample Details

- Print sample labels online (See "How to Print Labels", below).
- Record equipment and sample details.
- Include sample date, hr/mi/km on oil and equipment, etc.

When, where, and how you sample impacts the quality of your results.

To hit the target, sample at a consistent frequency from the correct sample location using proper sampling techniques.



HOW TO : Print labels

To print sample labels **before taking samples**:

1. Click the **Home** page.
2. Click the Labels icon for the account. You will see the ***Sample Points - Sample Labels*** view.
3. Click **Search** from the **Sample labels** tool bar, enter your search criteria, then click **Go.** The labels that meet your search criteria will appear.
4. Click **Select All**. If you would like to further limit the labels you print, just click the **checkboxes** for the desired labels.
5. Click the **Create Labels** button.
6. The Report dialog box appears. Make sure that the **Select Report** print box has the correct selection **(Print Selected)** and your correct paper size - either Letter (US) or A4, then click **OK.**
7. If you would like to designate the location on the label paper to start the labels, just click the location's circle that corresponds to the desired location.
8. Click OK in the Reports dialog box and you will see the desired labels as an Acrobat file.
9. Click Print from the Adobe toolbar.

You can fill in (hand write) the sampling details (date sampled, equipment age, oil age, etc.) on the label prior to placing it on the sample. These details will be captured by the Signum laboratory at login, so please write legibly. You can also **print a sheet of 8 labels** for a single sample point to keep on hand by choosing "Print list 8x/Pg" in the Report dialog box, and your correct paper size - Letter (US) or A4.

To print sample labels **after taking samples**:

If you have already taken the sample, use Signum to print a computer-coded label which will help speed your sample through the laboratory. Follow steps 1-3 above. After searching, click the Edit button in the **Edit** field for the desired label; modify as desired and click **Save**. The sample label you have edited is automatically checked to print.
Then follow steps 5 - 9 above.

[1] Please note that the standard paper size for Europe is A4.
[2] When you have Acrobat Reader not installed on your PC, you can download it from http://www.adobe.com/products/acrobat/readstep2.html and install it.

Sampling and Labeling Instructions

When sampling, remember to:

- Update or add Sample Point registration data online.
- Print sample labels, adding the sampling details online to reduce your administration time, improve accuracy of data, and expedite your sample through the laboratory.
- Ensure area where sample will be taken is clean.
- Sample as close to operating temperature as safely possible.

Start with a representative sample to obtain accurate analysis results. For best results:

❶ Draw a representative oil sample from the sample point.

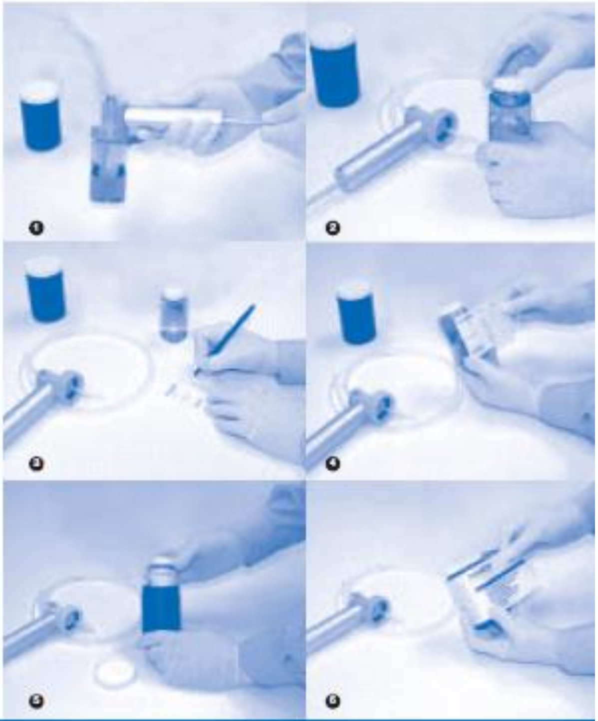
❷ Secure the cap to the sample bottle.
Visually inspect the sample for particulate, water or other contaminants.
If contamination is visible, take corrective action. Resample once the condition is corrected.

❸ Print your completed sample label online (See "How to Print Labels" on page 8).
If necessary, add any additional trend data (date, hr/mi/km, etc.) using a ballpoint pen.

❹ Affix the completed preprinted sample label to the sample bottle.

❺ Place the sample bottle into the black shipping container and secure the cap.

❻ Affix the preprinted mailing label to the container. Mail your sample immediately. Or place multiple samples in the provided express mailing bags.



Packing Instructions

❶ Use Signum approved sample materials.

❷ Do not tape sample bottle lids.

Inspecting Your Sample

A great deal of information can be gathered simply by looking at the sample. Inspect each sample carefully before submitting it for analysis.

Clarity

Clarity is an excellent indicator of contamination. A lubricant in good condition is clear and bright. Haziness or cloudiness indicates materials like water, wax, machine coolant, refrigerant, or incompatible lubricant are present. In some cases, the agent causing the haze or cloud actually forms a separate layer on the bottom of the container or on top of the oil.

Sediment and Particulate

Sediment and particulate tell more of the story. Non-magnetic sediment in an otherwise clear and bright sample may suggest dirt, dust, or sand contamination. Magnetic particulate could indicate rust or a severe wear situation.

Take corrective action before sending sample to the laboratory if contamination (water, dirt, metal, etc.) is visible. Since large amounts of contamination in the oil can damage laboratory equipment, resample once the condition is corrected.

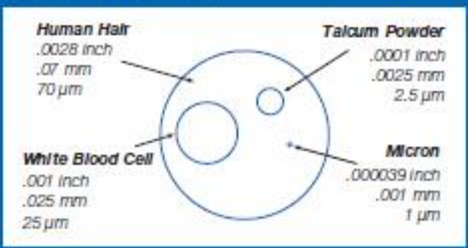
Retrieving Your Results

The Signum Oil Analysis laboratory is committed to providing complete and accurate analysis results. Your results are emailed or posted online typically within one to two business days after receiving your sample.

You can improve turnaround time by following these steps:

1. Mail your sample immediately.
2. Use approved shipping materials provided in the sample kit.
3. Use the online sample label printing feature which helps expedite your sample through the laboratory registration process.
4. Mail samples via Overnight/Courier Service or use First Class/ Priority delivery.

How big is a micron (μm)?



Lower range of visibility with the naked eye is 40 μm.

Points to Consider - Contamination Analysis

Laboratory analysis typically targets contaminants < 8 microns, which is 5x smaller than what is visible with the human eye *(see "How big is a micron?")*. Visible particles or water in a sample reflect the possibility of abnormal equipment conditions and corrective action is recommended.

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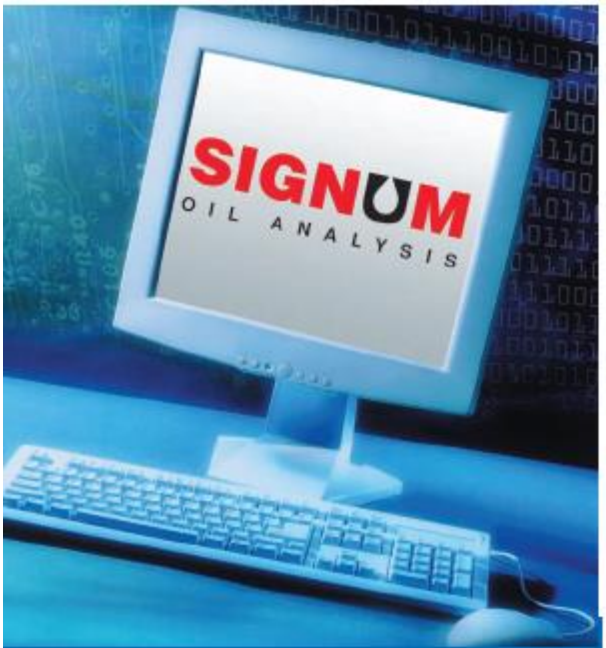

Track your sample online. The Sample status will be "In Progress" once registered at the laboratory.

Interpreting Your Analysis Results

Signum Oil Analysis provides an unparalleled knowledge of ExxonMobil lubricants through decades of experience and close OEM relationships. Our strong heritage of hands-on application expertise provides you a reliable analysis.

The overall assessment focuses on three areas that help identify:

- Equipment Condition
- Contamination Condition
- Lubricant Condition

Your Signum Oil Analysis report provides an easily readable, color-coded performance assessment with one of the following ratings:

- **Alert** – Conditions exist that exceed acceptable limits or require corrective action. Steps should be taken to confirm and correct the condition.
- **Caution** – Conditions are present that may require monitoring or diagnosis to minimise impact on equipment and lubricant performance.
- **Normal** – Equipment, contamination, and lubricant conditions are within an acceptable range.

Sample comments are provided to help identify potential problems, list possible causes, and recommend actions for follow-up.

Monitoring the Trend

To assess your equipment's condition:

1. **Interpret Your Analysis Results** – Gain an understanding of your equipment's operating conditions and its lubricated components. Limits applied to each sample can vary based on your Sample Point's registered manufacturer, model, application, and lubricant-in-service.
2. **Monitor the Sample Trend** – Trend identification is important to understanding oil analysis results. You should include critical sample information (e.g. date sampled, hr/mi/km, make-up oil, etc.) on the sample label. This data allows you to normalise the analysis trends to enhance your assessment.
3. **Review the Entire Report** – Proper condition assessment requires a complete review of the report. Changes in equipment condition typically coincide with the presence of contamination or changes in lubricant properties.

HOW TO: Print, Save, or View a Sample Report

1. Click the **Home** page.
2. Click the **Results** icon next to your account. You will be taken to the **Sample Points** screen, **My Results** view tab.

If there are no results available for your account, you will receive an error message.

3. Review the results. Click the checkbox next to the result you wish to display as a graphic report.
4. Click the **Create Report** button on the view tab tool bar.
5. Click OK in the Reports dialog box. The sample point result is now displayed as a graphic report in Adobe reader format.
6. Use the Adobe toolbar to print or save the report.

To view your results online without retrieving the Adobe report for each result, use the Unit ID hyperlink to drill down to the report details.

1. Click the Unit ID hyperlink, this will take you to Sample Point - History view for that sample point.
2. Click the Sample Point - Results view tab.
3. The results for that Sample Points last 4 samples are displayed.

[1] When you have Acrobat Reader not installed on your PC, you can download it from http://www.adobe.com/products/acrobat/readstep2.html and install it.

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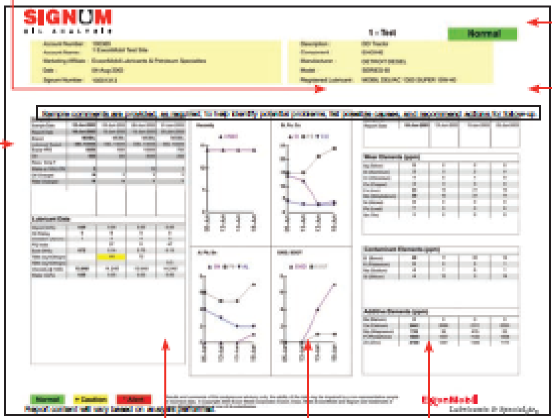
Signum Oil Analysis – Graphic Sample Report

Sample Point Data

Sample Point data that you provide during online registration is used to interpret the analysis results. By including equipment manufacturer, model, and other operating parameters, an overall assessment can be made for your application.

Sample Label Data

A completed sample label provides critical information for processing and interpreting your equipment's condition. By including key information, like hr/mi/km and date sampled, you help establish data points that assist in condition trending.



Results Interpretation

Proprietary control limits are applied based on your equipment's manufacturer, model, lubricant, and application. Sample Comments are provided, as required, to help identify potential problems, list possible causes, and recommend actions for follow-up.

Analysis Results

The Signum Oil Analysis report provides an easy-to-read, color-coded display of your sample analysis results in order to:

- Trend elements of equipment wear
- Identify contaminates that may impact performance
- Monitor lubricant condition

Confirming Alerted Conditions

You should confirm **Alert** analysis conditions prior to replacing or shutting down equipment.

Consider these confirming steps before taking action:

1. Review maintenance/operator records to identify condition.
2. Verify condition with other equipment monitoring tools – i.e. inspections, vibration, or thermography.
3. Utilise an on-site analysis test designed for the alerted condition.
4. Submit another sample to the laboratory for analysis.

Points to Consider - Applied Limits

Limits applied to each sample can vary based on your Sample Point's registered manufacturer, model, application, and lubricant-in-service.

In addition, the review process considers all report data and may correlate multiple results to determine an abnormal condition.

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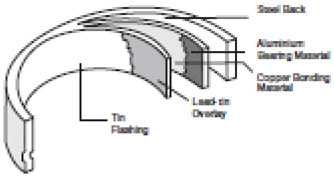
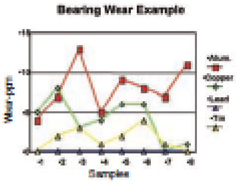
Understanding Equipment Condition

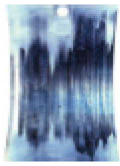
If you know what to look for in the analysis report, oil analysis can unlock a wealth of information about the condition of your equipment. You should understand the metallurgy of your components to respond to the trends in your analysis report. Reference your OEM material list to identify the metallurgical make-up of your components and to help evaluate sample results.



Understand Metallurgy



Monitor Elements



Plan Maintenance

Typical Equipment Component Metals

	Engine	Transmission	Differential	Final Drive
Aluminum (Al)	Pistons, Bearings, Blocks, Housings, Bushings, Blowers, Thrust Bearings	Pumps, Clutch, Thrust Washers, Bushings, Torque Converter Impeller	Thrust Washers, Pump Bushings	Oil Pump, Thrust Washers
Cadmium (Cd)	Journal Bearings			
Chromium (Cr)	Rings, Roller/Taper Bearings, Liners, Exhaust Valves	Roller/Taper Bearings	Roller/Taper Bearings	Roller/Taper Bearings
Copper (Cu)	Wrist Pin Bushings, Bearings, Cam Bushings, Oil Cooler, Valve-Train Bushings, Thrust Washers, Governor, Oil Pump	Clutches, Steering Discs, Bushings, Thrust Washers, Oil Cooler	Bushings, Thrust Washers	Bushings, Thrust Washers
Iron (Fe)	Cylinders, Block, Gears, Crankshaft, Wrist Pins, Rings, Camshaft, Valve Train, Oil Pump Liners, Rust	Gears, Discs, Housing, Bearings, Brake Bands, Shift Spools, Pumps, PTO	Gears, PTO, Shafts, Bearings, Housings	Gears, Bearings, Shaft, Housing
Lead (Pb)	Bearings			
Silver (Ag)	Bearings, Wrist Pin Bushing (EMD)	Bearings	Bearings	Bearings
Tin (Sn)	Pistons, Bearing Overlay, Bushings			
Titanium (Ti)				

Points to Consider - Normalise Your Data

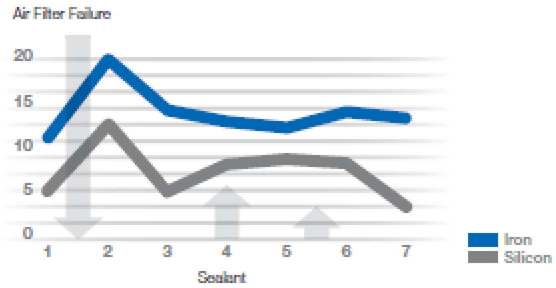
Looking at the analysis data without considering time or distance may lead to inaccurate conclusions about condition severity.
Evaluating the data trend relative to wear rate per **hr/km/mi** can enhance your assessment.

Points to Consider - Make-up Oil - Effect on Results

Equipment with high oil consumption will not return representative sample results. A potentially abnormal condition can be masked by escaping lubricant and by new lubricant make-up diluting the system volume. Record Make-up Oil on your sample label to include in your trend and sample assessment.

12

Understanding Silicon Conditions



Typical Equipment Component Metals (continued)

	Natural/Landfill Gas Engine	Turbine (Gas/ Steam)	Hydraulic/ Circulating	Compressor	Gear Drive	Paper Machine Oil
Aluminum (Al)	Pistons, Bearings, Blocks, Housings, Bushings, Blowers, Thrust Bearings		Pump Motor Housing, Cylinder Gland	Rotors, Pistons, Bearings, Thrust Washers, Block Housing	Thrust Washers, Oil Pump, Bushings	
Cadmium (Cd)						
Chromium (Cr)	Rings, Roller/Taper Bearings, Liners, Exhaust, Valves		Rods, Spools, Roller/ Taper Bearings	Rings, Roller/Taper Bearings	Roller/Taper Bearings	Bearings
Copper (Cu)	Wrist Pin Bushings, Bearings, Cam Bushings, Oil Cooler, Valve-Train Bushings, Thrust Washers, Governor, Oil Pump	Bearings, Oil Cooler	Pump Thrust Plates, Pump Pistons, Cylinder Glands, Guides, Bushing, Oil Cooler	Wear Plates, Bushings, Wrist-Pin Bushings, Bearings (Recips.), Thrust Washers	Thrust Washers, Bushings, Oil Cooler	Bearings Cages, Bushings, Oil Cooler
Iron (Fe)	Cylinders, Block, Gears, Crankshaft, Wrist Pins, Rings, Camshaft, Valve Train, Oil Pump Liners	Bearings	Pump Vanes, Gears, Pistons, Cylinder Bores, Rods, Bearings, Pump Housing	Camshaft, Block, Housing, Bearings, Shafts, Oil Pump, Rings, Cylinder	Gears, Bearings, Shaft	Bearings, Gears, Housings
Lead (Pb)	Bearings	Bearings	Bearings	Bearings		Bearings
Silver (Ag)	Bearings	Bearings	Bearings	Bearings	Bearings	
Tin (Sn)	Pistons, Bearing, Bushings	Bearings	Bearings	Pistons, Bearing, Bushings		Bearings
Titanium (Ti)		Bearings, Turbine Blades				

Points to Consider - Interpreting Silicon

The presence of silicon is often the reason for an increase in wear metals (see graph to the left). If however, high wear metals are not indicated then the silicon or dirt may have been introduced during sampling or from a non-abrasive silicone (i.e. silicone-based sealant, silicone defoamant, siloxane from fuel gas, or silicon rubber).

Identifying Contamination

Contamination is a primary cause of component wear or failure. You should identify the source and take corrective action to remedy the contamination; doing so will ultimately extend component and lubricant life while improving equipment reliability.

Three general sources of contamination include:

1. **Built-In Contamination** – Contamination from component manufacturing process or from the rebuild process.
2. **Self-Generated Contamination** – Contamination from system components worn or damaged by other contamination particles.
3. **ExternalIn gression** – Contamination from external sources.

The following elements can help identify contamination:

Element	Source
Boron (B)	Coolant, Possible Oil Additive
Chlorine (Cl)	Landfill Gas Contaminant
Potassium (K)	Coolant
Sodium (Na)	Coolant, Road Salt, Additive,
Silicon (Si)	Dirt, Dust, Sealant, Additive, Silicone Defoamant, Siloxane from Fuel Gas
Vanadium (V)	Residual Fuel Contamination

Remedies for Typical Contaminants

Contaminant	Description	Condition	Effect	Remedy
Fuel Dilution	Fuel dilution reduces viscosity and can accelerate wear. Unburned fuel may indicate a fuel system leak or incomplete combustion.	Extended Idling, Stop & Go Driving, Defective Injectors, Leaking Fuel Pump or Lines, Incomplete Combustion, Incorrect Timing	Metal to Metal Contact, Poor Lubrication, Cylinder/Ring Wear, Depleted Additives, Decreased Oil Pressure, Reduced Fuel Economy, Reduced Engine Performance, Shortened Engine Life	Check Fuel Lines, Check Cylinder Temperatures, Worn Rings, Leaking Injectors, Seals, and Pumps, Examine Driving or Operating Conditions, Check Timing, Avoid Prolonged Idling, Check Quality of Fuel, Repair or Replace Worn Parts
Fuel Soot	Fuel soot provides an indication of engine combustion efficiency.	Improper Air-to-Fuel Ratio, Improper Injector Adjustment, Poor Quality Fuel, Incomplete Combustion, Low Compressions, Worn Engine Parts/Rings	Poor Engine Performance, Poor Fuel Economy, Harmful Deposits or Sludge, Increased Component Wear, Carbon Deposits, Clogged Filters	Ensure Injectors are Working Properly, Check Air Induction/Filters, Extended Oil Drain Intervals, Check Compression, Avoid Excessive Idling, Inspect Driving/ Operating Conditions, Check Fuel Quality
Insolubles (Solids)	Solid particles in the lubricant that were ingested or internally generated.	Extended Oil Drain Interval, Environmental Debris, Wear Debris, Oxidation Byproducts, Leaking or Dirty Filters, Fuel Soot	Shortened Equipment Life, Filter Plugging, Poor Lubrication, Engine Deposits, Formation of Sludge, Accelerated Wear	Drain Oil, Flush System, Change Operating Environment, Reduce Oil Drain Interval, Change Filters
Particle Count High	Particle count provides a measure of contaminant levels in the oil.	Defective Breather, Environmental Debris, Water Contamination, Dirty Filters, Poor Make-up Oil Procedure, Entrained Air, Worn Seals	Erratic Operation, Intermittent Failure, Component Wear, Valve Sticking, Oil Leakage	Filter New Oil, Evaluate Service Techniques, Inspect/Replace Oil Filters, Inspect/Replace Breather, High Pressure System Flush, Evaluate Operating Conditions
Particle Quantifier (PQ) Index	PQ Index measures the mass of metallic (ferromagnetic) particles in the sample.	Wear Debris, Shock/ Overloading Conditions, Metallic Contamination, Dirty Filters	Metal-to-Metal Contact, Shortened Equipment Life, Intermittent Failure	Replace Worn Parts, Inspect/Replace Filters, Inspect/Clean Reservoir Magnets, Evaluate Operating Conditions
Ultra Centrifuge (UC) Rating High	Ultra Centrifuge rates the soluble sub-micron contaminants that can be precursors to system deposits (scale 0-8).	High Operating Temperature, Overloading Condition, Overextended Oil Drain, Improper Oil in Service	Erratic Operation, Intermittent Failure, Harmful Deposits or Sludge, Valve Sticking, Shortened Oil Life	Evaluate Operating Conditions, Shorten Oil Drain Intervals, Evaluate Equipment Use Versus Design, Use Oil with Oxidation Inhibitor Additives, Flush System
Water/Coolant	Water/coolant is a harmful contaminant that can cause significant damage to internal parts, e.g. bearings.	Low Operating Temperature, Defective Seals, New Oil Contamination, Coolant Leak, Improper Storage, Condensation	Engine Failure, High Viscosity, Improper Lubrication, Corrosion, Acid Formulation, Reduce Additive Effectiveness	Tighten Head Bolts, Check Head Gasket, Inspect Heat Exchanger/Oil Cooler, Evaluate Operating Conditions, Pressure Check Cooling System, Check for External Sources of Contamination

Points to Consider - Coolant Contamination

Indications of coolant (ethylene or propylene glycol mixed with water) can appear as water, sodium, potassium or boron elements (typical coolant additives). The water phase of coolant may be removed during operation leaving only a trace element of coolant additive to reveal this potentially serious problem.

Understanding Lubricant Condition

A lubricant performs a variety of functions in your application. The most important functions include friction control and efficient power transmission.

Maintaining the physical properties of the lubricant is important to extending the equipment's reliability and the life of the lubricant.

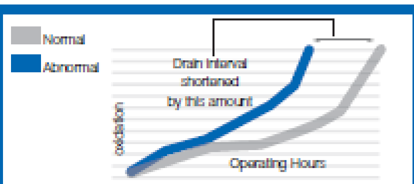
The following elements can help identify lubricant condition:

Element	Source
Barium (Ba)	Anti-wear, Corrosion Inhibitor, Detergent
Calcium (Ca)	Anti-wear, Corrosion Inhibitor, Detergent, Dispersant, Rust Inhibitor, Anti-oxidant
Magnesium (Mg)	Anti-wear, Corrosion Inhibitor, Detergent, Dispersant, Rust Inhibitor
Molybdenum (Mo)	Anti-wear, Anti-friction
Phosphorus (P)	Anti-wear, Corrosion Inhibitor, Detergent, Extreme Pressure
Zinc (Zn)	Anti-oxidant, Anti-wear, Corrosion Inhibitor

Remedies for Abnormal Lubricant Conditions

Contaminant	Description	Condition	Effect	Remedy
Acid Number High	Acid Number is a measurement of additives and the build up of harmful acidic compounds produced by oil degradation.	High Sulfur Fuel, Overheating, Excessive Blow-by, Overextended Drain Intervals, Improper Oil	Corrosion of Metallic Components, Promotes Oxidation, Oil Degradation, Oil Thickening, Additive Depletion	Evaluate Oil Drain Interval, Confirm Type of Oil in Service, Check for Overheating, Check for Severe Operating Conditions, Drain Oil
Base -Number -Low	Base Number is a measurement of an oil s ability to neutralise harmful acidic compounds produced during combustion process.	Overheating, Overextended Oil Drain, Improper Oil in Service, High Sulfur Fuel	Increased Wear Rate, Acid Build-up in Oil, Oil Degradation, Increase in Sludge Formation	Evaluate Oil Drain Intervals, Verify New Oil Base Number, Verify Oil Type in Service, Change Oil, Test Fuel Quality
Nitration	Nitration quantification can provide invaluable insight into the likelihood of deposit formation from oil breakdown.	Improper Scavenge, Low Operating Temperature, Defective Seals, Improper Air-to-Fuel Ratio, Abnormal Blow-by	Accelerated Oxidation, Acidic By-Products Formed, Increased Cylinder and Valve Wear, Oil Thickening, Combustion Area Deposits, Increased TAN	Increase Operating Temperature, Check Crankcase Venting Hoses and Valves, Ensure Proper Air-to-Fuel Mixture, Perform Compression Check or Cylinder Leak-down Test
Oxidation	Oxidation quantification can provide invaluable insight into the likelihood of deposit formation from oil breakdown.	Overheating, Overextended Oil Drain, Improper Oil in Service, Combustion By-Products/Blow-by	Shortened Equipment Life, Lacquer Deposits, Oil Filter Plugging, Increased Oil Viscosity, Corrosion of Metal Parts, Increased Operating Expenses, Increased Component Wear, Decreased Equipment Performance	Use Oil with Oxidation Inhibitor Additives, Shorten Oil Drain Intervals, Check Operating Temperatures, Check Fuel Quality, Evaluate Equipment Use Versus Design, Evaluate Operating Conditions
Viscosity High	Viscosity is a measurement of a fluid s resistance to flow at a given temperature relative to time.	Contamination Soot/Solids, Incomplete Combustion, Oxidation Degradation, Leaking Head Gasket, Extended Oil Drain, High Operating Temperatures, Improper Oil Grade	Harmful Deposits or Sludge, Restricted Oil Flow, Engine Overheating, Increased Operating Costs	Check Air-to-Fuel Ratio, Check for Incorrect Oil Grade, Inspect Internal Seals, Check Operating Temperatures, Check for Leaky Injectors, Check for Loose Crossover Fuel Lines, Evaluate Operating Conditions
Viscosity Low	Viscosity is a measurement of a fluid s resistance to flow at a given temperature relative to time.	Additive Shear, Fuel Dilution, Improper Oil Grade	Overheating, Poor Lubrication, Metal to Metal Contact, Increased Operating Costs	Check Air-to-Fuel Ratio, Check for Incorrect Oil Grade, Inspect Internal Seals, Check Operating Temperatures, Check for Leaky Injectors, Check for Loose Crossover Fuel Lines, Evaluate Operating Conditions

Points to Consider - Impact of Oxidation on Lubricant Life



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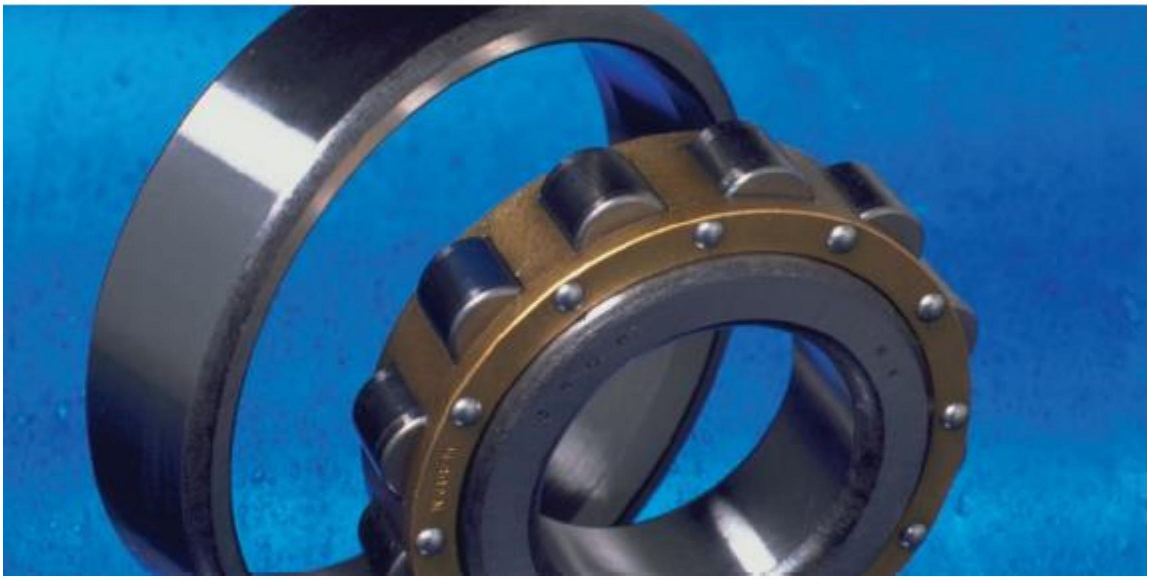
Engine Operating Conditions

Gasoline, Diesel, Natural Gas, Landfill/Digester Gas

You can be better prepared to take corrective action before equipment fails if you understand the potential sources of abnormal engine conditions.

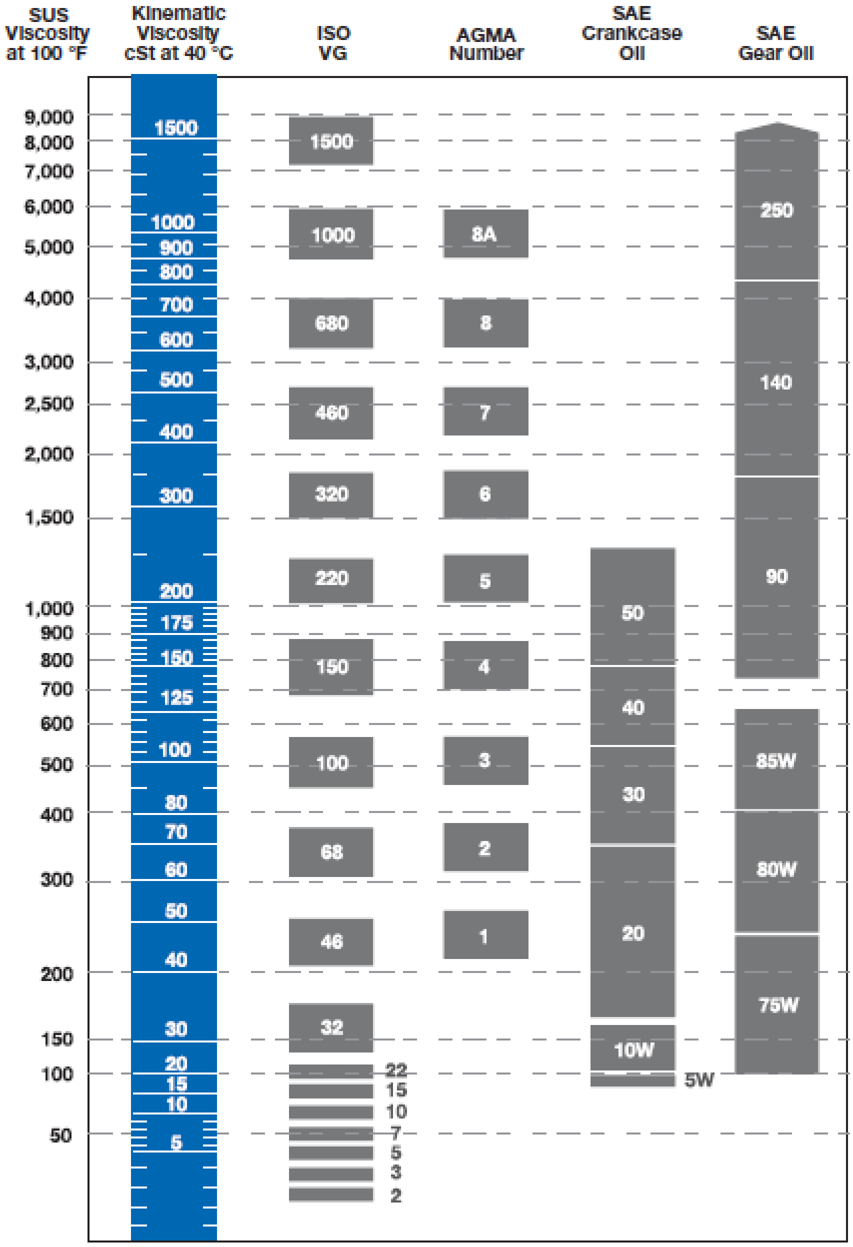
Potential Sources of Abnormal Engine Conditions

Condition	Potential Source
Crankcase Deposits	High Oil Temperature, Low Oil Temperature, Poor Combustion, Poor Oil Filtration, Blow-by, Condensation, Leaking Water Jacket, Clogged Crankcase Breather or Vent, Excessive Oil Spray, Inadequate Piston Cooling
High Oil Consumption	Worn or Stuck Rings, Ineffective Oil Ring Control, Low Oil Viscosity, High Oil Pressure, Leakage, Worn Pistons or Cylinders, Excessive Bearing Clearance, High Oil Level (Crankcase), High Crankcase Vacuum, High Oil Feed Rate to Cylinders, Normal in Landfill/ Digester Gas Applications
High Oil Temperature	Continuous Overload, Insufficient Jacket Water Cooling, Clogged Oil Cooler, Clogged Oil Lines, Sludged Crankcase, Overheated Bearing, Incorrect Oil Viscosity, Insufficient Oil in Pump or Crankcase, Insufficient Oil Circulation, Improper Timing
Improper Combustion	Unsuitable Fuel, Insufficient Air, Low Water Jacket Temperature, Sticking, Leaking, or Plugged Injectors, Unbalanced Cylinder Load, Low Injection Pressure, Incorrect Injection Timing, Low Compression Pressure, Leaking or Sticking Intake or Exhaust Valves Low Load
Ring Sticking	Poor Oil Quality, Continuous Overload Operation, High Oil Level (Crankcase), High Crankcase Vacuum, High Oil Feed Rate to Cylinders, Worn or Weak Rings, Insufficient Ring Side Clearance, Worn Pistons, Distorted Pistons or Cylinders, High or Low Jacket Water Temperature, Gas with High Siloxane Content



Lubricant Viscosity Grade Comparisons

For use as a general guide only. Viscosities are based on a 95 VI Oil.



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