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January 11, 2017

Board of Commissioners of Public Utilities
Prince Charles Building
120 Torbay Road, P.O. Box 21040
St. John's, NL A1A 5B2

Attention: **Ms. Cheryl Blundon**
Director of Corporate Services & Board Secretary

Dear Ms. Blundon:

Re: A Report by Newfoundland and Labrador Hydro (Hydro) pursuant to Order No. P.U. 22(2016) regarding the refurbishment of the gas generator engines at the Hardwoods Gas Turbine Plant and the Stephenville Gas Turbine Plant - Final Report

Enclosed please find the original plus 12 copies of Hydro's final report on the failure analysis, including recommendations for long-term reliability.

Please note that due to the size of the Appendix 1 (Consultant's Report), Hydro will be filing it electronically, with the exception of the Original to the Board. Should the Board or any Party require a paper copy please contact us and we will arrange to forward it to you.

Should you have any questions, please contact the undersigned.

Yours truly,

NEWFOUNDLAND AND LABRADOR HYDRO

Tracey Pennell

Tracey L. Pennell
Legal Counsel

TLP/bs

cc: Gerard Hayes – Newfoundland Power
Paul Coxworthy – Stewart McKelvey Stirling Scales
Sheryl Nisenbaum – Praxair Canada Inc.
Thomas Johnson – Consumer Advocate
Thomas J. O'Reilly, Q.C. – Cox & Palmer
Larry Bartlett – Teck Resources Ltd.

A REPORT TO
THE BOARD OF COMMISSIONERS OF PUBLIC UTILITIES

NEWFOUNDLAND AND LABRADOR HYDRO

Gas Turbine Failure Analysis

Final Report

January 11, 2017

Executive Summary

During the winter of 2016, in-service engine failures occurred at Newfoundland and Labrador Hydro's (Hydro) Stephenville and Hardwoods gas turbine facilities. On February 8, Hardwoods End A suffered a combustion can failure. On March 26, Stephenville End A suffered a low pressure compressor number 2 bearing failure. In both cases, damage was extensive and the units required refurbishment.

Failure analysis was completed for each engine to determine the root cause(s). In the case of Hardwoods, the root cause of the engine failure could not be conclusively determined, but through the process of investigation and analysis a number of potential causes were identified and a number of recommendations for improvement were made.

In the case of Stephenville, while not entirely conclusive, an external consultant has suggested the most probable cause of failure to be lube oil condition (breakdown of the oils capability to maintain a lubricating film), or a potential secondary cause of failure to be lube oil contamination (particulate in the oil). A number of recommendations for improvement were made for this unit as well.

The recommendations contained in this report will positively impact the reliability of the units. These recommendations are being actioned and Hydro commits to keeping the Board of Commissioners of Public Utilities (the Board) informed on the status of these actions in future reporting.

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1. Background

During the winter of 2016, in-service engine failures occurred at Newfoundland and Labrador Hydro's (Hydro) Stephenville and Hardwoods gas turbine facilities. On February 8, Hardwoods End A[1] suffered a combustion can failure. On March 26, Stephenville End A[2] suffered a low pressure compressor number 2 bearing failure. In both cases, damage was extensive and the units required refurbishment.

Both engines were shipped to Alba Power Ltd. for detailed analysis and refurbishment. In addition to this work, analysis was carried out to determine the root cause of the failures, and recommendations were investigated to improve reliability of the two generation plants. This report is the second of two reports, with the first submitted on December 6, 2016, in response to Board Order No. P.U. 22(2016) directing Newfoundland and Labrador Hydro (Hydro) to:

> *file a report by November 30, 2016 in relation to the refurbishment of the gas generator engines addressing the causes of the failures and the impacts and considerations in relation to the reliability of Hardwoods and Stephenville.*

2. Initial Actions

2.1 Hardwoods

On Monday, February 8, 2016, Hardwoods End A engine failed in service. Staff had been monitoring the engine during operation on the previous Friday and noticed a high exhaust gas temperature spread. While a high gas exhaust temperature spread can be indicative of carbon build up on the burners (nozzles), the readings were below any alarm levels. Staff completed troubleshooting of the high temperature readings by removing the burners. In doing so they found carbon build up. Staff cleaned and reinstalled the burners, and the unit was made available for service. At the time of failure on the following Monday, the engine was being shut

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[1] Engine serial number 202205

[2] Engine serial number 202204

down due to another observed high exhaust gas temperature (EGT)[3] spread that had also not reached the alarm level, but was observed to be trending upward. As employees initiated a shutdown to intervene and prevent damage, the failure occurred. The preliminary investigation by Alba Power Ltd. indicated that a combustion can[4] had failed causing internal damage to the housing and turbine sections of the engine. The engine was removed from the plant and replaced with a leased spare unit provided by Alba Power Ltd., maintaining a 38 MW plant rating from the normal 50 MW. The engine was last overhauled in 2011 as a planned overhaul, and had operated approximately 1100 hours to the time of failure. A tender was prepared for the overhaul and repair of the Hardwoods engine, as it was not under warranty. The contract was awarded to Alba Power Ltd., the only bidder, where it was disassembled for refurbishment and analysis to determine the cause of failure.

2.2 Stephenville

On March 26, 2016, Stephenville End A engine also failed in service. Preliminary investigation suggested that a bearing in the low pressure (LP) section (No. 2 LP compressor bearing) of the engine had failed and caused other internal damage. The Stephenville engine was not replaced and the plant remained de-rated to 25 MW from 50 MW while the engine was removed for overhaul. The engine was last overhauled in 2014 as a planned overhaul, and had operated approximately 110 hours since being returned to service. The Stephenville unit was returned to Alba Power Ltd. for disassembly, refurbishment, and analysis to determine the cause of the failure. This engine was still under warranty from its last overhaul in 2014.

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[3] Exhaust gas temperature (EGT) spread refers to the differential in readings between the thermocouples placed radially around the exhaust of a gas turbine.

[4] Each engine has 8 combustions cans. These cans are hollow metal cylinders in which compressed high pressure air is mixed with fuel for combustion. The combustion creates significant heat and creates a high temperature and pressure gas stream to drive the turbine.

Hydro engaged a consultant,[5] Performance Improvements Ltd. (PI), with expertise in gas turbines through AMEC Foster Wheeler to oversee the failure analysis process for the Stephenville engine. Their scope of work included being present for the disassembly of the engine at each stage, participating in the analysis, and advising Hydro on matters related to the failure investigation and recommendations. The consultant's report is contained in Appendix 1.

3. Failure Analysis

Root cause failure analysis was commenced for each of the Hardwoods and Stephenville engines. In each case, the engines were transported to an overhaul facility and progressively disassembled, noting any damage that might identify causal factors to the failure. Additional analysis was undertaken throughout the process when necessary for further understanding or investigation. Both engines were overhauled, successfully performance tested at the overhaul facility, and returned to Newfoundland to be installed and commissioned in November 2016. The Hardwoods engine has been successfully reinstalled and is in service with a full plant capacity of 50 MW. The Stephenville engine was successfully tested, including vibration checks, at the factory following refurbishment; however, it has not been able to be returned to service due to vibration issues experienced during on-site commissioning. Hydro has been working with the vendor to resolve the issue, but has not yet determined the cause for the continued vibration. Hydro is in the process of reinstalling the leased loaner engine, bringing the capacity of the Stephenville plant to 38 MW.

The root cause analysis was completed by Alba Power Ltd., with input from Hydro technical staff and the involvement of PI. The PI report related to the root cause failure analysis of Stephenville is contained in Appendix 1. The Alba Power Limited report related to the root cause failure analysis of Hardwoods is contained in Appendix 2. The analysis, as described in

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[5] Hydro engaged Performance Improvements (PI) as an owner's representative given that warranty remained on the Stephenville engine from its most recent overhaul. There was no remaining warranty on the engine at Hardwoods.

the following sections, includes recommendations for improving the operation and reliability of the engines.

3.1 Hardwoods

The Hardwoods engine was received at the overhaul facility on August 3, 2016. There were three steps to the inspection: 1) initial inspection without disassembly; 2) bulk strip inspection; and 3) detail strip inspection.

After initial inspection without disassembly, the engine was inducted into the facility and progressed through a bulk strip inspection which involves disassembling the machine into its major assemblies.

During the bulk strip inspection the following was observed:

- The front section of the gas turbine was found to be in reasonable condition and displayed typical signs of wear, coating deterioration and corrosion;
- The combustion section was found to be in poor condition with significant deterioration and material loss[6]; and
- The hot end components high pressure nozzle guide vanes and turbine blades displayed varying degrees of spatter and impact damage, resulting from the failed combustion can, which would require further detail strip and inspection.

The engine then progressed to the detailed strip inspection, which involved further disassembly of the major assemblies to determine the condition of component parts.

During this detailed inspection, the majority of components were found to be in a condition typical for a service run gas turbine. However, the combustion section and downstream

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[6] This engine had a Boroscope inspection of the combustion section completed in December 2015, with no indications of deterioration or material loss.

components were found to be in worse condition. The majority of the defects found were initiated by the combustion can failure which released material into the main gas path and resulted in secondary impact damage throughout the affected area.

As a result of the damage found, a number of components were rejected and could not be reused in the overhaul of the engine. This included combustion cans and casings, high pressure turbine blades and nozzle guide vanes, as well as other damaged components. Hydro's overhaul specification requires that when a unit is overhauled, all mainline bearings are replaced. This engine received the same overhaul as if it was a planned overhaul, and therefore, the time period is re-set for when the next overhaul is required.

The inspections performed identified the following potential factors in the combustion can failure. Also noted are any conclusions related to the potential factors. The root cause analysis, at this time, has not confirmed any of the following factors as conclusive, nor can it be confirmed that any of the following conditions existed. It is important to note that this engine had a planned boroscope inspection of the combustion section completed in December 2015, with no indications of deterioration or material loss or any recommendations for intervention.

Potential Factor	Conclusion
Incorrect material specification of the combustion can may have caused its premature failure	From the information available, the combustion chamber was found to be manufactured to the correct specification, and thus incorrect material specification has been eliminated as a potential cause of failure
Insufficient cooling within the combustion chambers could have resulted in overheating of the component and subsequent failure	During review of the individual components, there was no evidence of blocked cooling holes or any restrictions, therefore insufficient cooling within the combustion chambers is considered unlikely

Controls issues may have allowed the components to operate at higher than expected temperatures	A review of the site information related to the alarm and trip settings for exhaust gas temperature spread confirmed that the settings were in agreement with the Original Equipment Manufacturer recommended limits
Any contamination or defect in the exit burner could have affected the flame pattern and caused overheating of the combustion chamber	The burners were found to be clean on inspection for the Root Cause Analysis. However, they had been cleaned during the trouble shooting exercise on the Friday prior to the Monday failure. Thus, it cannot be determined conclusively if the burner condition containing some carbon build up prior to the failure would have contributed to the failure.
Contamination within the fuel can result in erratic combustion and affect the overall performance by inducing excitation into the gas turbine components	A review of previous fuel sampling and analysis conducted at the site indicates that the fuel was within the required specification and thus would not be a contributing factor to the failure. However, the sample is not indicative of the fuel being used at the time of failure, and thus cannot be ruled out.
Overheating was apparent on a number of the components within the gas turbine suggesting that these were subject to higher than normal operating temperatures	The remaining combustion chambers also displayed heavy burning and cracking indicating the complete combustion section was subjected to nonstandard operating conditions.

The root cause analysis into the failure of the Hardwoods engine has not conclusively determined a single root cause of the failure. The potential contributing factors in the failure have been determined to be related to fuel quality, nozzle/burner defects or contamination, and changes in operating temperature within the engine. The investigations performed have resulted in a number of recommendations which are presented below.

The investigation and failure analysis to date has resulted in the following recommendations:

1. Review and adjust, if required, the operating temperature conditions of the gas turbine throughout its operation.

2. Initiate fuel sampling and analysis on a regular basis to remove any potential concern with fuel quality in future.
3. Review and adjust, if required, alarm and trip settings for EGT spread that supersedes the previous protection settings recommended by the Original Equipment Manufacturer. Hydro has since modified, marginally, the alarm settings to increase protection. This will be further evaluated to determine if additional changes should be incorporated.
4. Increase regular preventive maintenance borescope inspection frequency to identify any indications of combustion chamber deterioration. This was recently completed on a bi-annual basis, and had already moved to an annual basis, but due to recent operation frequency, Hydro is moving to semi-annual frequency.
5. Review the control system for correct setting in acceleration/deceleration curves to ensure they are within specifications.

Hydro is reviewing the recommendations provided as a result of the failure analysis. As noted above, Hydro has already made some changes and will implement the remaining improvements in the existing systems, as appropriate. Some of the recommendations provided will require detailed review of historical data and a full engineering review of the recommended changes to identify how these changes could be implemented into the existing systems.

3.2 Stephenville

As the Stephenvile engine was still under warranty from its last overhaul performed by Alba Power Ltd. in 2014.[7], it was removed and returned to Alba Power Ltd. for investigation into the cause of the failure.

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[7] Payment of the overhaul work on this engine during warranty period will be determined once root cause analysis has been completed.

The engine was received at the overhaul facility on June 7, 2016, and underwent bulk strip inspection. This inspection confirmed that the No. 2 bearing had failed catastrophically, resulting in large quantities of debris which contaminated the oil system internally and externally. The extent of deterioration of the bearing also allowed the low pressure (LP) rotor to move forward, causing contact at numerous points within the gas turbine with the following damage:

- LP front shaft and air intake casing bearing cover;
- LP rotor stage 5 rotor blades and stator vanes; and
- LP coupling and oil thrower.

The engine then progressed through a detailed strip inspection which revealed the following:

- The impact/rub damage which occurred as a result of the LP rotor moving forward resulted in a large number of components requiring replacement or overhaul processing to return them to a serviceable condition;
- The extent of impact damage resulted in three of the main casing assemblies requiring replacement. These are the air intake, low pressure, and intermediate casings; and
- Overall, significant rework and replacement of components was required to return the gas turbine to a serviceable/overhauled condition.

As a result of the damage found, the following components were rejected and not reused: bearings, stator vanes, rotor blades, as well as other damaged components. This engine received the same overhaul as if it was a planned overhaul, and therefore, the time period is re-set for when the next overhaul is required.

The inspections performed identified the following potential factors in the Stephenville engine failure. While not conclusive, an external consultant has suggested the most probable cause of the failure to be lube oil condition (breakdown of the oil's capability to maintain a lubricating film), or a potential secondary cause could be lube oil contamination (particulate in the oil).

Potential Factor	Conclusion
Bearing failure	The bearing may have experienced catastrophic failure itself as a result of fit, etc. Further verification of the bearing assembly and installation has been completed and indicated that the bearing assembly and installation were correct.
Oil contamination	The majority of contamination present in the oil system is a result of the bearing failure. However, the current design of the oil system allows for contamination from any source within the oil system to potentially get into the engine, therefore, it cannot be conclusively determined that the contamination is from the failure or another operating condition.
Oil deterioration	A post failure oil sample was analyzed and found to be in poor condition. From the analysis, it appears that an oil change cannot be confirmed to have been completed after a previous oil test indicated that the oil was beyond acceptable limits[8].
Overheating of the bearing	Inspection of the failed bearing indicated signs of overheating on the bearing and housing assembly, but the remaining engine bearings showed no obvious signs of overheating. It was thus concluded that the overheating of the failed bearing was a consequence of the bearing failure and not a cause.
Correct lubrication oil specification	The oil used is an approved oil for the Olympus gas turbines.
Oil pump deterioration	The oil pumps were inspected and while they showed signs of contamination and scoring, this was considered to be a result of the bearing failure and therefore not a contributing factor.
Inadequate lubrication	Inspection of the remaining bearings did not reveal any evidence of oil starvation, therefore inadequate lubrication is not considered to be a contributing factor.

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[8] Reference Appendix 1, Root Cause Analysis Report, section 3

As a result of the investigation and failure analysis, the following recommendations were made:

1. Carry out a review of the vibration settings at site to further refine the alarm and trip settings.
2. Review maintenance scheduled for appropriate actions for step changes in vibration and appropriate actions for alarms.
3. Review the completed oil system to ensure cleanliness and filtration is adequate.
4. Continue to clean and flush oil system prior to re-installation of the gas turbine
5. Consider the addition of an off engine filter between the lube oil tank and the engine.
6. Review and adjust maintenance schedules for oil analysis, reporting, and replacement to remove any potential future concern with oil quality.

Further review and investigation during the onsite commissioning process has identified the most probable cause of failure was due to lube oil condition, or a potential secondary cause could be lube oil contamination. The lube oil parameter of concern is oxidation, which can potentially be caused by moisture within the oil, overheating of the oil, use of improper oil, or by the presence of combustion products within the oil. The specific cause(s) of the oxidation of the oil is not known, but the oil tank heater operation has been confirmed and ruled out as a cause, as discussed in section 4.2.

4. Operational Improvements

A number of operational changes have been identified which are expected to improve the operation of both units, and enhance the units' future short and long term reliability. These are essentially design upgrades to the various auxiliary and monitoring systems, which are expected to improve specific aspects of engine operation, monitoring and control, as well as specific process improvements.

In fall 2016, Hydro requested a proposal from Performance Improvements Ltd. to provide thorough review of aspects of gas turbine system design and operation. The scope of work to be completed, which is applicable to both the Hardwoods and Stephenville engines, has now been accepted by Hydro and encompasses the broad categories noted below, with further detail in this section. The consultant will proceed with this work, now that the root cause analysis is complete.

Design Review:

1. Vibration Protection System: Review the failure of the vibration system to identify an issue which could prevent catastrophic failure. Evaluate the effectiveness of the system design to protect the turbine.
2. Lube Oil System: review instrumentation and filter systems. Verify system status, correctness to specifications, and operability for return to service.
3. Magnetic Chip Detection System: Magnetic chip detection (MCD) system review for possible instrumented online option instead of manual inspection checks. MCD gives the earliest warning of turbine bearing wear/degradation.

As a result of the findings from PI regarding the lube oil condition and contamination, Hydro is taking the following immediate and comprehensive actions with respect to operational means and methods:

1. Operations Practices: review operations practices with respect to turbine operating condition/integrity monitoring and OEM recommendations.
2. Planned maintenance: review planned maintenance with respect to turbine operation/safety critical elements, operating condition/integrity monitoring and OEM recommendations.

Further detail on some of the above items affecting operational improvements, as well as additional actions, are further explained in the following sections.

4.1 Vibration Monitoring

4.1.1 Vibration monitoring location

During a review of the vibration monitoring system for the engines, an alternate vibration monitoring location recommended by the engine Original Equipment Manufacturer, Rolls Royce, was investigated. The existing monitoring location and the new alternate location were compared during the post overhaul engine performance testing process. When comparing the test data across the operation of the engines through all load points, the recommended new location consistently provided higher vibration readings. Higher vibration readings between sensor locations for the same operating condition are an improvement as it will trigger protection sooner than the previous location. The plan was to monitor this new location during commissioning of the engines to determine whether it is appropriate to make the change. The original location for the vibration monitoring was recommended by the package original equipment manufacturer, Curtis Wright Power Systems.

During the installation and commissioning process, however, testing of the new monitoring location recommended by Rolls Royce presented an issue. When installed, engine piping obstructed access to the recommended location, which is likely why the monitoring location has remained unchanged from its original location. Further consideration of changing the monitoring location will require additional detailed review with the engagement of Performance Improvements Ltd. to determine an appropriate alternate monitoring location.

4.1.2 Vibration settings

In its preliminary report, Hydro noted that due to concerns related to vibration alarm and trip settings, a review of alarm and trip settings was underway and would be finalized in the coming weeks. While settings were found to be in accordance with original recommendations, consideration is being given to setting more conservative limits to enhance unit protection without causing operational issues, such as nuisance tripping.

Further review of the vibration alarm and trip settings has confirmed that the alarm and trip settings are in agreement with the recommended limits. However, further review has indicated that there are delays associated with the activation of these alarms and trips which impact the timing of their activation. Additional review of the delay settings is required to ensure they are appropriate. OEM information is being sourced for these settings to confirm. This review is part of the Performance Improvements Ltd.'s. engagement.

4.2 Lube Oil System

4.2.1 Lube oil handling, sampling, and analysis

Due to concerns raised related to oil handling, sampling and analysis, specifically the condition of the lube oil prior to failure, a review of Hydro's procedures related to oil sampling and analysis has been initiated and Hydro intends to include this in the engagement with Performance Improvements Ltd. As a result of increased levels of operation, Hydro had previously made a change in oil sampling and analysis frequency from annually to quarterly.

Hydro has further increased the frequency of its sampling and analysis to monthly during the current operating season. This will ensure appropriate level of monitoring during the units' highest operational period. The results of this approach will continue to be reviewed and an appropriate frequency of oil sampling and analysis determined. This review is part of Performance Improvements Ltd.'s engagement.

4.2.2 Lube oil filtration

While lube oil contamination was identified as a possible cause of failure, there was no prior indication of issues with oil contamination. However, the level of debris found in the engine post failure indicates that contamination in the lube oil system from any source has the potential to find its way into the engine due to the inadequate level of filtration provided by the on-engine[9] filters. While the current design of the lube oil system includes a micron level of filtration, the filter is installed on the return to the tank. As a result, Hydro is investigating the benefit of installing additional lube oil filtration on the outlet of the tank before the engine. This review will be completed within Q1 2017. In addition, due to concerns related to the potential for moisture to enter the lube oil system, consideration will be given to the addition of a filter to remove any water which may find its way into the system. This review is part of Performance Improvements Ltd.'s engagement.

4.2.3 Lube oil heating

The engine lube oil is heated by a thermostatically controlled heater located in the lube oil tank. The function of the heater has been previously tested and proven to be operating correctly in all engine lube oil systems.

Additional testing and monitoring of the lube oil tank heater during site commissioning has confirmed that it functions within specified limits during operation. Therefore, it was determined not to have had a detrimental effect on oil condition.

4.3 Borescope inspections

It is recommended that the frequency of borescope inspections be increased to help identify any potential issues with combustion section components. Hydro was completing these inspections once a year and will increase the frequency of borescope inspections to twice a year, as recommended by Alba.

4.4 Review alarm and trip settings for Exhaust Gas Temperature spread

A review of all alarm and trip settings related to combustion section operation is being completed. Hydro will consider more conservative settings which will enhance engine

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[9] On-engine filters are an original design filtration system contained within the engine itself, and are not part of the external lubrication system.

protection without causing operating problems such as nuisance tripping. This review will be completed within Q1 2017.

4.5 Gas Turbine Resources

The Gas Turbine group has grown since spring 2014 due to increases in operational requirements for these generation units, and the changes in culture to increase operational reliability, beginning with the appointment of a General Manager for Gas Turbine facilities. Since that time, additional dedicated resources, such as an equipment engineer, asset specialist and production supervisor have been added. In the last two years, this team has made improvements to the reliability, availability and operation of the gas turbines, and continue to seek ways to improve reliability. The recommendations from these root cause analysis reports are important for continuing to drive the advancement of improved processes and procedures in order to increase reliability of these units.

4.6 Action Tracking

Hydro acknowledges there are a number of actions in this report that require close monitoring to ensure successful implementation. These actions will be tracked over the coming months, and Hydro will provide the Board with an update on the implementation, targeting submittal April 15, 2017.

5. Short Term Reliability Considerations

Both the Hardwoods and Stephenville gas turbines have had improved reliability in recent years as is described in the quarterly Rolling Generation Report submitted to the Board[10]. The reliability measure captured in that report is Utilization Forced Outage Percentage (UFOP) which is a standard measure for gas turbines. UFOP is defined as the probability that a generation unit will not be available when required. It is used to measure performance of standby units with low operating time such as gas turbines. The UFOP for Hardwoods and

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[10] http://pub.nl.ca/applications/IslandInterconnectedSystem/ComplianceFilings.html

Stephenville in 2015 was less than 7% and less than 16%, respectively, and are projected to be less than 5% and less than 15%, respectively, for 2016. Recent efforts on unit reliability therefore reflect this improvement over the years prior when both locations each had a year when UFOP exceeded 20%.

Hydro acknowledges that additional effort on unit reliability is required and is placing increased focus on these units. In the short term, the additional measures noted in this report will add to the improvements made in recent years as Hydro continues to refine its processes and procedures. This is a result of actions being taken in relation to operational issues, improvements in monitoring and control, etc.

Specifically, changes in vibration monitoring, alarms, and trips will allow earlier intervention and also help to prevent secondary damage in the event of a component failure. Further, improvements in lube oil handling, sampling, analysis and filtration will help to ensure the health of the bearings and ensure the longest life possible.

6. Long Term Reliability Considerations

In the longer term, a review of the entire operation, maintenance, and control of the units will ensure that all required protection is in place for the units and that the settings are in accordance with industry standards.

Performance Improvements Ltd. have been engaged to review all aspects of operation and control and will provide recommendations which will further improve the reliability of these units going forward.

Continued capital investment in equipment upgrades to more up-to-date technology related to monitoring, control and protection will provide trending operational data and the ability to monitor unit performance. For example, consideration of additional lube oil filtration is an item that, if it is determined will provide the appropriate benefit, will be included in the capital program for these assets.

As a result of the implementation of the actions identified thus far, along with improved operational controls, increased maintenance and inspection, staffing of plants during operation to allow for increased attention while operating, and aggressive investigation of issues, Hydro expects the short term and long term reliability of these units to improve.

Hydro is currently evaluating the long term need and role for gas turbines on the Island Interconnected System, both on the Avalon and at other locations across the island. This evaluation will inform if heavy investment into the Hardwoods and Stephenville current gas turbine engines is appropriate or if other options such as repowering or replacing is more appropriate. Hydro expects to complete this evaluation as part of the Phase Two Outage Inquiry.

7. Conclusion

Hydro's investigation into the root cause of the failures of the engines at Hardwoods and Stephenville is complete and has resulted in a number of operational and design improvements. These improvements are expected to enhance the units' short and long term reliability, where long term is contemplated to be current forecasted end of life dates of 2025 and 2028 for Hardwoods and Stephenville, respectively. The Hardwoods engine has been installed and commissioned, and has restored this generation plant to 50 MW. The Stephenville engine has vibration issues and will be returned to Alba Power. Hydro is committed to reliable operation of these units, and implementing the various recommendations contained in this report, with submission of an update to the Board on April 15, 2017.

APPENDIX 1 – CONSULTANT’S REPORT

PERFORMANCE IMPROVEMENTS (PI) LIMITED

Report To

NEWFOUNDLAND & LABRADOR HYDRO (NALCOR)

ROLLS ROYCE OLYMPUS C GAS TURBINE FAILURE INVESTIGATION
- Root Cause Analysis (RCA) Report -

Document Number P10854-RPT-004

Date	Rev	Description	Prepared	Checked	Approved
8 September 2016	0	Issued for Review	Doug Eynon	Chris Smith	Mike Guinee
9 January 2017	1	Issued as Final with Hydro comments agreed and incorporated	Doug Eynon	Chris Smith	Mike Guinee
11 January 2017	2	Issued as Final (2) with Hydro comments agreed and incorporated	Doug Eynon	Chris Smith	Mike Guinee

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CONTENTS

1. INTRODUCTION

Newfoundland & Labrador Hydro (Hydro), a Nalcor Energy company, operates a power station in Stephenville, NL Canada. The plant includes a power generation package driven by two Rolls-Royce Olympus Mk 2022C gas turbines. One of the Olympus gas generators (GG), s/n 202204, was taken out of service 26 March 2016 due to a catastrophic failure of the LP Compressor rear thrust bearing (GG No 2 Bearing).

The GG was removed and shipped to gas turbine specialist vendor Alba Power Ltd (Alba) workshop in Aberdeen UK, who had previously overhauled the GG for Hydro, for inspection and investigation to determine the cause of failure.

Performance Improvements Ltd (PI) were commissioned by our parent company AMEC/FW (Power & Process Americas business unit) on behalf of Hydro to attend and report on the strip and inspections at Alba, and to conduct a failure investigation and root cause analysis (RCA).

PI's Specialist Rotating Equipment Consultant, Doug Eynon, was assigned to perform the agreed scope of work covering the inspections and bearing failure investigations. Doug liaised and shared information with Hydro's focal point for the investigations, Ryan Cooper.

Bulk Strip and Detail Strip Reports were issued previously to Hydro on the 18 July and the 18 August 2016 respectively. An interim Preliminary RCA Report was also issued on 25 July 2016 at Hydro request.

Much of the failure investigation findings contained in the previous reports naturally feed into this the final RCA Report, which is the concluding deliverable in our contractual arrangement with Amec/Hydro. Being the most recent in PI's investigations sequential reporting, our Detail Strip Report, doc ref P10854-RPT-003 is contained for reference in Appendix 1.

2. BACKGROUND

The GG had previously been overhauled and performance tested by Alba in Aug/Sept ’14, and installed and commissioned in October ‘14. The GG No 2 bearing failed on the 26 March ’16 after seventeen months in service, having operated for approximately 90 hours (on standby duty) during that time. The deteriorating operating condition of the bearing remained unknown to Hydro Operations staff and was revealed only when the GG vibration detection system activated shutting the unit down. However, this was too late in preventing the failure of the bearing.

Post failure checks at Hydro by Alba field service engineer found that the HP rotor rotated freely by hand but the LP rotor was tight to turn and was snagging internally. Inspection of the magnetic chip detectors (MCD’s) & baskets in the main line bearings lube oil return lines revealed very significant metallic debris in the No 2 and No 3 bearings common detector, which along with the tight LP rotor confirmed a mechanical failure at the No 2 bearing – the LP Compressor rear/thrust ball bearing. The Alba engineer also found the GG lube oil to be a very dark colour with an acrid/burnt odour (possibly indicating oil oxidation). Alba’s Field Service Report of 29 March ’16 is contained for reference in Appendix 2.

The GG was removed and returned to Alba in Aberdeen for strip inspection and failure investigation. PI were in attendance at Alba’s workshop throughout the GG Receipt/Induction, Bulk and Detail Strip Inspections. (Partial Detail strip and inspections were added to the Bulk Strip scope, comprising removal of GG main line bearings and lube oil system components for inspection, in order to help expedite the failure investigations.) With Alba support PI conducted close visual inspections of components identified as potential contributors to the failure and those damaged as a result of the failure.

This Report discusses the failure investigations and RCA process, and PI’s analysis of the findings leading to our conclusions on the causes behind the No 2 bearing failure and resulting damage.

3. RCA CONCLUSIONS ON CAUSE OF FAILURE

3.1. Summary

From analysis of evidence found during our investigations PI's conclusion is that the No 2 bearing failure was most probably caused by poor lube oil condition, specifically oxidation. Collapse of the bearing ball/race interface oil film resulting in metal to metal contact skidding is considered to be the most likely failure initiation mechanism.

However, in view of the critically inadequate on-engine lube oil supply Pressure Filter (250 microns, versus 5 microns typical for turbo machinery), along with the easily possible ingress of dirt into the oil reservoir tank during top-ups, it is considered that lube oil contamination cannot be ruled out and so must be considered as a second potential initiating cause of failure.

Ultimately, there is no way to conclude with certainty which one was the initiating cause of failure.

Recommendations

Poor oil condition/oxidation is of itself an effect, not a cause. In PI's view the condition was probably due to a lube oil operation/maintenance management related cause. It is recommended that Hydro considers a review to identify causal factors and changes in operational practices to address them in order to help prevent similar bearing failures in the future. (PI also make further recommendations with respect to other concerns highlighted in our investigations relating to the Lube Oil and Vibration Detection Systems and Hydro's Operations/Maintenance. Refer to Section 8 of this Report, Outstanding Issues & Recommendations.)

3.2. Failure Cause Analysis

To define "cause" (and effect) in context with, and for the wider purposes of, the investigations PI have broken it into the three elements below.

- Initiating Cause, which is the physical causal mechanism
- Root Cause, which is the reason behind the Initiating Cause
- Damage Cause, which is the reason behind the extent of damage incurred.

Initiating Cause of Failure

The initiating cause of failure is concluded to be poor lube oil condition, specifically oxidation. It is also considered that ingress of foreign contaminants into the lube oil system (and passed through the inadequate oil supply Pressure Filter to the GG bearings) may have been causal. Although PI consider it less likely than oil oxidation, oil contamination cannot be excluded as a potential initiating cause. There is no way to conclude with certainty which one was causal in the failure.

Lube Oil Oxidation

Laboratory analysis of the GG lube oil was carried out by two independent tribology specialists AGAT Laboratories, Calgary, Canada and SKF (UK) Ltd, Aberdeen, Scotland. (AGAT is Hydro's oil condition monitoring/analysis Contractor, and SKF (bearing manufacturer/specialist) was contracted by Alba to analyse an oil sample as part of bearing failure investigations.)

The AGAT Report shows Oil Sample number 130090 dated 16 March 2015 as the most recently recorded sample analysis prior to the bearing failure 26 March 2016. AGAT report the sample as being oxidised to Upper Critical level with a high Viscosity.

(PI note that the AGAT Report on Oil Sample number 131037 dated 6 May 2016, several weeks after the bearing failure, reports the sample as having a very low oxidation level. As this sample is understood to have been taken from the same tank fill/inventory as the previous sample of March 2015 the analysis would suggest that the high oxidation condition had improved. As such improvement is not possible PI believe there must have been a mix-up in sampling or analysis and therefore dismissed the matter from further consideration with respect to the bearing failure.)

The SKF Report was on an oil sample taken from the GG on receipt at Alba workshop after the bearing failure. SKF report the sample viscosity as being outside the oil manufacturer's recommended limits, with a high Total Acidity which SKF state typically indicates oxidation of the oil.

Although the AGAT and SKF Reports do not provide a like for like comparison in all analysis aspects/parameters they both agree on the oil oxidation, pre and post failure respectively, and that the oil condition was outside of recommended operating limits.

It is considered that the continued use of the lube oil in the critical condition as reported in the AGAT Report of March 2015 may have resulted in localised collapse of the interface oil film at the No 2 bearing resulting in metal to metal contact and skidding of the bearing balls on the races, initiating a process of continuous metal loss by contact abrasion leading to the mechanical failure of the bearing.

(It should be noted that a ball bearing is likely to fatigue and fail sooner than a roller bearing (in a given application) where the lube oil film has degraded and its load carrying capacity compromised. This is due to the ball's "point contact", compared to the roller's "line contact", having a greater dependency on oil film integrity. Additionally, in the case of the GG application the ball bearings (Nos 2 and 4) have a high thrust load component, further increasing the dependency on the oil film integrity.)

The AGAT and SKF Reports are contained for reference in Appendix 3 and Appendix 4 respectively.

Lube Oil Contamination

Early in our investigations PI expressed concern about the suitability of the Olympus package "on-engine" lube oil Pressure Filter and queried its micron rating. The Filter, located downstream of the main lube oil pump in the oil supply piping to the GG, is the last line of defence in protecting the GG main line bearings from potentially damaging contaminants in the lube oil and yet it is only a metal gauze open mesh design. (There is also a Low Pressure Filter located upstream of the lube oil pump which is of a larger mesh.)

It was later confirmed that the Pressure Filter gauze is a 60 standard mesh, meaning its filtration rating is 250 microns nominal. From known industry standards/practices, and in PI's experience, the lube oil filtration rating for turbo machinery is typically around 5 microns. (The Low Pressure Filter mesh was confirmed as 40 mesh, 425 microns nominal.) Photos showing confirmation of the mesh/filtration micron rating of both Filters, along with an ISO Standard Mesh Table, are contained for reference in Appendix 5.

There is an off-engine true "micronic media" filter located in the scavenge/return oil piping to the reservoir tank with a 10 microns nominal rating. However, there is no off-engine filter in the lube oil supply piping from the reservoir tank to the GG. The oil system is therefore exposed to the ingress of dirt, or contaminants in replacement oil that has not been pre-filtered, and is dependent on a filter (the Pressure Filter) which allows particles up to 250 microns (10 thou) in size to pass through to the GG bearings. As mentioned, the filtration rating for turbo machinery is typically 5 microns (0.2 thou) - ie smaller than the Pressure Filter rating by a factor of 50.

In view of the critical inadequacy of the on-engine Pressure Filter along with the easily possible introduction of foreign contaminants into the lube oil system, it is PI's view that oil contamination cannot be ruled out and so must be considered as a second potential initiating cause of failure.

Root Cause of Failure

Poor oil condition/oxidation is of itself an effect, not a cause. It is considered that insufficient oil condition monitoring/management and responsiveness to oil analysis recommendations may ultimately be the root cause of failure.

Hydro advised that the last oil change before the bearing failure was at the GG reinstallation & commissioning October 2014. If PI's interpretation of AGAT Laboratory lube oil analysis trend Report provided by Hydro is correct, and the Report details are correct, the oil's oxidised condition was at "Upper Critical" level (ref sample No 130090 dated 16 March 2015), requiring replacement of the oil, but continued in operation for a further year until the bearing failed on 26 March 2016.

Also according to the AGAT Report, it would appear that the sample/analysis of 16 March ’15 was the only one between the GG commissioning and the bearing failure, a period of seventeen months. The AGAT Lube Oil Analysis Report on the pre bearing failure oil condition is contained for reference in Appendix 3.

In addition to the above, the post failure lube oil sample analysis by SKF agreed with AGAT’s analysis that the oil was highly oxidised and its condition exceeded manufacturer recommended operating limits, as well as identifying significant ferrous based metallic particles/contaminants in the oil from the bearing failure.

The No 2 bearing was also sent to SKF for failure analysis. SKF’s assessment of the bearing failure initiation mechanism aligns with PI’s opinion regarding the metal to metal contact causing skidding and abrasion of the balls and races, which SKF describe in their Report as “adhesive wear”. The SKF Report, ref RPCM507_ALBA PO POWER_160617_DF dated 17 June 2016, is contained for reference in Appendix 4.

Cause of Failure Damage

The cause of failure damage at the No 2 bearing and the secondary damage throughout the GG was the vibration detection system not activating early enough to prevent and protect against such failure per its design purpose. The extent of damage incurred was a direct result of the late activation.

On review of the vibration system during PI’s investigation into the bearing failure, Hydro confirmed that the high vibration Alarm and Trip set points were correct in accordance with system design specifications, at 1.0 inch/second peak and 1.2 inch/second peak respectively with a 1 second time delay for both.

Close review of the vibration trend leading up to the bearing failure showed that although there were several high amplitude spikes above the trip level before the failure their duration appeared to be less than 1 second which would explain why the trip did not activate until such a late stage. (It was also noted that several spikes above the Alarm level were more than 1 second duration and should have activated the Alarm but did not do so. At the time of writing, the reason for this has not been established.) The vibration trend is contained in Appendix 8 for reference.)

From the information provided to PI, it appears that the vibration trip might well have operated correctly per system design. Whether by design or not, it is clear that the vibration system did not operate early enough to protect the GG from the bearing failure and consequential damage incurred.

PI suggest that the vibration system requires further review and remedial action to improve GG protection and prevent similar failure in the future. (Refer to this Report Section 8.2, Vibration Detection System.

4. ANALYSIS OF NO. 2 BEARING FAILURE CHARACTERISTICS

From PI's failure investigation findings and RCA, the following are identified as the key attributes that characterize the No 2 bearing failure process and consequential damage.

- The multiple flat facets and misshape of all the No 2 bearing balls clearly demonstrate that they had experienced multiple instances of locking up and skidding over a considerable period of time, releasing metal fines and fragments from contact abrasion into the lube oil.

- The bearing's continuing contact abrasion along with the LP Compressor rotor's natural operating thrust forward resulted in extensive metal loss particularly on the forward side of the outer race ball grooves due to centrifuging of the abrasion debris within the bearing. The LP Rotor "ground" its way forward, coming into running contact with adjacent static components. The continuing running contact caused secondary damage of varying severity over the length of the LP Rotor, and also resulted in impact damage to a significant percentage of HP Compressor Rotor blades from damage debris released into the compressor air path.

- The lube oil was found to be in an oxidised condition at an "Upper Critical" level prior to the bearing failure (ref AGAT Report, oil sample No 130090 dated 16 March 2015) which had affected its viscosity beyond oil manufacturer recommended operating limits, undermining its oil film load carrying capacity. From Hydro records it appears that the oil continued in use in the degraded and worsening condition for at least a year before the bearing failure. It is thought that oil film collapse locally within the No 2 bearing, resulting in ball/race metal to metal contact, was the most likely initiating cause of failure.

- The lube oil was also found to be very significantly contaminated with metal particles and fines from the bearing failure damage. Metal particles were found in the on-engine Pressure Filter which is the final filter in the oil supply piping to the GG bearings. Simple pour tests of supply oil samples showed that all of the fines and some of the metal particles could pass through the Pressure Filter gauze and therefore to the GG bearings. It was apparent from the test that metal particles in the oil must have been recirculating around the system through the GG bearings, with the scavenge/return oil filter relief bypass valve having lifted due to filter blockage. It is clear that recirculation of metallic contaminants in the lube oil would accelerate the bearing failure process. (All the GG main line roller bearings surfaces showed a dull pitted appearance caused by the metallic contaminants.)

- The on-engine lube oil supply Pressure Filter gauze was confirmed to be a standard 60 mesh with a 250 microns filtration rating which is inadequate to prevent potentially damaging particles/contaminants in the oil passing into the GG bearings. (Turbo machinery lube oil filtration rating is typically around 5 microns.)

- Considering the extensive ground away metal loss of several millimetres axially at No 2 bearing and LP Compressor front bearing housing, and rotor blades rubbing and eventually clashing with stator vanes, PI woud have expected the GG to be operating in a high and worsening vibration condition for a considerable period of time leading up to the final mechanical failure of the bearing. However, the GG vibration trend (ref Appendix 8) does not indicate a high/increased vibration level until two minutes before the GG high vibration trip, which we believe is likely to be when the bearing cage started to fail mechanically and break up.

  It is unlikely that such extensive wear and damage in process as the bearing balls ground forward into the races, and with the balls worn/faceted out of round due to skidding, could occur within two minutes and without causing vibration high enough to warrant/cause a trip.

  It is clear that there is a question on the vibration system operation or sensitivity/effectiveness (and assuming the alarm/trip set points were indeed correct).

5. RCA PROCESS

It became apparent during the early stage of investigations that the cause of failure was either related to a lube oil issue or to a GG build bearing/installation issue, which allowed PI to focus our efforts accordingly to determine root cause. The RCA was therefore centred on the elements below identified as being potentially causal in the failure, with their respective outcomes presented.

5.1. Review of Alba Records

- Verification of GG build records to verify correctness to specifications, with particular regard to bearings installation.
  Outcome: Completed. Records were verified as complete and correct to OEM/ Alba specifications.

  At the time of issue of PI's Preliminary RCA Report, verification of the No 2 bearing assembly and installation criteria remained outstanding. These have since been confirmed as correct to specifications. PI's Verification Report is contained for reference in Appendix 6.

- Confirmation of main line bearings correct part numbers and traceability back to OEM Modification Standard.
  Outcome: Completed. Verified as correct to OEM/Alba specifications.

- Information on any previous repair of No 2 bearing.
  Outcome: Not completed. Alba confirmed that the No 2 bearing (matched pair) was refurbished (as were all the main line bearings). PI repeatedly requested a copy of the repair report from Alba to verify repair compliance to the bearing manufacturer's original design specifications. However, from PI's discussions with Alba it appears that the Repairer is unwilling to divulge information on the repair process and technical criteria as they are considered to be confidential Intellectual Property.

- Confirm correct lube oil supply to main line bearings - comprising main and scavenge oil pumps, pressure regulators, in-line filters, and flow metering jets to verify correct oil pressure and flow distribution.
  Outcome: Completed. Verified as correct to OEM/Alba specifications (and in particular the oil flow metering jet for the No 2 bearing). A diagram of the GG lube oil system showing the main line bearings and metering jets arrangements is contained for reference in Appendix 7.

  In addition, inspection of the main line bearings assemblies confirmed there was no oil system over heating, eg from reservoir tank heater fault. Only the points of damage resulting from metal to metal contact during the No 2 bearing failure process showed signs of discoloration caused by friction over heat.

- GG post overhaul performance test results vs acceptance specifications – in particular, main line bearings lube oil system operating pressures/flows/ temperatures, vibration levels and LP & HP rotors run down times.
  Outcome: Completed. Verified as correct to OEM/Alba specifications.

- Commissioning records for the GG return to service.
  Outcome: Completed. Verified as correct to OEM/Alba specifications.

5.2. Review of Hydro Operations Records

- Operating trends data and events logs leading up to the time of failure.
  Outcome: Completed.

  Hydro provided PI with samples of GG vibration trends and the turbine operation Events Log leading up to the No 2 bearing failure. From the data provided there is no clear change in pattern/trend over the samples time period from 4 March to the failure run on 26 March.

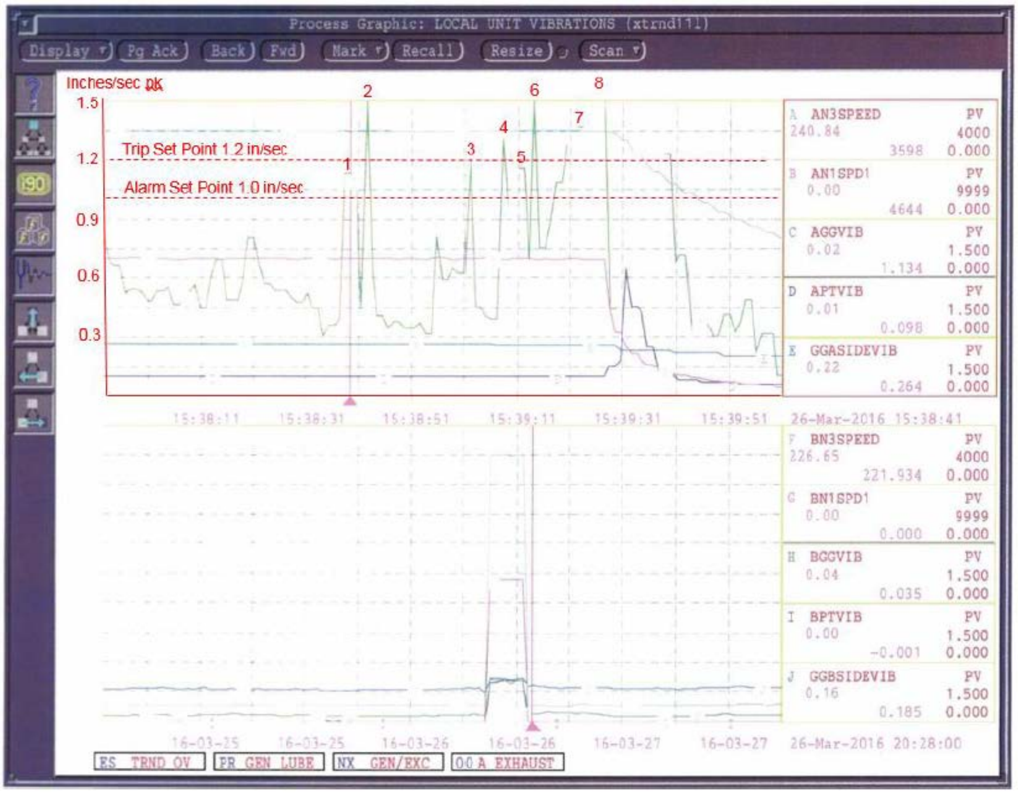
  The vibration trend on the date of failure shows a steady running level slightly higher than the previous samples which, however, don't reach N1 full speed and so comparison validity is uncertain. Levels remained steady up until approximately two minutes before the bearing failure where the vibration level step-changed, increasing dramatically and becoming erratic until the GG finally tripped on high vibration. It is clear that the sudden change was the onset of mechanical failure of the bearing.

  During the erratic period seven or eight high spikes occurred, all at amplitudes above the high vibration alarm set point 1 inch/second peak. Five of the spikes were above the high vibration trip set point 1.2 inches/second peak. However, close review of the spikes showed that those above the trip level appear to be of a duration less than the 1 second time delay designed into into the trip function. The trip finally activated at the fifth (prolonged) spike at 1.57 inches/second peak, which is obviously significantly higher than the design trip set point, but is presumably due to the time delay.

  It was also noted that several spikes above the Alarm level were more than 1 second duration so should have activated the Alarm but did not do so, except for a single activation 4 seconds before trip. The reason for this anomaly has not yet been established. The vibration trend is contained in Appendix 8 for reference.)

  Given the above and the extensive damage incurred before the GG finally tripped, there is unquestionably a serious concern on the design or operation of the vibration detection system.

The trend graph below shows the sudden change in vibration level and pattern and the multiple alarm and trip level spikes leading up to the trip activation (recorded in the Events Log at 15:39:27 pm). Analysis of the GG Vibration Trend along with the operation Events Log are contained for reference in Appendix 8



A AN3SPEED PV
240.84 4000
3598 0.000

B AN1SPD1 PV
0.00 9999
4644 0.000

C AGGVIB PV
0.02 1.500
1.134 0.000

D APTVIB PV
0.01 1.500
0.098 0.000

E GGASIDEVIB PV
0.22 1.500
0.264 0.000

F BN3SPEED PV
226.65 4000
221.934 0.000

G BN1SPD1 PV
0.00 9999
0.000 0.000

H BGGVIB PV
0.04 1.500
0.035 0.000

I BPTVIB PV
0.00 1.500
-0.001 0.000

J GGBSIDEVIB PV
0.16 1.500
0.185 0.000

- Lube Oil System - design, operation and maintenance.
  <u>Outcome:</u> Competed as far as practicable within the scope of PI's investigations. Several concerns were noted and reported to Hydro along with our recommendations for review or further investigation. Refer to Section 8.1 of this Report, Lube Oil System.

- GG Vibration Detection System - design, operation and maintenance.
  <u>Outcome:</u> Competed as far as practicable within the scope of PI's investigations. Several concerns were noted and reported to Hydro along with our recommendations for review or further investigation. Refer to Section 8.2 of this Report, Vibration Detection System.

- Operations/Maintenance records and practices.
  <u>Outcome:</u> Competed as far as practicable within the scope of PI's investigations. Several concerns were noted and reported to Hydro along with our recommendations for review or further investigation. The concerns mainly centre around lube oil condition monitoring and management practices, particularly in consideration of the inadequate filtration of the lube oil supply to the GG. Refer to Section 8.3 of this Report, Operations/Maintenance.

- GG Commissioning records.
  <u>Outcome:</u> Completed. Verified as correct to Alba procedures and specifications.

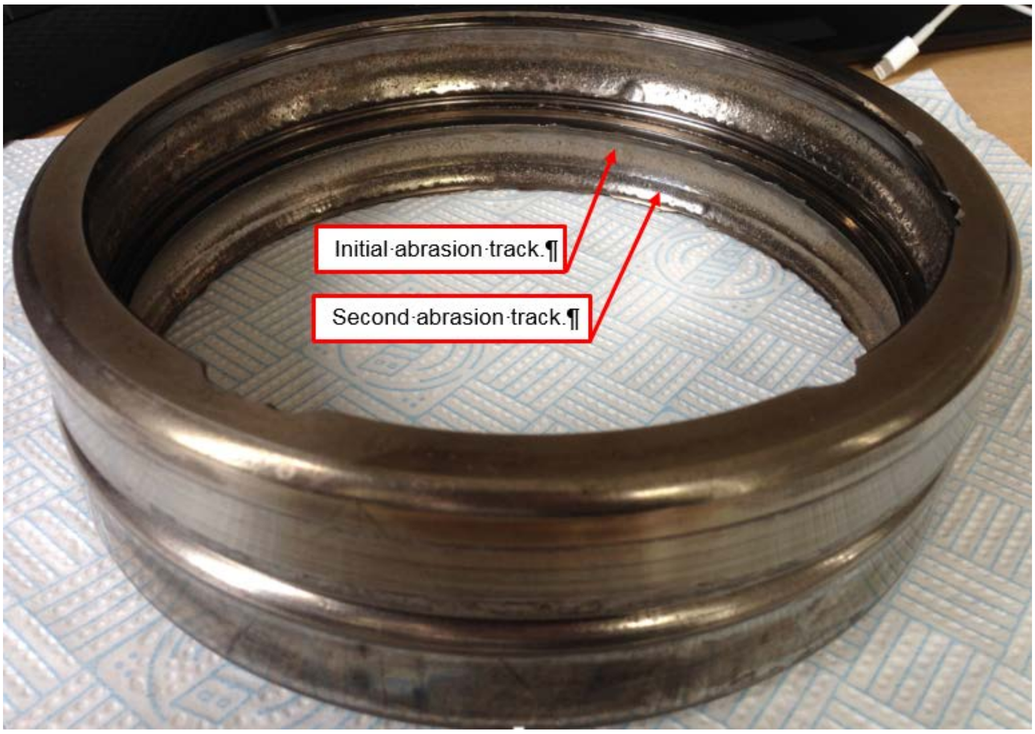
6. PRINCIPAL FAILURE FINDINGS

This Section is substantially a summary extract from PI's Bulk & Detail Strip Reports and is included in this Report to aid completeness.

6.1. No 2 Bearing Failure Process

The photo below shows the surface conditions and misshape of the bearing balls. Multiple flat facets are clearly visible caused by skidding of the balls on the races which is thought to have resulted from the collapse of the lube oil film locally within the bearing due to the oil's oxidised condition. A segment of broken bearing cage is shown in the background.

The photo below shows the extensive damage and metal loss at the bearing outer races ball grooves, particularly on the forward side (bottom side in photo) resulting from the axially biased abrasion process due to the LP Compressor Rotor thrust forward.



The arrowed areas in the above photo show two distinct abrasion track rings in the axial direction that are thought to indicate two phases of wear. The initial track ring was early in the failure process where the LP Compressor Rotor was moving forward within its build axial clearance. The second track ring is where the Rotor came into contact with neighbouring static components which caused an increased resistance to the Rotor forward movement resulting in the distinctive change in ring pattern.

6.2. Lube Oil Condition

Residual lube oil in the GG oil sump and in the pressure/supply side piping was found to be contaminated. Of particular concern, the oil in the on-engine Pressure Filter was found to contain metallic fines and particles from the No 2 bearing damage. The Filter serves as the “last chance” protection against potentially damaging contaminants in the lube oil reaching the GG bearings.

The photo below shows residual lube oil taken from the Pressure Filter during GG receipt inspection checks at Alba. Contaminant particles and fines (black areas and cloud swirls) are clearly visible.

Bench tests by PI using supply oil samples showed that metallic fines and particle contaminants could pass through the Pressure Filter gauze, and therefore to the bearings. The test thus demonstrated that the Pressure Filter is not sufficiently rated to protect the GG bearings from potentially damaging contaminants in the oil. The test also indicated that some metallic particles from the bearing damage must have been recirculating around the oil system and through the GG bearings, with the scavenge/return oil filter bypass having activated.

The Pressure Filter gauze was later confirmed to be a standard 60 mesh with a 250 microns nominal rating Industry standard for turbo machinery oil filtration is typically 5 microns. Therefore, at 250 microns the Pressure Filter is critically inadequate to protect the GG bearings from potentially damaging particle contamination in the lube oil.

Analysis of the post failure lube oil sample by SKF also evaluated its condition as typical of oxidation as indicated by its very high acidity level, and the oil's viscosity was found to be outside manufacturer recommended limits compromising its load carrying capacity.

Supporting the above findings by SKF, Hydro's lube oil analysis report from AGAT Laboratory also showed oxidation at "Upper Critical" level. It appears from the Report, and from site information provided by Hydro, that the lube oil was renewed at the time of the GG commissioning in October '14 but it was not renewed in response to the AGAT Report alert (ref sample dated 16 March '15) or indeed at all during the seventeen months of operation to the bearing failure. The AGAT Report is contained for reference in Appendix 3.

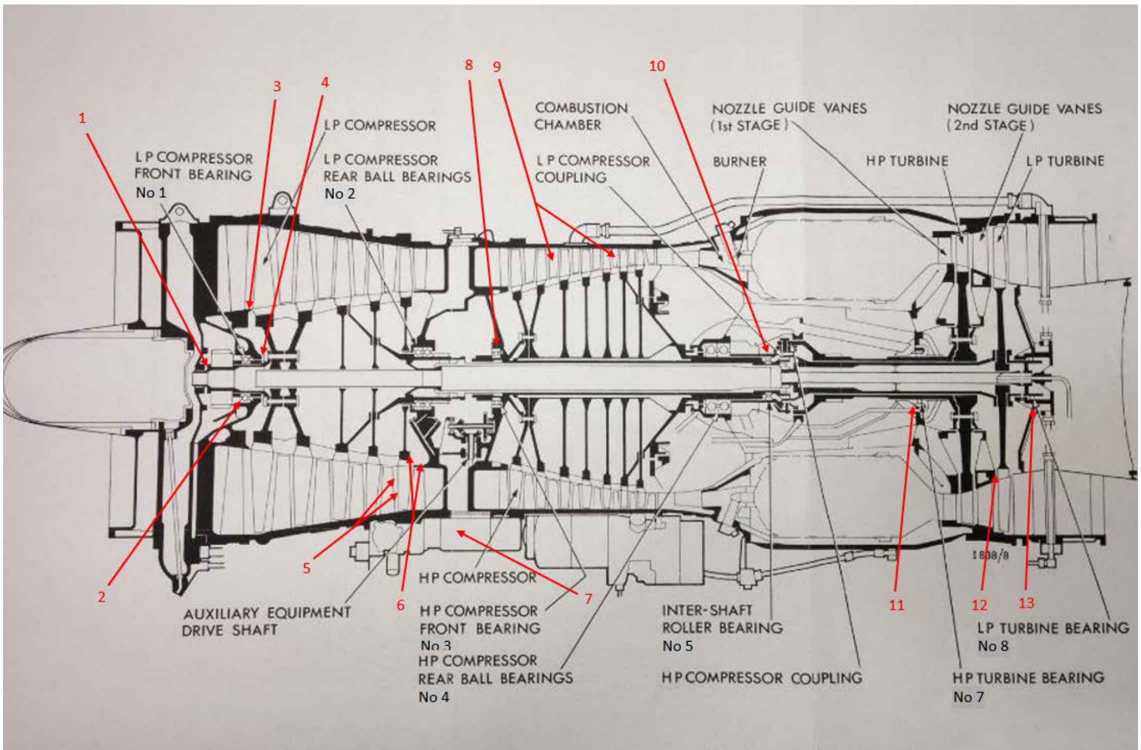
6.3. Note on SKF Failure Analysis Report

From evidence of bearing outer race rotation in the housing SKF suggested that the bearing was a “poor fit” which may have contributed to the bearing failure (among other potential causes cited). However, PI’s examination of Alba build records showed that the bearing part number, fit in the housing and installation in the GG, and also the paired bearing match-marking and orientation were correct to OEM specifications.

It is PI’s opinion that in SKF suggesting a poor fit they did not take into consideration the differing thermal expansions occurring in the bearing assembly (ref in particular the relatively thin walled housing) caused by the friction heat generated during the bearing failure process, with the addition of high rotational forces acting on the race due to the bearing balls locking/skidding. SKF’s Report, ref RPCM507_ALBA POWER_160617_DF dated 17 June ’16 is contained for reference in Appendix 4.

7. SECONDARY DAMAGE

The GG illustration below shows the areas that incurred secondary damage resulting from the No 2 bearing failure. Details and explanations of the damage points are presented in PI's Secondary Damage Report contained in Appendix 9.



Olympus Engine showing main areas of secondary damage resulting from No 2 Bearing failure

8. OUTSTANDING ISSUES & RECOMMENDATIONS

PI's failure investigations and RCA highlight the following concerns that we would suggest require review or further investigation.

8.1. Lube Oil System

- The main concern is that the supply/pressure side lube oil is not filtered to an acceptable standard by the on-engine LP and Pressure Filters alone to properly protect the GG bearings due their extremely large micron ratings.

- The scavenge oil return piping filter is 10 microns 90% efficiency rating. It is the only true "micronic media" filter in the Lube oil system but its rating is below the normal standard of 5 microns for gas turbine applications. Also, its location on the oil return side leaves the tank and oil supply side vulnerable, unprotected from contaminants introduced into the oil reservoir tank passing through to the GG bearings.

- From the large amount of metallic debris from the bearing failure damage found in the supply side oil it was apparent that the filter in the oil return line was passing. Hydro checked and confirmed that there was no defect or rupture found in the filter or its seals and so it is concluded that the filter bypass relief valve had operated due to filter blockage during the process of continued metal loss and mechanical failure of the bearing.

- According to the tank design drawing the GG oil supply outlet pipe open end is less than 1/2" above the tank bottom surface which seems low by normal design practice. There is a risk that water/sediment can accumulate and may be drawn into the supply piping to the GG. The lube oil tank design drawing is contained for reference in Appendix 10.

8.2. Vibration Detection System

(Hydro confirmed that the vibration alarm & trip installed settings at the time of failure were in accordance with OEM recommended set points. Hydro also confirmed that the vibration system's single transducer is positioned at the GG Intermediate Casing front flange per the original OEM configuration.)

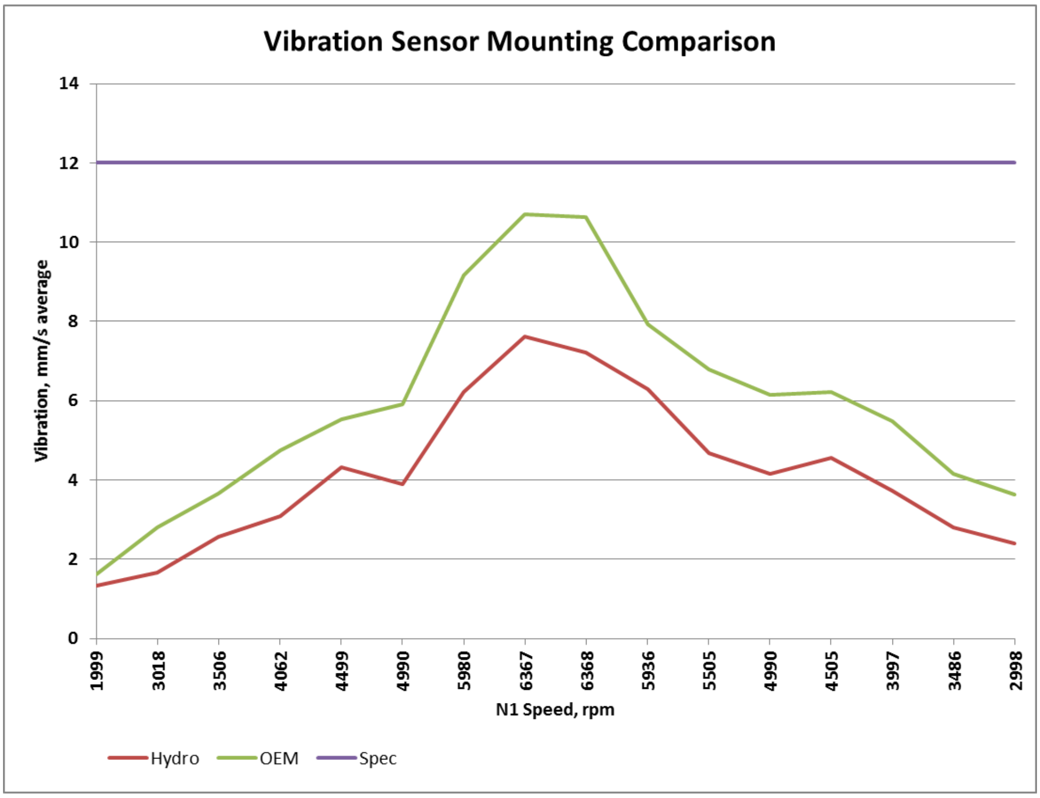
- The vibration detection system did not activate early enough to prevent mechanical failure of the No 2 bearing and the consequential damage. It is clear from the extent of damage incurred that the GG must have been operating in a high vibration condition for a considerable period of time leading up to the failure. There is a question on the vibration detection system design, sensitivity or operating condition/reliability. In view of the apparent inconsistency in comparing with vibration trends, the actual alarm/trip set points at the time of failure appear to be in question.

- The vibration transducer position is not in accordance with R-R current recommendation for improved protection effectiveness. See Note ** below.

- Consider upgrading the system or changing the alarm/trip philosophy from fixed set points to a percentage above normal operating maximum. See Note ** below.

  Note**:
  PI believe there is a question/doubt on the ability of a single transducer to provide effective coverage and protection for the seven main line bearings over the 3.6 metre long GG. We arranged with Alba to conduct a test during post engine build performance tests (November 2016) to compare vibration levels measured at different axial positions in order to test transducer sensitivity/effectiveness.

  Alba were unable to carry out tests over the length of the engine as we requested. However, tests were carried out comparing the Hydro transducer position (Intermediate Casing front flange) with the RR recommended position (Delivery Casing front flange). The test results showed consistent significant differences in vibration levels measured, with the RR position showing the higher amplitudes/sensitivity. The comparison test results, presented below, appear to support PI's doubt of the ability of a single transducer to provide effective sensitivity/coverage over the length of the engine.



  PI have presented budget proposals to Hydro for review and potential upgrade of the vibration system to provide improved coverage and protection.)

8.3. Operations/Maintenance

- In view of the significant amount of metallic debris found in the lube oil from the No 2 bearing degradation process which occurred over a considerable period of time, there may be a question on the frequency/philosophy of MCD's check inspections. (Hydro did not confirm the date of the most recent inspection before the bearing failure, as requested by PI.)

  It is to be noted that the MCD's are far more effective than the vibration system is in detecting early signs of bearing degradation. (PI have presented budget proposals to Hydro for review and potential upgrade of the MCD system to provide continuous on line monitoring and protection.)

- Other than metallic contamination from the bearing damage, the lube oil was found to be in a very poor condition oxidised beyond recognised operating limits, at "Upper Critical" level as reported by AGAT Laboratory approximately a year before the failure. However, it appears that the oil was not replaced. There is a question on the frequency of lube oil sampling/analysis (and sufficiency of analysis scope), and on Ops responsiveness to analysis reports alerts recommendations (if information received from Hydro is correct). (PI have presented budget proposals to Hydro for review of lube oi condition monitoring, analysis and operating practices.)

- New lube oil is not pre-filtered at tank top-ups or replacement. New oil from suppliers typically falls well below the NAS/ISO cleanliness standard set by turbine manufacturers and industry best practice.

- It is not clear how/if Ops are able to carry out lube oil tank bottom sampling to check for water/sediment due to there being no test valve fitted in the tank drain line (and the line open end is approx. ½" above tank bottom).

APPENDIX 1 –PI Detail Strip & Inspection Report

PERFORMANCE IMPROVEMENTS (PI) LIMITED

Report to

NEWFOUNDLAND & LABRADOR HYDRO (NALCOR)

ROLLS-ROYCE OLYMPUS C GAS TURBINE FAILURE INVESTIGATION

- Gas Generator Detail Strip & Inspection Report -

Document Number P10854-RPT-003 Rev. 0

Date	Rev	Description	Prepared	Checked	Approved
18 August 2016	0	Issued for Comment	Doug Eynon	N/A*	N/A*

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CONTENTS

1. INTRODUCTION

Newfoundland & Labrador Hydro (Hydro), a Nalcor Energy company, operates a power station in Stephenville, NL Canada. The plant includes Rolls Royce Olympus Mk 2022C gas turbine driven power generators, and diesel driven generators which provide back-up support. One of Hydro's two Olympus gas generators (GG), s/n 202204, was taken out of service 26 March 2016 due to a catastrophic failure of the LP Compressor rear thrust bearing (GG No 2 Bearing).

The GG was removed and shipped to gas turbine specialist vendor Alba Power Ltd (Alba) in Aberdeen UK for strip inspection and failure report.

Performance Improvements (PI) Ltd were commissioned by our parent company AMEC/FW (Americas branch) on behalf of Hydro to witness and support the initial GG strip and inspections at Alba's Aberdeen workshop, and conduct a failure investigation and root cause analysis (RCA).

PI's Specialist Rotating Equipment Consultant, Doug Eynon, was assigned to perform the agreed scope of work covering the inspections and bearing failure investigations. Doug liaised and shared information with Hydro's focal point for the investigations, Ryan Cooper.

This Report follows on in GG strip inspection sequence from PI's Bulk Strip Report and is the second of three reports to be submitted as our contracted deliverables for Hydro. The third Report is the Failure Root Cause Analysis (RCA) Report. (PI issued a Preliminary RCA Report (25 July '16) at Hydro's request to support their immediate requirement at the time. The full RCA Report is to be issued after completion of our failure investigations and technical reviews.)

This Report discusses the findings from the Detail Strip inspections with particular focus on elements considered as potentially causal in the No 2 bearing failure and on areas of secondary damage resulting from the failure. (This Report does not cover the full scope of the Detail Strip inspections. This is covered in Alba's Detail Strip Report dated 27 July 2016, contained for reference in Appendix 1.)

Given that "partial" Detail Strip inspections were added to the Bulk Strip scope to help expedite PI's failure investigations, and a Preliminary RCA Report was issued earlier to Hydro, this Report inevitably includes some information that was reported previously. (Refer to PI's Bulk Strip Report dated 18 July 2016, and Preliminary RCA Report dated 25 July 2016.)

PI's reporting to Hydro during the Detail Strip inspections and checks included regular progress updates in the form of Project Notes. The Notes issued over that period are contained for supplementary reference in Appendix 8.

2. BACKGROUND BRIEF

The GG had previously been overhauled and performance tested by Alba in Aug/Sept ’14, and installed and commissioned in October ‘14. The GG bearing failed on 26 March ’16 after seventeen months in service, having operated for approximately 90 hours (on standby duty) during that time. The deteriorating condition of the bearing remained unknown to Hydro Operations staff and was revealed only when the GG vibration protection system activated shutting the unit down, but too late in preventing failure of the bearing.

Initial in situ site checks by Alba after the failure confirmed that the HP rotor was able to rotate freely by hand but the LP rotor was tight to turn and was snagging internally. Inspection of the magnetic chip detectors & baskets in the main line bearings lube oil return lines revealed very significant metallic debris in the No 2 & 3 bearings common detector. Those checks combined confirmed that the No 2 bearing (LP Compressor rear/thrust bearing) had suffered a mechanical failure.

The Alba engineer also reported that the GG lube oil was found to be a very dark colour and contaminated with black fines and metallic particles.

The GG was removed and shipped to Alba’s workshop in Aberdeen for strip inspection and failure report. Alba’s Field Service Report dated 29 March ’16 is contained in Appendix 2.

PI attended the Induction, Bulk and Detail Strips at Alba workshop and conducted inspections and checks focused on identifying and investigating potential causes of the bearing failure and reviewing areas of damage resulting from the failure.

3. EXECUTIVE SUMMARY

3.1. Synopsis

As in the case of the Bulk Strip findings, no evidence was found during the Detail Strip inspections and checks that indicted the No 2 bearing failure resulted from a GG component defect or failure, or from error or deviation from specifications in the GG build by Alba.

Based on the evidence gathered to date from the Bulk and Detail Strips inspections (and from site information provided by Hydro) it is PI’s opinion that poor/contaminated lube oil operating condition with high oxidation resulting in oil film breakdown in the bearing was the most likely initiating cause of failure.

(The extent of the secondary damage was a result of late activation of the GG vibration protection system.)

Pour tests of the contaminated lube oil demonstrated that the GG oil system Pressure Filter is not sufficiently rated to protect the GG bearings from potentially damaging contaminants in the oil. The test also indicated the contamination particles (from the bearing failure) must have been recirculating around the oil system and through the GG bearings, with the scavenge return oil filter having failed or its bypass activated.

PI recommends that investigation actions now turn to the GG lube oil and vibration protection systems and site operations to identify elements that may have contributed to the bearing failure and damage, and to propose improvements to help prevent further similar failures in the future.

3.2. Lube Oil Condition

Contamination of residual lube oil in the GG oil sump and in the pressure/supply side piping was found during Induction inspections at Alba. Of particular concern, the oil in the Pressure Filter was found to contain metallic fines and particles from the No 2 bearing damage. The Filter serves as the “last chance” protection against potentially damaging contaminants in the lube oil reaching the GG bearings.

As part of Detail inspections and checks PI conducted a simple pour test of the oil through the Pressure Filter which showed many of the metallic particles could pass through the filter gauze, and therefore to the GG bearings. The test thus demonstrated that the Pressure Filter is not sufficiently rated to protect the GG bearings from potentially damaging contaminants in the oil, and the metallic particles must have been recirculating around the oil system and through the GG bearings, with the scavenge return oil filter having failed or its bypass activated.

SKF’s analysis of the lube oil found that the contamination also included significant carbon/oxidation product, affecting the viscosity of the oil beyond manufacturer/industry limits and compromising its load carrying capacity.

In addition to the above findings during the Detail Strip, Hydro's lube oil analysis report from AGAT Laboratory also showed oxidation at "Upper Critical" level (ref sample dated 16 March '15). It appears from the Report, and from information provided by Hydro, that the lube oil was renewed at the time of the GG commissioning in October '14 but it was not renewed subsequently in response to the AGAT Report alert or indeed at all during the seventeen months of operation to the bearing failure. The AGAT Report is contained for reference in Appendix 4.

3.3. SKF Failure Analysis Report

From evidence of bearing outer race rotation in the housing, SKF suggested that the bearing was a "poor fit" and may have contributed to the bearing failure (among other potential causes they cited). However, PI's examination of Alba build records showed that the bearing part number, fit in the housing and installation to the GG (and also the paired bearing match-marking and orientation) were correct to OEM specifications.

It is PI's opinion that in SKF suggesting a poor fit they did not consider the different thermal expansions occurring in the bearing assembly (ref the thin walled housing) caused by the friction heat generated during the bearing failure process, with the addition of high rotational forces acting on the race due to the bearing balls locking/skidding. SKF's Report, ref RPCM507_ALBA POWER_160617_DF dated 17 June '16 is contained for reference in Appendix 3.

3.4. Secondary Damage Rejected Components

PI reviewed the major (cost) components that were rejected for reuse in the overhaul process with Alba with respect to repair/replace options, comparative costs and lead times. There was nothing new of relevance to the bearing failure or of significance to damage/repair (costs) on the Rejected Components List that wasn't already known and previously reported to Hydro. However, in reviewing the List PI verified it as valid and a fair and accurate assessment of the damaged components. The Rejected Components List is contained in Appendix 5.

4. DETAIL STRIP INSPECTIONS RESULTS

4.1. Cause of Failure

Following on from the Bulk Strip (& partial Detail) inspections, the Detail Strip inspections carried out found no evidence indicating that the No 2 bearing failure resulted from a GG component defect or failure, or from error or deviation from specifications in the GG build by Alba.

The bearing had been repaired by Alba's contracted specialist prior to installation at the GG build in August/September 2014. A copy of the repair report requested from Alba for PI review remains outstanding. The specialist company is extremely reputable and it is considered highly unlikely that the bearing repair was outside of design specifications or anyway potentially contributed to the failure. Nevertheless, this verification check remains outstanding at the time of writing. (PI have made repeated requests to Alba for the repair report.)

In summary, the Detail Strip Inspections revealed no new findings relating to potential cause of bearing failure or to secondary damage (of any significance) that were not already known from the Bulk (& partial Detail) Strip inspections and Preliminary RCA previously reported to Hydro.

4.2. No 2 Bearing Failure Damage

The GG No 2 bearing (LP Compressor rear/thrust bearing, double ball design) was found to have suffered catastrophic mechanical failure comprising of very significant metal loss (into the lube oil system) and break-up of the bearing cage.

Photo 1 below shows the extensive damage and metal loss at the bearing outer races ball grooves, particularly on the forward side (bottom side in photo) resulting from the axially biased abrasion process due to the LP Compressor Rotor thrust forward.

The arrowed areas in the above photo showing two distinct abrasion track rings in the axial direction are thought to indicate two phases of wear. The initial track ring was early in the failure process where the LP Comp Rotor was moving forward within its build axial clearance. The second track ring is where the Rotor came into running contact with adjacent static components which caused an increased resistance to the Rotor forward movement resulting in the distinctive change in pattern.

Photo 2 below shows the multi-faceted flat surfaces and misshape of the bearing balls, clearly resulting from lock-up and metal to metal skidding abrasion in many contact positions over an indeterminate but apparently considerable period of time leading up to the mechanical failure of the bearing by the break-up of the cage, pieces shown in the background. (Confirmation by Hydro of the last MCD’s inspection date before the bearing failure would help to determine the approximate time period of the failure process.)

4.3. No 2 Bearing Installation

Photo 3 below shows a diagram from OEM/Alba build instructions showing the correct positioning and orientation for installing the match marked bearings.

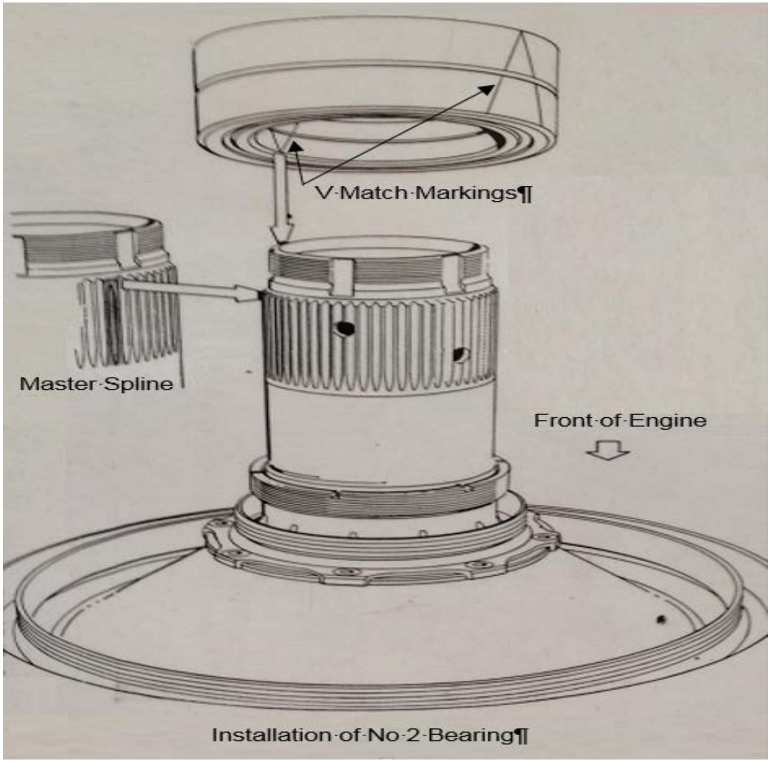
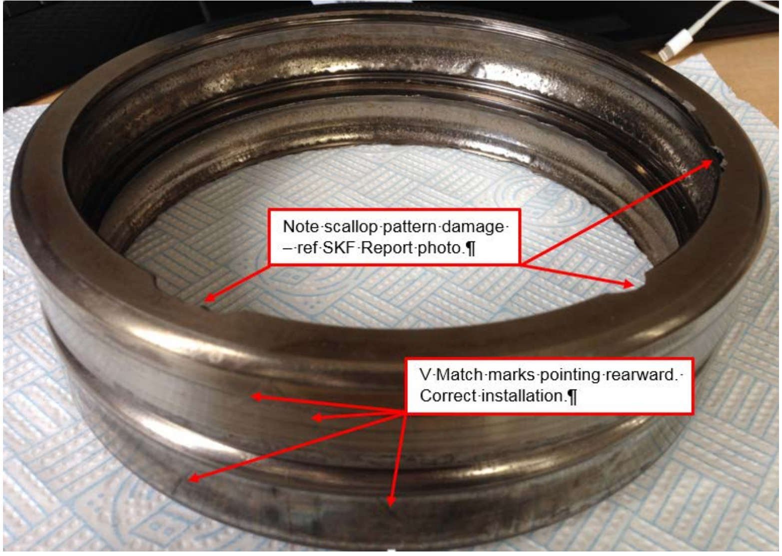


Photo 4 below from the SKF Report shows the bearing assembly (from the rear side) as received with the outer races still stuck in the housing. SKF denote the “Front bearing” as uppermost in the photo - it’s actually the rear bearing. Note the damage scallops on the race (rear) face for reference further below.

Figure 3 *– Housing ‘as received’ with both outer rings in place. The Front bearing is uppermost in the photo.*

Photo 5 below shows the outer races removed from the housing after SKF returned the bearing to Alba. The V match mark is only just visible spanning across the two races, pointing in a rearward direction per the installation drawing further above. It can be seen that the annotated damage scallops on the rear face of the rear race are as in the above SKF photo of the as received condition, demonstrating that the races were installed correctly. Also note the ball grooves worst abrasion damage being at the front (bottom) side of the races due to the LP Compressor forward thrust.)



Note scallop pattern damage – ref SKF Report photo.¶

V Match marks pointing rearward. Correct installation.¶

Photo 6 below shows the V match marks on the outer races more clearly, albeit the rear race (top) part of the V is somewhat faded due to circumferential scoring caused by rotation of the race in the housing during the bearing failure process.

Photo 7 below shows the two inner races (pair). The V match mark is clearly visible spanning across the four half-races. PI witnessed the removal of the races from the GG as being in the correct order and orientation with the V pointing in a forward direction per the installation drawing further above, thus confirming the bearing assembly and installation were correct to specification.

4.4. Lube Oil Condition

Residual lube oil taken from the GG sump and from the Pressure Filter in the supply line to the GG bearings was found to have very significant metal particulates and oxidation product contamination. Metal particles were found in the Low Pressure Filter (LP Filter) and the High Pressure Filter (Pressure Filter), located respectively immediately before and after the lube oil pump.

Photo 8 below shows residual lube oil taken from the Pressure Filter. Metal particles and fines (cloud swirls) are clearly visible. The metal particles and the fines were found to be magnetic thus ferrous based and had resulted from the bearing damage.

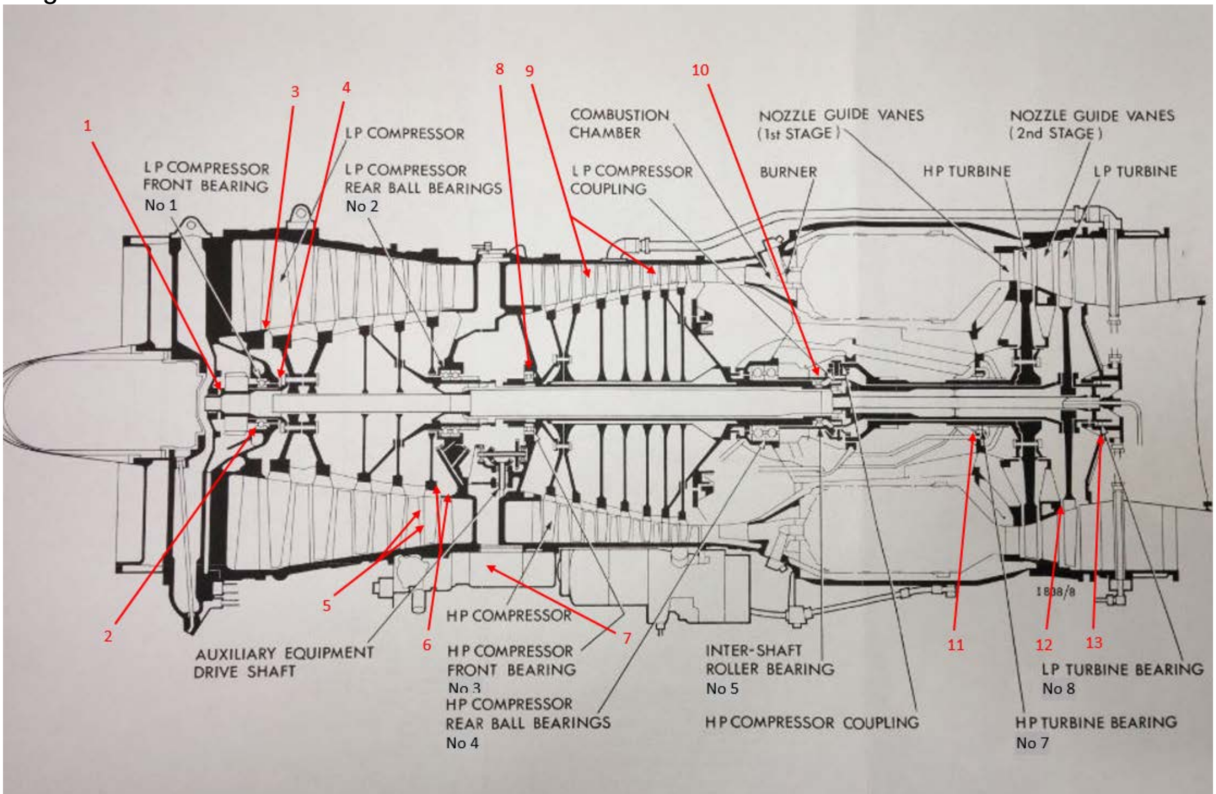
PI carried out a simple pour test of the oil through the Pressure Filter which showed that many particles passed through the mesh. **The test thus demonstrated that the Filter is not sufficiently rated to protect the GG bearings from potentially damaging contaminants in the oil. The test also indicated the particles must have been recirculating around the oil system and through the GG bearings, with the scavenge return oil filter having failed or its bypass activated.**

4.5. Secondary Damage

The forward movement of the LP Rotor caused secondary damage of varying severity along the length of the LP Rotor from Compressor front end to Turbine end. The HP Rotor appeared to be unaffected except for impact damage to Compressor stages blades from damage debris released into the air stream and aluminium melt spatter on the turbine blades.

PI were unable to attend the component level accept/reject Detail inspections of all of the secondary damage components carried out in-house by Alba as by routine process they are divided into multiple parallel inspection streams. Also, around that time Hydro requested PI to urgently develop and issue a Preliminary RCA Report which took priority over attending the inspections. However, in view that no new failure evidence or secondary damage of any significance was found during the inspections PI missed nothing at the accept/reject component inspections other than damage found on very minor components and damaged blades counts.

The GG illustration below shows the main areas of secondary damage found along the length of the LP Rotor.



Olympus Engine showing main areas of secondary damage resulting from No 2 Bearing failure

The following listing summarises the secondary damage points shown above found during (Bulk and) Detail Strip inspections. The damage points are shown and described in more detail in a separate report which also includes sectional illustrations of the GG to help visualize the damage areas in context with the GG design layout. The Secondary Damage Report is contained in Appendix 7.

1. LP Compressor Rotor shaft front labyrinth seal running contact damage.

2. LP Compressor No 1 roller bearing surface micro pitting due to lube oil contamination, also larger corrosion pitting.

3. LP Compressor Rotor 1st stage blades platforms to Variable Inlet Guide Vanes inner platform casing running contact damage.

4. LP Compressor Rotor 1st/2nd stage discs bolt heads to No 1 bearing housing rear face running contact damage.

5. LP Compressor Rotor 5th stage blades to stator vanes running contact damage, some blades bent back by the force. Also, vanes dovetail slots opened – ie LP Compressor casing local distortion.

6. Impact damage at LP Compressor Rotor 5th stage disc/bolts and Intermediate Casing caused by two No2 bearing housing studs/heads having snapped off due to stress at the housing from the bearing failure.

7. Scavenge lube oil pump gears housing abrasion metal loss due to damage debris in lube oil.

8. HP Compressor No 3 roller bearing surface micro pitting due to lube oil contamination, also larger corrosion pitting.

9. HP Compressor Rotor blades impact damage due to LP Compressor front end running contact damage debris released into the Compressor air stream.

10. Inter-shaft No 5 roller bearing surface micro pitting due to lube oil contamination, also larger corrosion pitting. Also LP Compressor Rotor drive coupling hub to bearing oil thrower running contact damage.

11. HP Turbine No 7 roller bearing surface micro pitting due to lube oil contamination, also larger corrosion pitting.

12. LP Turbine Rotor blades fir tree roots lock tabs to Nozzle Guide Vanes disc bolts heads running contact damage.

13. LP Turbine No 8 roller bearing surface micro pitting due to lube oil contamination, also larger corrosion pitting.

It was also observed that the turbine section nozzle guide vanes and rotor blades exhibited aluminium melt spatter impingement on the aerofoils from the LP Compressor front end damage debris released into the compressor air stream and carried through the combustion system.

4.6. Rejected Components

As a consequence of the bearing failure many major components were damaged beyond OEM acceptance limits for reuse in the overhaul process and were rejected accordingly by Alba as unserviceable, requiring replacement or repair. PI had previously reviewed with Alba, and reported to Hydro, all the major components rejections (excluding blades counts) with respect to potential repair/replace options, comparative costs and lead times. We reviewed and verified the rejection list as valid and correct against OEM acceptance criteria.

The list of Rejected Components (with reasons for rejection) is contained in Appendix 5.

An example of OEM Acceptance Limits for (blending) Blade Damage is contained for interest in Appendix 6.

5. CONCLUSIONS FROM INSPECTIONS ON CAUSE OF FAILURE

As in the case for the Bulk (& partial Detail) Strip, no evidence was found from the Detail Strip inspections that indicated the No 2 bearing failure resulted from a GG component defect or failure, or from error, deviation or concession in the GG build processes and standards applied by Alba.

Evidence found to date during inspections and checks at Alba (and from Hydro site information, still to be reviewed in detail) indicates that the initiating cause of the bearing failure appears to have been related to lube oil contamination/poor condition.

Oil samples analyses by both SKF and AGAT Laboratories reported high oxidation levels that had adversely affected the oil viscosity beyond recognised industry limits and compromised its load bearing capacity.

(Alba conducted a RCA which also indicated the lube oil as the most likely cause of failure. PI reviewed the Report and found no obvious flaws in the analysis approach and no evidence or argument to dispute the indicative conclusion.)

It is PI’s opinion that oil film breakdown resulting from high oxidation levels and causing metal to metal contact in the bearing was the most likely initiating cause of failure.

5.1. Bearing Failure Analysis by SKF

Alba sent the No 2 bearing to SKF (bearing manufacturer/specialist) Tribology Laboratory for failure analysis. From the signs of frettage and rotation of the bearing outer race in the housing, SKF suggested in their Report that “poor fit” of the bearing may have been a contributory factor. However, PI’s examination of Alba GG build records showed that the bearing installation was correct to OEM specifications.

It is PI’s opinion that in SKF suggesting a poor fit they did not consider the different thermal expansions occurring in the bearing assembly (ref the thin walled housing) caused by the friction heat generated during the bearing failure process, with the addition of high rotational forces acting on the race due to the bearing balls locking/skidding.

It was SKF’s opinion that the condition of the bearing had been deteriorating for “some time” (which agreed in principle with PI’s assessment), but they were unable to estimate the time period. From PI’s enquiries, Hydro confirmed that the GG MCD’s are inspected either monthly or every two hundred operating hours (presumably whichever comes first). As the GG had reportedly operated approx. only ninety hours over the seventeen months period from installation to failure, then it seems reasonable to conclude that the 200 hours based inspection was not due/carried out, and the routine monthly inspections showed no indication of bearing metal. Thus it is assumed that the bearing started to deteriorate (losing metal) one month at most before the date of failure, or anyway after the last MCD inspection before the failure.

6. RECOMMENDATIONS - FURTHER INVESTIGATIONS

PI’s failure investigations at Alba have now been completed with nothing found that indicates the bearing failure was caused by a component defect or failure, or by error or deviation from OEM specifications by Alba in the GG build.

From the combined evidences of the bearing failure mechanism and of the lube oil contamination and analysis results, along with site information provided by Hydro, it is PI’s recommendation that failure investigations now turn to Hydro’s operations, focusing in particular on the lube oil system as potentially causal in the bearing failure, and on the vibration protection system as certainly causal in the extent of damage incurred.

It is also suggested that Operations & Maintenance practices should be reviewed (also in view of increasing operating demand on the Olympus packages). From PI’s discussions with Hydro it is our understanding that Hydro have already started to review areas of O & M.

(The main issues and concerns found by PI during our investigations and enquiries are identified and discussed in detail in our Preliminary RCA Report. At the time of writing this Report, the Preliminary RCA Report remains to be completed and issued to Hydro as the full/formal RCA Report.)

APPENDIX 1 – Alba Detail Strip Report

Detail Strip
Inspection Report
For
Olympus Gas Turbine
Serial Number: 202204

Customer: Newfoundland Hydro

Date: 27 July 2016

Project Number: Alba 5269

Alba Power Ltd
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Quality Certification
ISO 9001:2008
ISO 14001:2004
OHSAS 18001:2007
Scotland

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Note:

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1 Introduction

Previously on the Bulk Strip it was noted that the No 2 bearing had deteriorated significantly, allowing the complete LP compressor rotor and LP turbine to move forward and contact a number of points with the gas turbine. This resulted in significant amounts of rub damage and impact damage throughout the gas turbine.

The detail strip and detailed inspection of Olympus gas turbine serial number 202204 was completed on 22 July 2016.

The following Report details the findings of the detail inspection.

2 Air Intake

Inspection findings:-

The air intake casing is found to have and area of excessive rub damage around the rear air/oil seal location. This was caused by forward movement of the LP compressor rotor which moved forward during the No 2 bearing failure. The extent of rub damage on the casing has resulted in the casing being rejected from further service. The No 1 bearing is found to have scoring on the individual roller elements and will be replaced during the course of the workscope. All entry guide vanes were found in a dirty condition, however the protective coatings have remained intact. No defects were noted with the vanes. The rear support ring for the entry guide vanes was rejected due to excessive wear and rub damage, caused by the LP rotor.	
	Air intake casing
	
	Rub damage around the rear air/oil seal location

	
Entry guide vane	Entry guide vane support rings
	
No 1 bearing	Rub damage on rear support ring

Rejected Parts:-

Description	**Part Number**	**Quantity**	**Reason**
Air intake casing	BDD1929	1	Rub damage
No 1 bearing	FB217981	1	Scoring/contamination
Entry guide vane support ring	47-1-1-002898	1	Rub damage

Major Coating Requirements:-

Description	**Works Required**
Air intake Casing	Enamel Coating
Entry Guide vanes	Apply K900
Cover	Enamel

3 LP Compressor Casing

Inspection findings:-

Detailed inspection of the LP compressor casings found these to have retained there protective coatings, however distortion was apparent on the Stage '4' stator vane location lands.

The distortion has been caused as a result of the stage '5' Rotor blades moving forward and contacting the stage '4' vanes.

The stage 1' stator vanes have retained there protective coatings and display no obvious defects.

The stage '2' – '3' stator vanes display no significant defects at this stage however, the stage '4' stator vanes display significant impact damage, due to the stage '5' LP blades contacting the aerofoil sections.

As a result all stage '4' stator vanes have been rejected from further service.

LP compressor casings

Distortion at the stage '4' stator vane location

Stage '1' stator vanes

Stage '2' stator vane

	
Stage ‘4’ stator vanes	Stage ‘4’ stator vanes

Rejected Parts:-

Description	Part Number	Quantity	Reason
Stage ‘4’ LP stator vane	Various	58	Rub/impact damage
LP compressor casings	NDY6880/2	1	Worn/distorted stage ‘4’stator vane locations

Major Coating Requirements:-

Description	Coating to be Applied
LP Casing	Enamel
LP stator vanes ‘1’ – ‘5’	Smooth seal

4 LP Compressor Rotor

Inspection findings:-

The LP compressor front and rear shafts displayed and area of rub damage on the seal fins, which has resulted in both assemblies being rejected from further service.

The compressor discs and spacers display varying degrees of light impact damage/rub damage on the air washed surfaces. At this stage the majority are expected to be serviceable following full overhaul, however further NDT inspection will be required to confirm this.

Dimensional inspection of the No2 bearing location was found to be within acceptable limits.

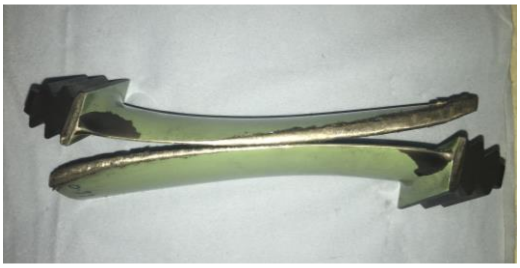
The stage '1' – '4' LP compressor blades, display areas of light impact damage/rub damage on the aerofoil sections, however it is expected that these will be fully recoverable during the overhaul process.

The stage '5' LP compressor rotor blades are found in a poor condition and display significant Impact damage and distortion due to contact with the stage'4' stator vanes, which was caused by movement of the LP rotor.

During detailed inspection a cupwasher, washer and retaining nut were also rejected due to wear and rub damage caused by the LP rotor movement.

LP front shaft rub damage

Rub damage on the rear shaft seal fins

	
Stage ‘1’ LP rotor blade	Stage ‘2’ LP rotor blade
	
Stage ‘5’ LP rotor blade distortion and impact damage	Stage ‘5’ LP rotor blade distortion and impact damage

Rejected Parts:-

Description	**Part Number**	**Quantity**	**Reason**
LP rear shaft	BDA6874	1	Rub damage to seal
LP front shaft	47-1-1-033028	1	Rub damage to seal fins
Stage ‘5’ LP rotor blade	BDA5709	13	Distortion/impact damage
Seal	BDA8730	1	Rub damage
Cup washer	B81912	1	Rub damage
Retaining nut	UB 81913	1	Rub damage

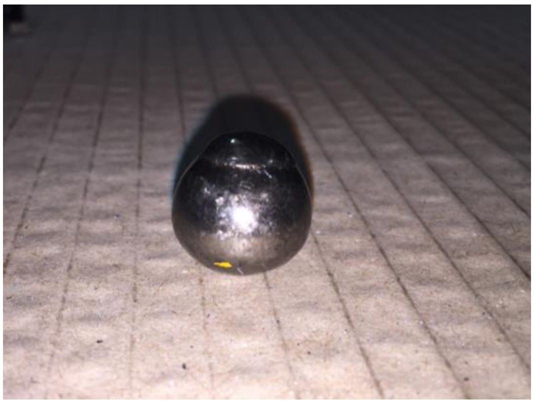
Major Coating Requirements:-

Description	**Coating to be Applied**
LP rotor front shaft	Ipcote
LP rotor rear shaft	Ipcote
LP disc stage ‘1’ – ‘5’	Ipcote
LP spacer stage ‘1’ – ‘4’	Ipcote
LP rotor blades ‘1’ – ‘5’	K900

5 Intermediate Casing

Inspection findings:-

<table>
<tr>
<td rowspan="4">
<p>The intermediate casing is found to have areas of impact damage and rub damage which has occurred as a result of the excessive movement and material release around the No 2 bearing Due to the extent of damage the casing has been rejected from further service.</p>
<p>The outlet guide vanes and entry guide vanes are found to be suffering from impact damage as a result of the material released from the forward components</p>
<p>This has resulted in 3 entry guide vanes being rejected from service. The remaining components are expected to be recoverable during the overhaul process.</p>
<p>The No 2 bearing was found to be in a poor condition and was consigned for full analysis to determine the root cause of the failure.</p>
<p>As a result of the No 2 bearing failure, the No 3 bearing was rejected form further service.</p>
<p>Inspection of the No 3 bearing hosing identified this to be suffering scoring and wear on the location diameter, therefore this was rejected from service.</p>
</td>
<td></td>
</tr>
<tr><td>Intermediate casing</td></tr>
<tr><td></td></tr>
<tr><td>Impact damage and scoring on the intermediate casing</td></tr>
</table>

	
Entry guide vanes	Impact damage on the entry guide vane
	
No 2 bearing	No 2 ball bearing
	
No 3 bearing	No 3 bearing housing

Rejected Parts:-

Description	**Part Number**	**Quantity**	**Reason**
Intermediate casing	BDD6362	1	Rub/impact damage
Housing	B173338	1	Scoring on location diameter
HP entry guide vanes	B204572	3	Impact damage outwith acceptable limits
No 2 bearing	BDA5927	1	Bearing deterioration/failure
No 3 bearing	FB207522	1	Contamination

Major Coating Requirements:-

Description	**Coating to be Applied**
Intermediate casing	Enamel
Guide vanes	Smooth seal
Covers	Enamel

6 HP Compressor Casing

Inspection findings:-

Detailed inspection of the HP compressor casings identified these to have retained the protective coatings external, however the internal surfaces did display minor impact damage and scoring which is considered to be recoverable during overhaul processing.

The stage ‘1’ – ‘7’ stator vanes displayed varying degrees of impact damage affecting the aerofoil sections. This resulted in the following belong rejected from further service: -

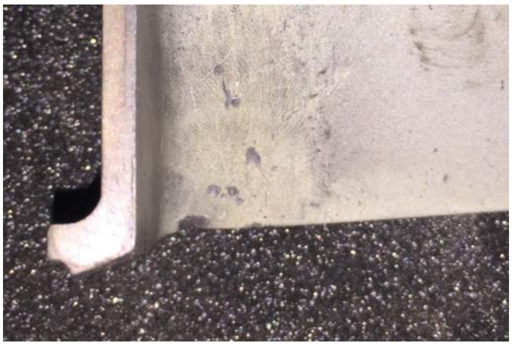
- 3 x stage ‘1’ stator vanes
- 1 x stage ‘2’ stator vane
- 3 x stage ‘3’ stator vanes
- 9 x stage ‘4’ stator vanes
- 4 x stage ‘5’ stator vanes
- 5 x stage ‘6’ stator vanes
- 1 x stage ‘7’ stator vane

It is expected that the remaining vanes will be recoverable during the overhaul processing.

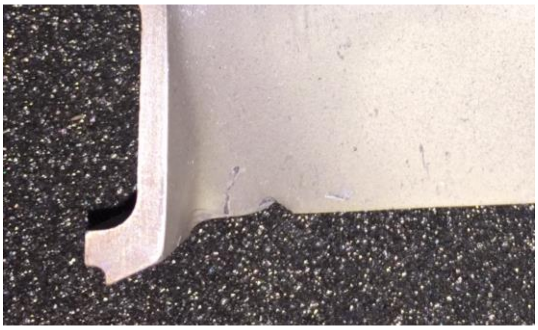
HP compressor casings

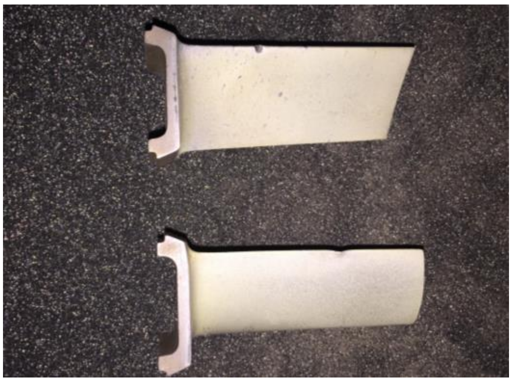
Impact damage on the internal surfaces of the HP compressor casings

Stage ‘1’ stator vane

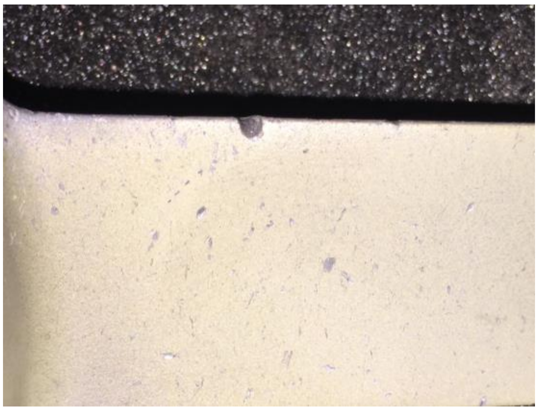


Impact damage on stage ‘3’ stator vane

	
Impact damage on stage ‘2’ stator vane	Impact damage on stage ‘2’ stator vane
	
Stage ‘3’ stator vane	Impact damage on stage ‘3’ stator vane
	
Stage ‘4’ stator vane	Impact damage on stage ‘4’ stator vane
	
Stage ‘5’ stator vane	Impact damage on stage ‘5’ stator vane



Stage ‘6’ stator vane



Impact damage on stage ‘6’ stator vane

Stage ‘7’ stator vane

Impact damage on stage ‘7’ stator vane

Rejected Parts:-

Description	**Part Number**	**Quantity**	**Reason**
Stage ‘1’ HP stator vane	B204544	3	Impact damage out with acceptable limits
Stage ‘2’ HP stator vane	B204545	1	Impact damage out with acceptable limits
Stage ‘3’ HP stator vane	B204546	3	Impact damage out with acceptable limits
Stage ‘4’ HP stator vane	B204547	9	Impact damage out with acceptable limits
Stage ‘5’ HP stator vane	B204548	4	Impact damage out with acceptable limits
Stage ‘6’ HP stator vane	B204549	5	Impact damage out with acceptable limits
Stage ‘7’ HP stator vane	B204760	1	Impact damage out with acceptable limits

Major Overhaul Requirements:-

Description	**Coating to be Applied**
HP Compressor casings	Ipcote
HP stator vanes stages ‘1’ – ‘7’	Smoothseal

7 HP Compressor Rotor

Inspection findings:-

Detailed inspection of the HP compressor discs and spacers identified these to be in a reasonable condition with no obvious defects identified. All components had retained the protective coatings.

Detailed inspection of the blades, did however identify a number of these to be rejected due to impact damage out with acceptable limits., as detailed below:

- 4 x stage ‘1’ HP rotor blades
- 4 x stage ‘2’ HP rotor blades
- 8 x stage ‘3’ HP rotor blades
- 2 x stage ‘4’ HP rotor blades
- 5 x stage ‘5’ HP rotor blades
- 6 x stage ‘6’ HP rotor blades
- 6 x stage ‘7’ HP rotor blades

The remainder of the HP rotor blades are expected to be fully recoverable during the overhaul process.

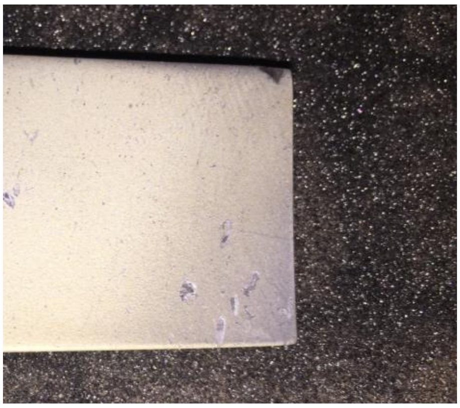
The oil thrower was rejected from further service due to rub damage caused by the LP rotor movement

Stage ‘1’ HP compressor disc

Oil thrower

Stage ‘1’ HP rotor blade

Typical impact damage on stage ‘1’ rotor blades

	
Stage ‘2’ HP rotor blade	Typical impact damage on stage ‘2’ rotor blades
	
Stage ‘3’ HP rotor blade	Typical impact damage on stage ‘3’ rotor blades
	
Stage ‘4’ HP rotor blade	Typical impact damage on stage ‘4’ rotor blades

	
Stage ‘5’ HP rotor blade	Typical impact damage on stage ‘5 rotor blades
	
Stage ‘6’ HP rotor blade	Typical impact damage on stage ‘6’ rotor blades

Rejected Parts:-

Description	**Part Number**	**Quantity**	**Reason**
Stage ‘1’ HP rotor blade	BDC1297	4	Impact damage out with acceptable limits
Stage ‘2’ HP rotor blade	B204538	4	Impact damage out with acceptable limits
Stage ‘3’ HP rotor blade	B204539	8	Impact damage out with acceptable limits
Stage ‘4’ HP rotor blade	B204540	2	Impact damage out with acceptable limits
Stage ‘5’ HP rotor blade	BDC1313	5	Impact damage out with acceptable limits
Stage ‘6’ HP rotor blade	B204542	6	Impact damage out with acceptable limits
Stage ‘7’ HP rotor blade	BDC8464	6	Impact damage out with acceptable limits
Oil thrower	B258495	1	Rub damage

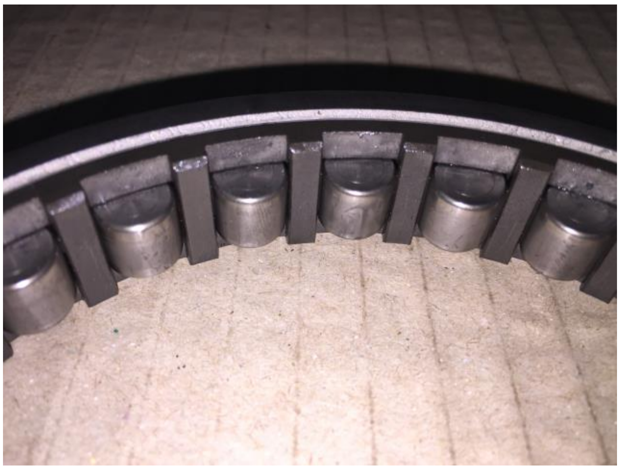
Major Coating Requirements:-

Description	**Coating to be Applied**
HP rotor front shaft	Ipcote
HP rotor rear shaft	Ipcote
HP discs stages ‘1’ – ‘7’	Ipcote
HP spacer stages ‘1’ – ‘7’	Ipcote
HP rotor blades ‘1’ – ‘7’	Smoothseal
Rear seal	Ipcote

8 Delivery Casing

Inspection findings:-

<table>
<tr><td>The Delivery casing is found to be in a reasonable condition with no obvious defects noted. The protective coating has remained intact.
The No 4 was found to be in a reasonable condition with no obvious defects noted however this will be replaced during the course of the workscope.
The No 5 bearing is found to have a deteriorated surface finish and will be replaced during the course of the workscope</td><td>
Delivery Casing</td></tr>
<tr><td></td><td></td></tr>
<tr><td>No 4 bearing</td><td>No 4 bearing</td></tr>
</table>

	
No 5 Bearing	No 5 bearing rollers

Rejected Parts:-

Description	**Part Number**	**Quantity**	**Reason**
No 4 bearing	BDA5928		Contamination
No 5 bearing	B217985		Surface finish deterioration/contamination
Housing	BDA9039	1	Rub damage to seal fins

Major Coating Requirements:-

Description	**Coating to be Applied**
Delivery Casing	Ipcote
Seal housing	Ipcote
Covers	Ipcote

9 Combustion chambers

Inspection findings:-

<table>
<tr><td>Detailed inspection of the combustion chambers found these to be in a reasonable condition, however carbon build up was noted on the internal surfaces
In addition to the above typical witness marks were noted around snout/rear location diameters.
The air intake snouts again display light witness marks on the location diameters, however no further defects were identified.</td><td>
Combustion chamber</td></tr>
<tr><td>
Internal condition</td><td>
Light witness marks on location diameter</td></tr>
<tr><td>
Light witness marks on interconnectors</td><td>
Air intake snout</td></tr>
</table>

10 Combustion chamber outer casing

Inspection findings:-

Detailed inspection of the combustion casings confirmed these to be in a reasonable condition with only minor hot spots and discoloration noted.	
	Combustion casings

Major Coating Requirements:-

Description	**Coating to be Applied**
Combustion casings	Ipcote
Covers	Ipcote

11 Fuel Nozzles

Inspection findings:-

Following cleaning the liquid fuel nozzles were found to be in a good condition with no obvious defects noted.	
	Liquid fuel nozzle
	
Exit nozzle	Exit nozzle

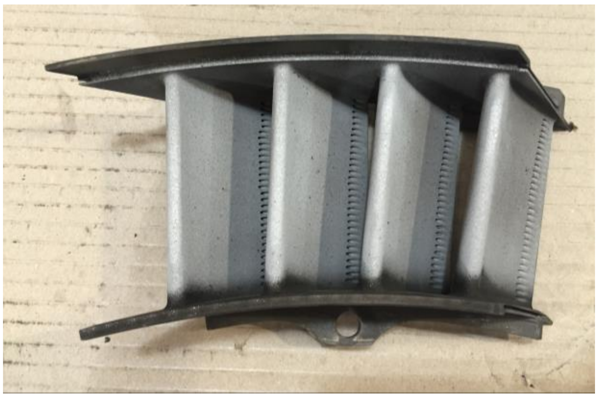
12 Turbine Entry Duct

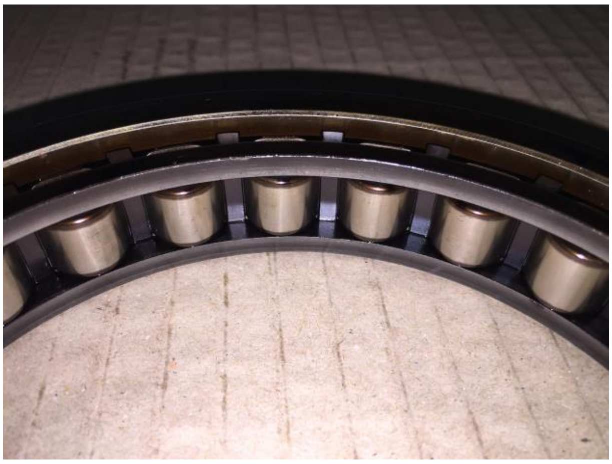
Inspection findings:-

The turbine entry duct displays aluminium spatter on the internal surfaces./ At this stage no obvious cracking or defects are noted, however further chemical cleaning an NDT inspection will be required to confirm this.	
	Turbine entry duct
	
Aluminium spatter on internal surfaces	Aluminium spatter on internal surfaces

13 Turbine Section

Inspection findings:-

<table>
<tr>
<td rowspan="4">Detailed inspection of the HP and LP nozzle guide vanes found these to be in reasonable condition with no obvious cracking or wear noted. All vanes did display aluminium spatter on the aerofoil sections.
The HP turbine blades display aluminium spatter on the aerofoil sections however no further defects are noted at this stage.
The LP turbine blades display light rub damage on the inner shroud platform and seal plates, caused by the LP rotor/turbine movement forward. This allowed the LP blades to contact the LP nozzle guide vane retaining bolts. The extent of rub damage is expected to be recoverable during the overhaul process.
The HP and LP turbine discs and shaft assemblies have retained the protective coating and appear in good condition.
The No7 and No 8 bearings were found in a reasonable condition with no significant defects noted an considered typical condition for service run components
The rear bearing turbine seal was rejected due to turbine seal</td>
<td></td>
</tr>
<tr>
<td>HP nozzle guide vanes</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Aluminium spatter on the HP nozzle guide vanes</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>HP turbine blades</td>
<td>Aluminium spatter on the HP blades</td>
</tr>
</table>

	
LP nozzle guide vanes	LP turbine blades
	
HP turbine disc	LP turbine disc
	
No 7 bearing	No 8 bearing

	
Rear bearing seal	Washer

Rejected Parts:-

Description	**Part Number**	**Quantity**	**Reason**
Washer	B119875	1	Worn retaining lugs
Rear bearing turbine seal	BDD9632	1	Rub damage on seal fins
No 7 bearing	FB218101		Contamination
No 8 bearing	FB217987		Contamination

Major Coating Requirements:-

Description	**Coating to be Applied**
LP turbine disc and shaft	Ipcote
HP turbine disc and shaft	Ipcote
HP turbine blade	IP1041
LP turbine blade	IP1041
HP nozzle guide vanes	IP1041
LP nozzle guide vanes	IP1041
Front seal	Ipcote
2nd stage turbine casing	Ipcote
Diaphragm unit	Ipcote

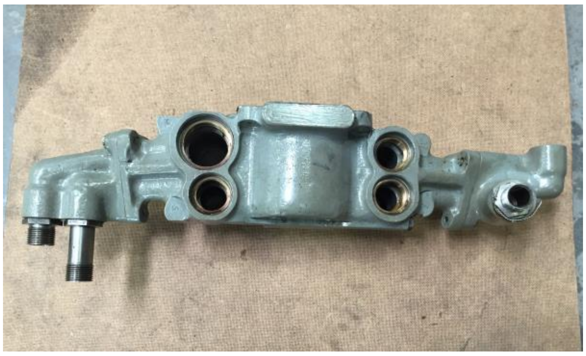
14 Accessories

Inspection findings:-

<table>
<tr><td rowspan="6">Cooling and Lubricating pipework appears in good condition, however all will require further cleaning and flushing throughout the workscope.

The Nose Bullet appears in good condition having retained the protective coating.

The oil pump and sump assembly were found to have scoring and contamination throughout the assemblies. The will require full overhaul and function testing prior to re-fitment.

The electric starter, fuel pumps and anti-icing valve appear in good condition at this stage with no defects noted.</td><td></td></tr>
<tr><td>Oil sump an pump</td></tr>
<tr><td></td></tr>
<tr><td>Oil pump</td></tr>
<tr><td></td></tr>
<tr><td>Scavenge pumps</td></tr>
</table>

Major Coating Requirements:-

Description	**Coating to be Applied**
Nose cone	Enamel

15 Report Summary

Detailed inspection of Olympus S/N 202204 identified the engine to have significant defects. This has resulted from the No2 bearing deteriorating to the extent that the complete LP compressor rotor and turbine assemblies have moved forward and contacted various points in the gas turbine.

The resultant impact/rub damage has resulted in a large number of components require replacement or overhaul processing to return these to a serviceable condition.

The extent of impact damage has also resulted in three of the main casing assemblies require replacement (air intake, LP and intermediate casings)

Significant replacement parts and re-work will be required to return the gas turbine to a serviceable/overhauled condition.

15.1 Complete list of all Rejected Parts:-

Description	Part Number	Quantity	Reason
No 1 bearing	FB217981	1	Scoring/contamination
No 2 bearing	BDA5927		Bearing deterioration/failure
No 3 bearing	FB207522		Contamination
No 4 bearing	BDA5928		Contamination
No 5 bearing	B217985		Surface finish deterioration/contamination
No 7 bearing	FB218101		Contamination
No 8 bearing	FB217987		Contamination
Air intake casing	BDD1929	1	Rub damage
LP compressor casings	NDY6880/2	1	Worn/distorted stage ‘4’stator vane locations
Intermediate casing	BDD6362	1	Rub/impact damage
Entry guide vane support ring	47-1-1-002898	1	Rub damage
LP rear shaft	BDA6874	1	Rub damage to seal
LP front shaft	47-1-1-033028	1	Rub damage to seal fins
Housing	BDA9039	1	Rub damage to seal fins
Housing	B173338	1	Scoring on location diameter

Rear bearing turbine seal	BDD9632	1	Rub damage on seal fins
Oil thrower	B258495	1	Rub damage
Washer	B119875	1	Worn retaining lugs
Seal	BDA8730	1	Rub damage
Cup washer	B81912	1	Rub damage
Retaining nut	UB 81913	1	Rub damage
Stage ‘4’ LP stator vane	Various	58	Rub/impact damage
Stage ‘5’ LP rotor blade	BDA5709	13	Distortion/impact damage
HP Compressor entry guide vanes	B204572	3	Impact damage outwith acceptable limits
Stage ‘1’ HP stator vane	B204544	3	Impact damage out with acceptable limits
Stage ‘2’ HP stator vane	B204545	1	Impact damage out with acceptable limits
Stage ‘3’ HP stator vane	B204546	3	Impact damage out with acceptable limits
Stage ‘4’ HP stator vane	B204547	9	Impact damage out with acceptable limits
Stage ‘5’ HP stator vane	B204548	4	Impact damage out with acceptable limits
Stage ‘6’ HP stator vane	B204549	5	Impact damage out with acceptable limits
Stage ‘7’ HP stator vane	B204760	1	Impact damage out with acceptable limits
Stage ‘1’ HP rotor blade	BDC1297	4	Impact damage out with acceptable limits
Stage ‘2’ HP rotor blade	B204538	4	Impact damage out with acceptable limits
Stage ‘3’ HP rotor blade	B204539	8	Impact damage out with acceptable limits
Stage ‘4’ HP rotor blade	B204540	2	Impact damage out with acceptable limits
Stage ‘5’ HP rotor blade	BDC1313	5	Impact damage out with acceptable limits
Stage ‘6’ HP rotor blade	B204542	6	Impact damage out with acceptable limits
Stage ‘7’ HP rotor blade	BDC8464	6	Impact damage out with acceptable limits

Report compiled by:		Date:	27 July 2016
Reviewed by:	Natasha Wiseman	Date:	27 July 2016

APPENDIX 2 – Alba Post Failure Field Service Report

Field Service Report
For
Investigation of High Vibration
Olympus Serial No: 202204

Customer: Newfoundland Hydro Stephenville

Date: 29th March 2016

Project Number: Alba 5269

Alba Power Ltd
Tel: (44) 01569 730088
Fax: (44) 01569 730099
sales@albapower.com
www.albapower.com

Quality Certification
ISO 9001:2008
ISO 14001:2004
OHSAS 18001:2007
Scotland

Table of Contents

Note:

The information contained within this documentation is Alba Power proprietary information and shall remain so at all times, no reproduction or passing to third parties shall be permissible

1 Introduction

Mr. Symon Hanna arrived at the Newfoundland Hydro site in Stephenville to investigate a high vibration trip and debris found on number 2 and 3 magnetic chip detector.

Date of works: Tuesday 29th March 2016 – Friday 1st April 2016.

Alba Power on site personnel: Mr. Symon Hanna.

2 Daily Report

2.1 Tuesday 29th March 2016

Symon checked in at Aberdeen airport and travelled to Deer Lake Newfoundland via London Heathrow and Toronto airports. Symon stayed overnight in Deer Lake.

2.2 Wednesday 30th March 2016

Symon travelled from Deer Lake to the Newfoundland Hydro Stephenville site. On arrival Symon was given a tailboard safety brief and the work scope of the job was discussed.

Both lube oil feed and return oil pipes were removed from the Olympus and the main oil tank. On removal of these pipes the oil contained fine black and metallic particles and also was discoloured with a burnt smell apparent.

The inlet oil strainer was removed and inspected for debris and found to be clean.

All magnetic chip detectors were removed and debris samples taken. All magnetic chip detector baskets were removed and debris samples were taken. There was severe bearing material debris in the green (Nos: 2 and 3) magnetic chip detector basket.

The air starter motor was removed and the HP rotor was rotated by hand. No abnormal noises or tightness was noted. The turning gear caps were removed from the fuel pump gear box and the LP rotor was attempted to be turned by hand. The LP rotor would not rotate.

The access was gained to the inlet plenum and the front of the LP rotor was inspected. On inspection a sizeable piece of debris was found between the LP rotor and the inlet casing stuck to the base of one of the first stage rotor blades. The LP rotor was rotated in an anti-clockwise direction and was tight to rotate. The LP rotor was then rotated in a clockwise direction and was very tight to turn with scraping noises noted.

2.3 Thursday 31st March 2016

Symon arrived on site and was given a tailboard safety brief before starting work.

All magnetic chip detector baskets were cleaned and replaced along with all corresponding magnetic chip detectors. All removed pipe-work was re-fitted along with the turning gear caps.

The oil used in the Olympus gas turbines was inspected and found to be in date in an adequate storage environment.

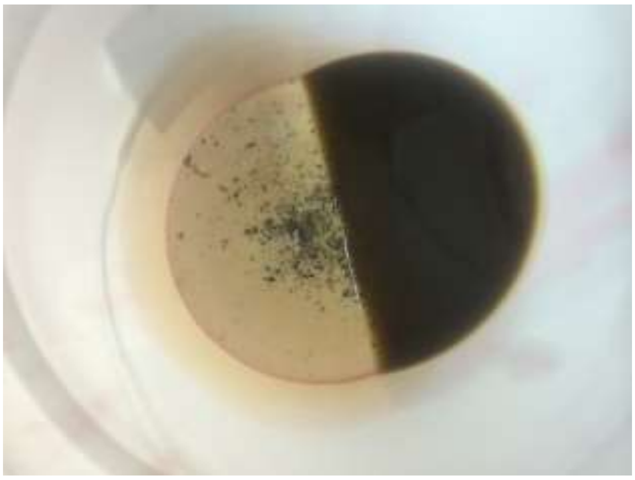
Symon left site and travelled to Dear Lake for his return flight to Aberdeen via Halifax and London Heathrow airports.

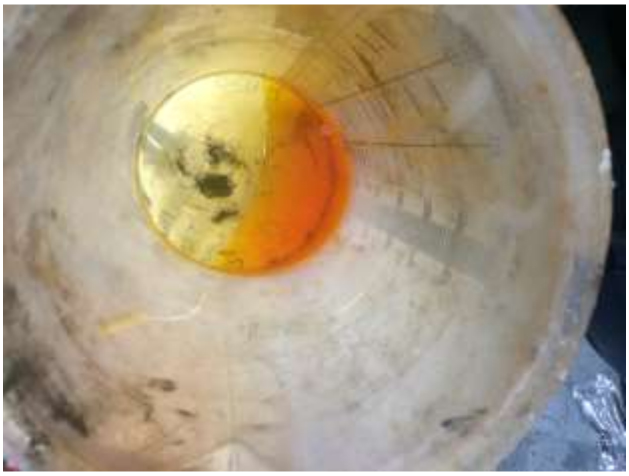
2.4 Friday 1st April 2016

Symon arrived back in Aberdeen.

3 Photographic Images

	
No.1 (Blue) Bearing magnetic chip detector and basket.	No.2 and 3 (Green) Bearing magnetic chip detector basket showing excessive debris.
	
No. 4 and 5 (Aluminium) Bearing magnetic chip detector and basket	No. 7 (White) Bearing magnetic chip detector and basket showing several large pieces of debris.

	
No. 8 (Yellow) Bearing magnetic chip detector and basket.	Oil and debris drained from the removal of the No. 2 and 3 (Green) Bearings magnetic chip detector basket showing contaminated burnt oil and excessive debris.
	
Oil Tank scavenge filter showing large quantities of metallic debris.	Oil feed pipe from the oil tank to the Olympus showing contaminated and discoloured oil through excessive heat.

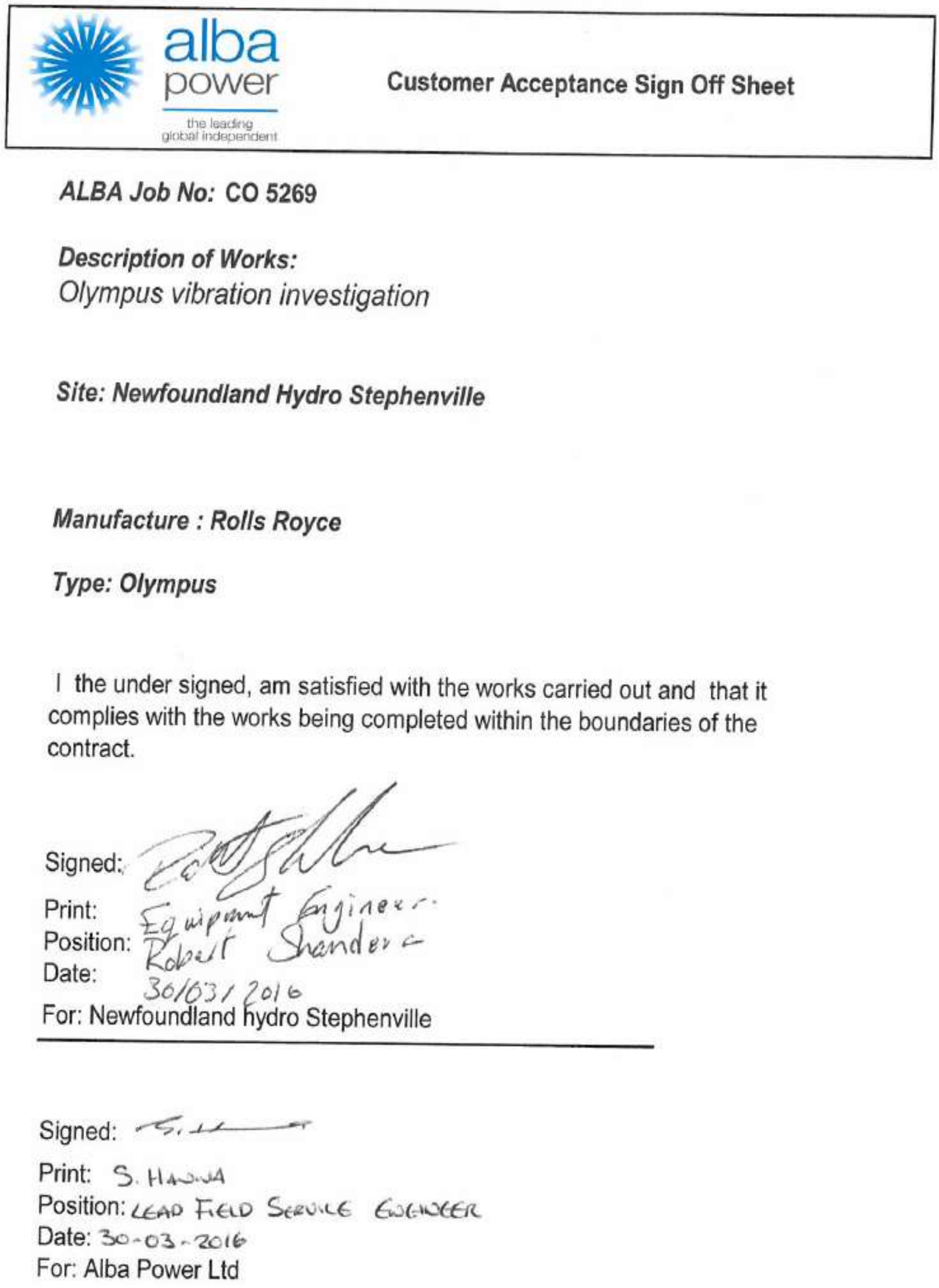
	
Oil scavenge pump filter removed. No signs of debris.	Mobil Jet 2 Oil tank showing that the oil is in date.
	
Fresh oil pumped from the oil drum used for the Olympus gas turbines showing its colour and cleanliness.	Piece of debris removed from between the LP compressor rotor and the intake casing.

4 Summary

All oil filters and magnetic chip detectors have been examined and excessive amounts of debris found in the No. 2 and 3 (Green) magnetic chip detector basket. This debris appears to be bearing material.

The lubricating oil for the Olympus gas turbine appears to be burnt and as a result Gas Turbine s/n: 202204 has suffered front end LP rotor main line bearing failure. The reason behind the excessive heat within the oil system could be due to the heating element within the oil tank becoming too hot or the way in which the gas turbines are shut down and not having a cool down period of at least 5 minutes at LP idle speed of 2000rpm.

5 Customer Acceptance



alba power
the leading global independent

Customer Acceptance Sign Off Sheet

***ALBA Job No:* CO 5269**

Description of Works:
Olympus vibration investigation

Site: Newfoundland Hydro Stephenville

Manufacture : Rolls Royce

Type: Olympus

I the under signed, am satisfied with the works carried out and that it complies with the works being completed within the boundaries of the contract.

Signed:
Print: Equipment Engineer.
Position: Robert Shandera
Date: 30/03/2016
For: Newfoundland hydro Stephenville

Signed:
Print: S. HANNA
Position: LEAD FIELD SERVICE ENGINEER
Date: 30-03-2016
For: Alba Power Ltd

6 Report Compilation

On site personnel:	Symon Hanna	Date:	29th March – 1st April 2016
Report compiled by:	Symon Hanna	Date:	1st April 2016
Reviewed by:	Alan Watson	Date:	1st April 2016

APPENDIX 3 – SKF Failure Analysis Report

ALBA POWER
ROLLS-ROYCE OLYMPUS
BEARING FAILURE ANALYSIS

DUNCAN FALLOW 17/06/2016

CONSULTANT (RELIABILITY ENGINEERING)

Distribution:

To:- Martin Cruickshank

cc:-

REPORT NUMBER: SKF REPORT RPCM507_ALBA POWER_160617_DF	
TITLE: ALBA POWER ROLLS-ROYCE OLYMPUS BEARING FAILURE ANALYSIS	
WRITTEN BY: D FALLOW **DESIGNATION: CONSULTANT**	**AUTHORISED BY: D ARMSTRONG** **DESIGNATION: TEAM MANAGER**

SUMMARY:

No root cause has been found for the bearing failures; however poor fit, moisture ingress, lubricant condition, cage integrity and loading appear contributing factors.

A review of monitoring and maintenance procedures might be beneficial to ensure they align with current best practices.

Advice on bearing selection and precision fit/mounting should be sought from a specialist.

Advice on lubricant selection, cleanliness, sampling frequency and analysis should be sought from specialist such as the Original Equipment Manufacturer (OEM) and lubricant supplier.

KEYWORDS: Lubricant contamination, load, fretting corrosion, poor fit, spalling, cage separation, temperature.

Project Quality Assurance

Carried out in accordance with SKF Quality Work Instructions as referenced. Accredited to ISO 9001:2008.

ALBA POWER
ROLLS-ROYCE OLYMPUS
BEARING FAILURE ANALYSIS

CONTENTS

(1) INTRODUCTION

A bearing housing containing two bearings from a Rolls-Royce Olympus gas turbine was received for analysis. The turbine had done approximately 90 hours of start/stop duty as a stand-by unit before removal of the housing.

An oil sample, taken from the engine sump, was received and sent for analysis – there was visible debris in the container on receipt.

1.1 Motor Unit Details

Rolls-Royce Olympus – no model designated.

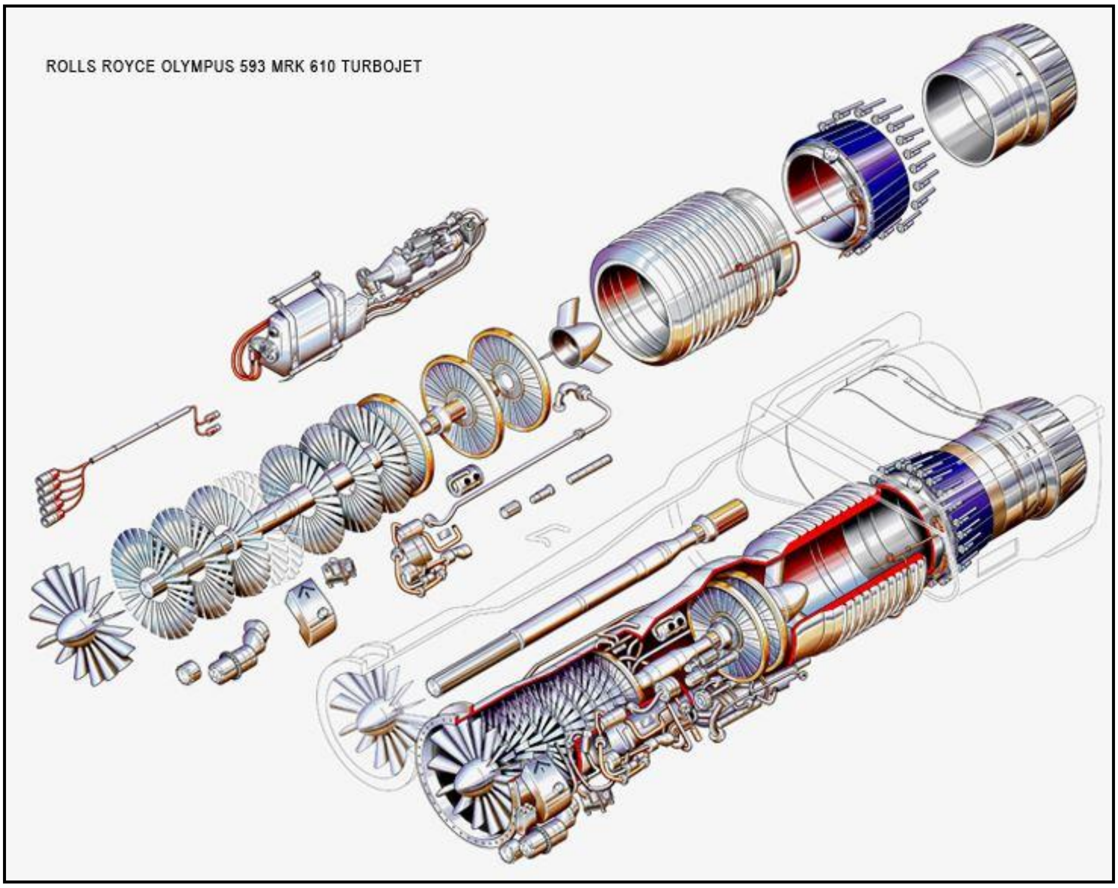
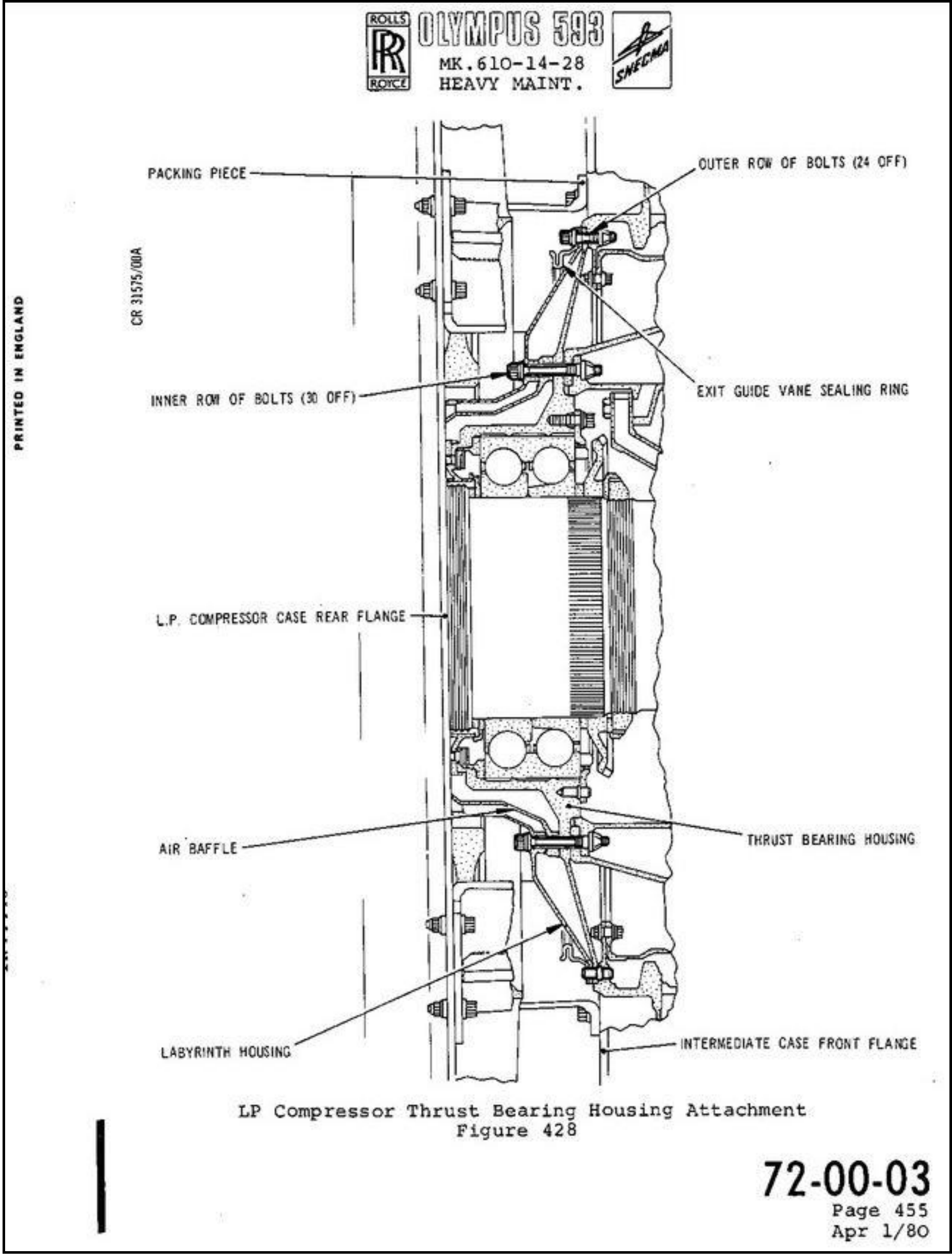


Figure 1 – *Exploded diagram of Olympus 593 engine.*

1.2 General Arrangement



LP Compressor Thrust Bearing Housing Attachment
Figure 428

72-00-03
Page 455
Apr 1/80

Figure 2 – *excerpt from Rolls-Royce Heavy Maintenance manual for Olympus 593 Mk-610, from the website www.Avialogs.com.*

1.3 Bearing Nomenclature

It has been impossible to positively identify the bearings due to the amount of wear on the side faces – where manufacturing marks and designations are normally situated.

1.4 Housing

Figure 3 – *Housing 'as received' with both outer rings in place. The Front bearing is uppermost in the photo.*

(2) FRONT BEARING – RHP UNKNOWN TYPE

Figure 4 – *Outer ring side face #1 'as received'.*

The bearing was received disassembled – the outer ring shown above and the inner ring (Figure 5 overleaf) split in two halves.

Twenty two rolling elements (Figure 6, overleaf) were received together with cage fragments (Figure 7, overleaf).

(2) <u>(Continued)</u>

Figure 5 – *Inner ring side face #1 'as received'.*

(2) (Continued)

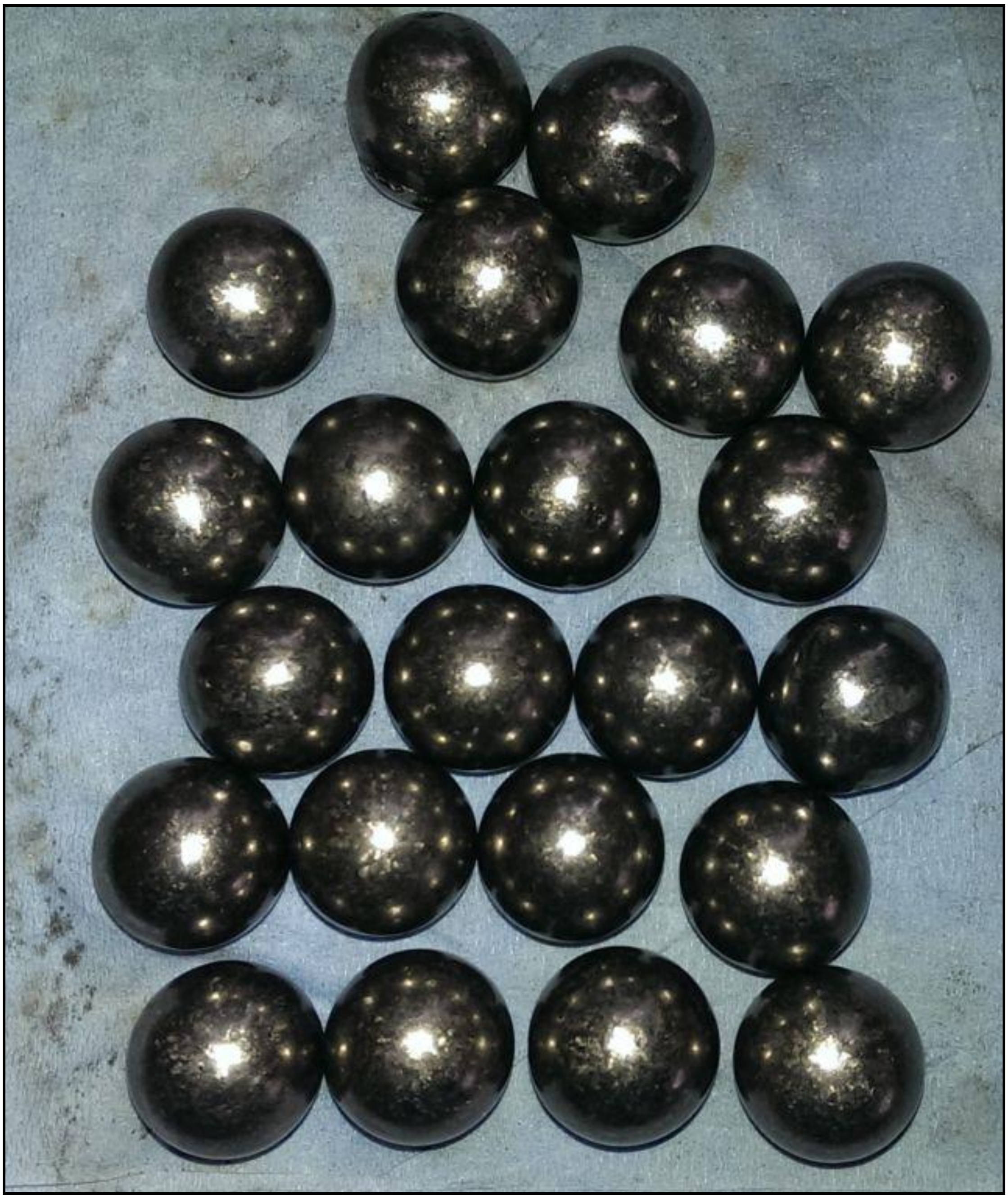


Figure 6 – *Rolling elements 'as received'.*

(2) **(Continued)**

Figure 7 – *Cage fragments 'as received'.*

2.1 Inner Ring Bore

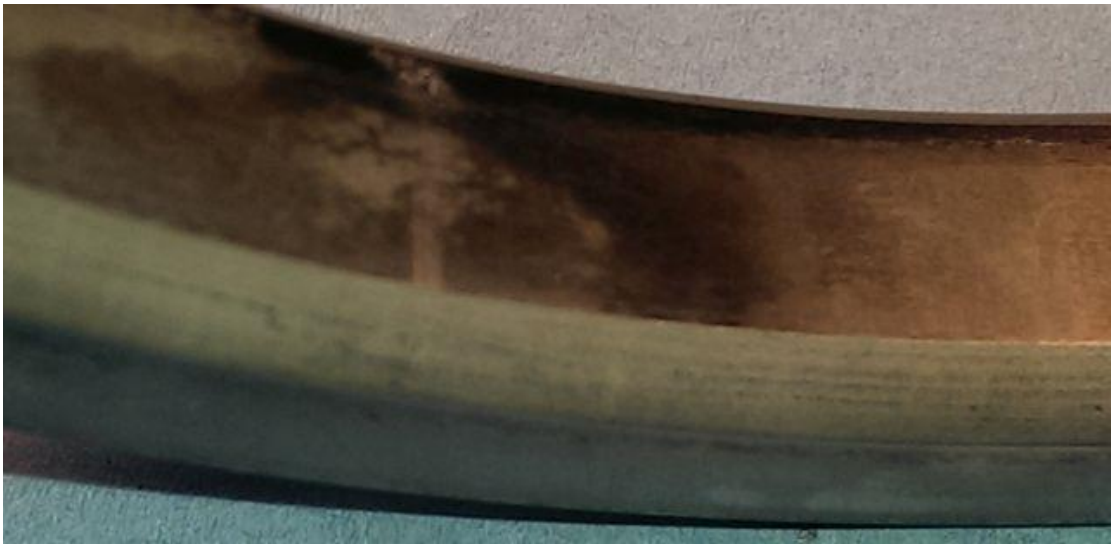


Figure 8 – *detail of inner ring bore.*

Staining and heat damage noted.

2.2 Inner Ring Side Faces

Figure 9 – *Inner ring #1 side face 1.*

Circumferential scoring, staining and blueing noted.

(2.2) (Continued)

Figure 10 – *Inner ring #1 side face 2.*

Staining and bluing noted.

(2.2) **(Continued)**

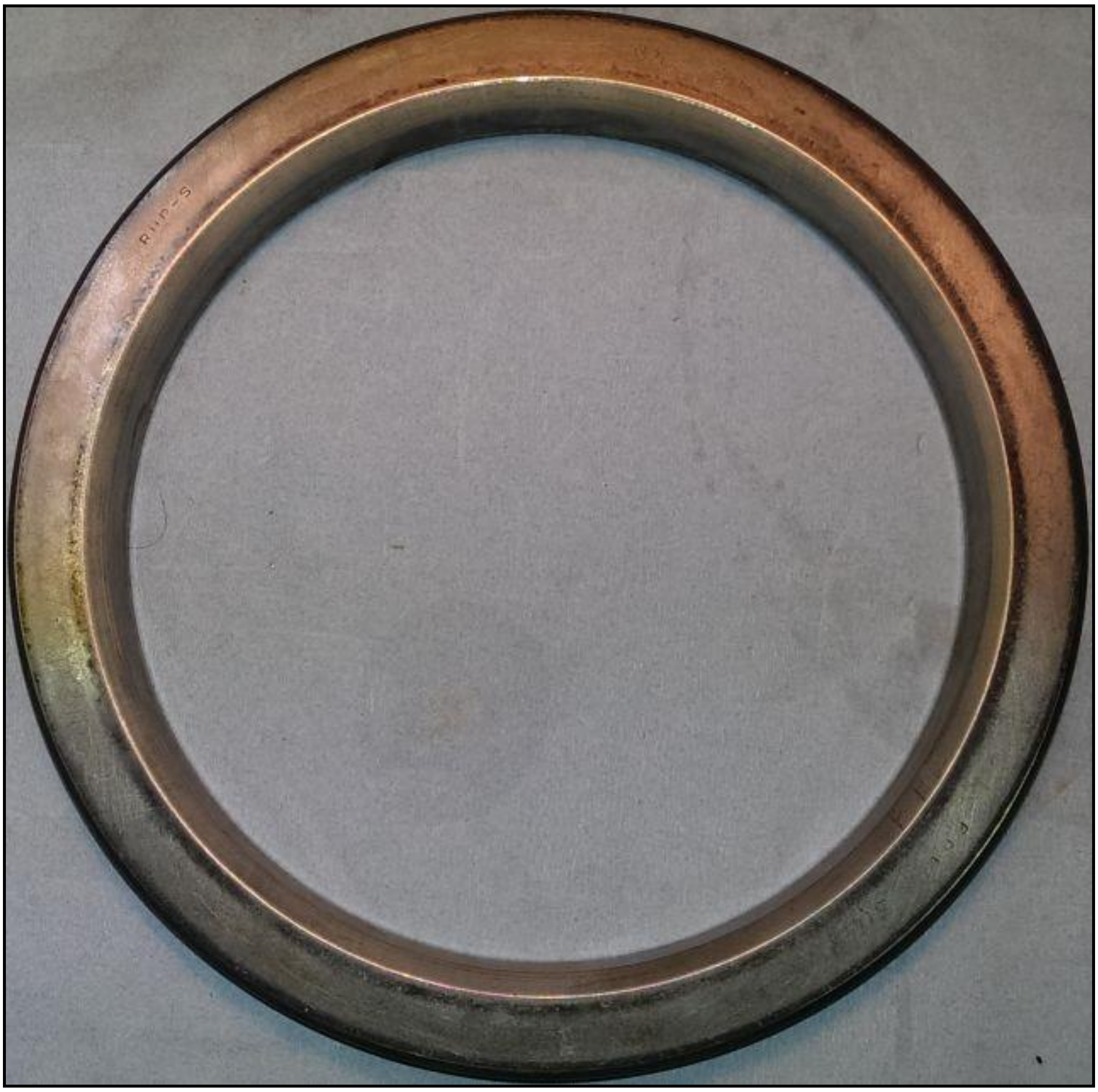


Figure 11 – *Inner ring #2 side face 1.*

Light staining noted.

(2.2) **(Continued)**

Figure 12 – *Inner ring #2 side face2.*

Fretting corrosion and surface damage noted. The surface damage (lower left of photo) appears relatively fresh and may have occurred during dismounting.

2.3 Outer Ring Outer Diameter (OD)

***Figure 13 –** detail of outer ring OD.*

Moisture corrosion, fretting corrosion and circumferential scratches noted.

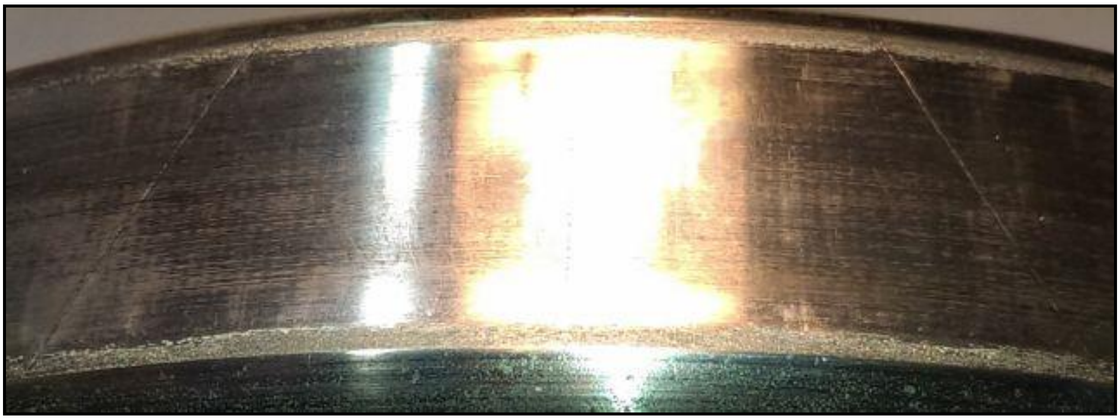


***Figure 14 –** detail of outer ring OD. Note "V-shaped" marking which indicates how the matched bearing set should be mounted to obtain the proper preload in the set (see matching marks on the rear bearing shown in Figure 36).*

2.4 Outer Ring Side Faces

Figure 15 – *Outer ring side face 1.*

Circumferential scoring, staining and fractures to the inner lip noted.

(2.4) (Continued)

Figure 16 – *Outer ring side face 2.*

Light staining noted.

2.5 Inner Ring Raceway

Figure 17 – *Detail of inner ring raceway (colour corrected).*

Spalling and staining noted.

2.6 Outer Ring Raceway

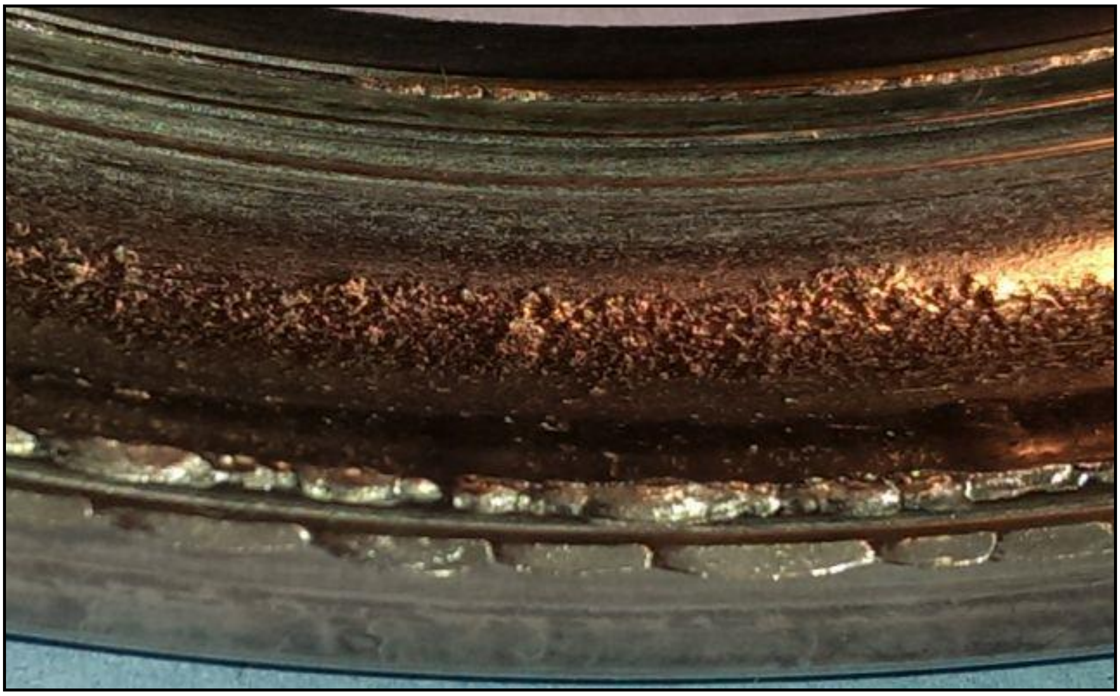


Figure 18 – *Detail of outer ring raceway.*

Heavy spalling, circumferential scoring, staining and fractures noted.

(2.6) **(Continued)**

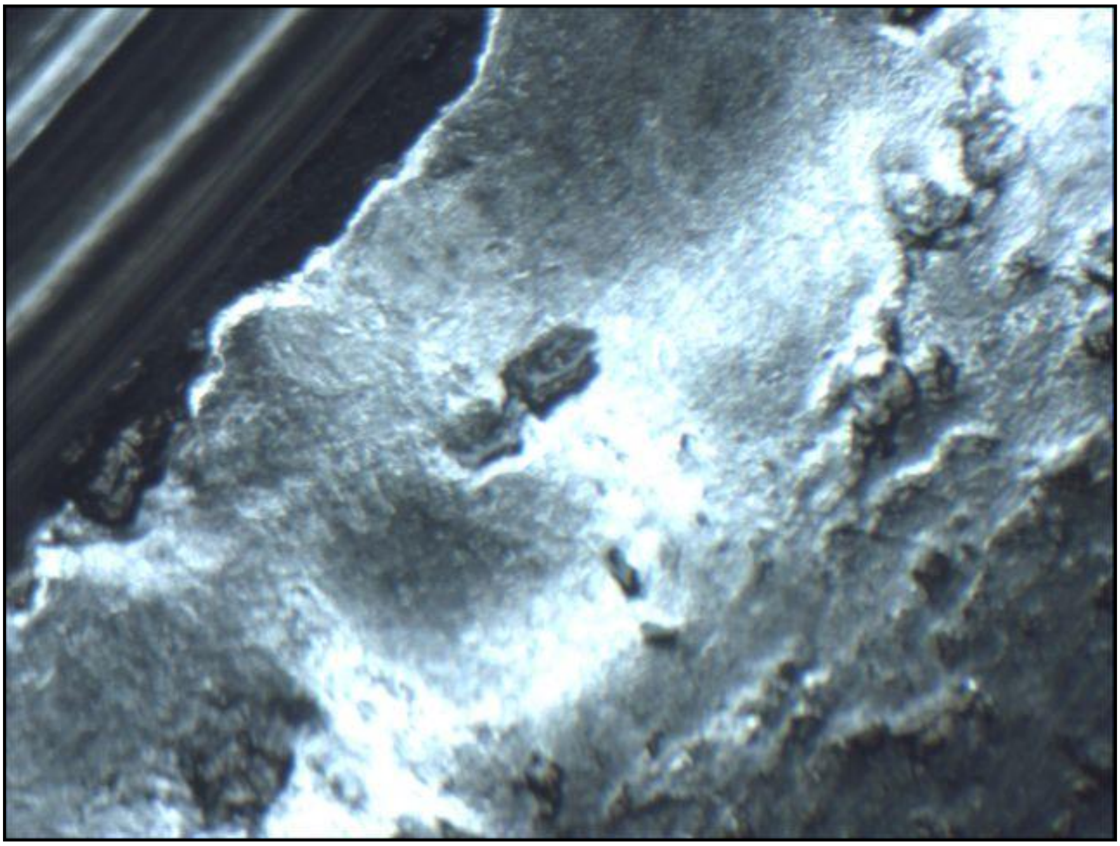


Figure 19 – *Detail of outer ring raceway damage showing heavy spalling and large indentations (deformation) at edge of raceway.*

2.7 Cage

Figure 20 – *cage fragments after cleaning.*

A quantity of the cage was found to be absent when re-construction attempted.

(2.7) (Continued)

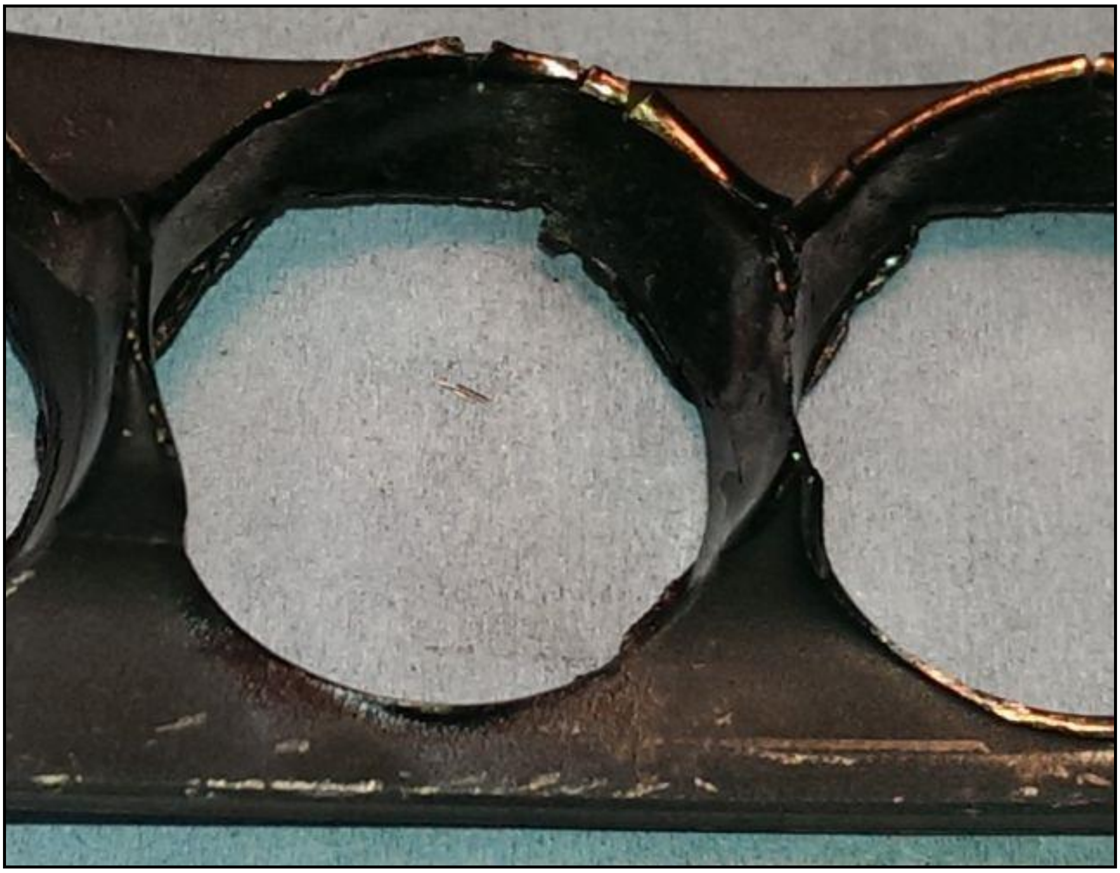


***Figure 21 –** Detail of cage showing flaring of material around the pockets.*

Significant distortion of cage pockets noted.

2.8 Rolling Elements

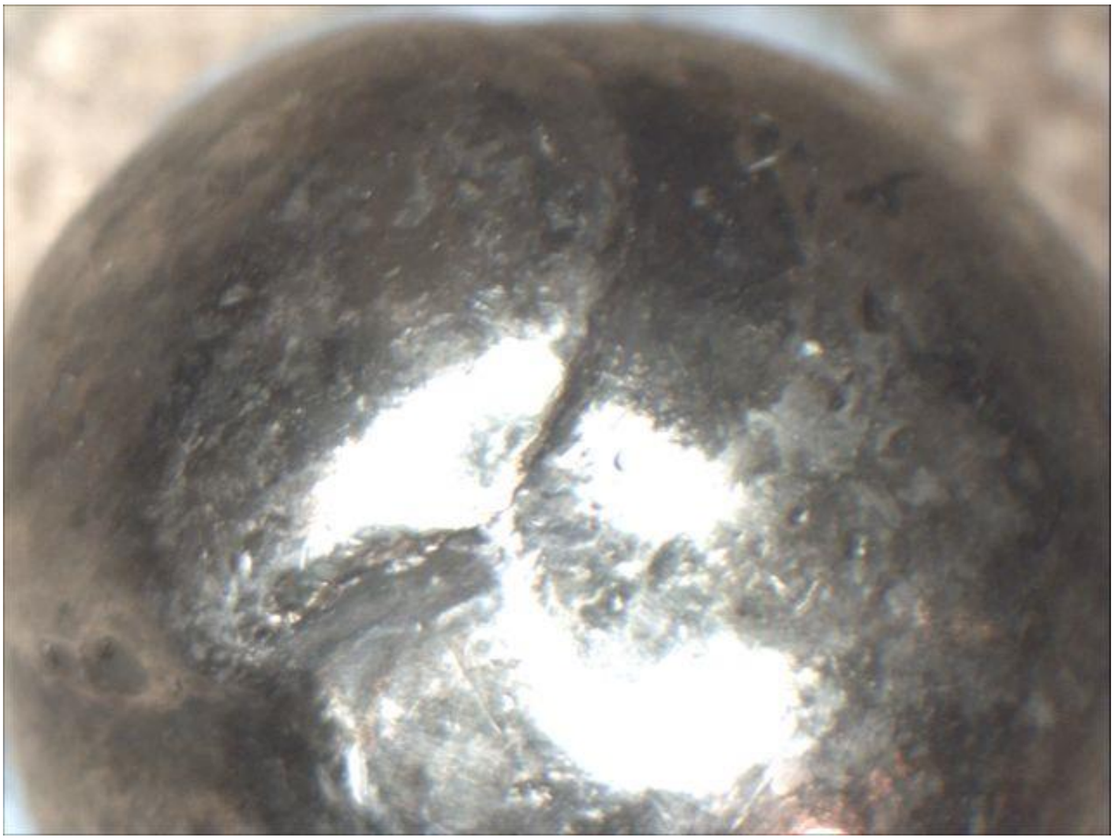


Figure 22 – example of typical ball condition. Note dents (deformation) and heavy surface damage.

Rolling elements were in very poor condition with a variety of defects noted.

A deep gouge is illustrated in Figure 23 (overleaf).

An accumulation of 'flat spots' are illustrated in Figure 24 (overleaf).

An instance of large scale adhesive wear is shown in Figure 25 (overleaf).

(2.8) **(Continued)**

Figure 23 – *example of deep gouge (deformation) on rolling element.*

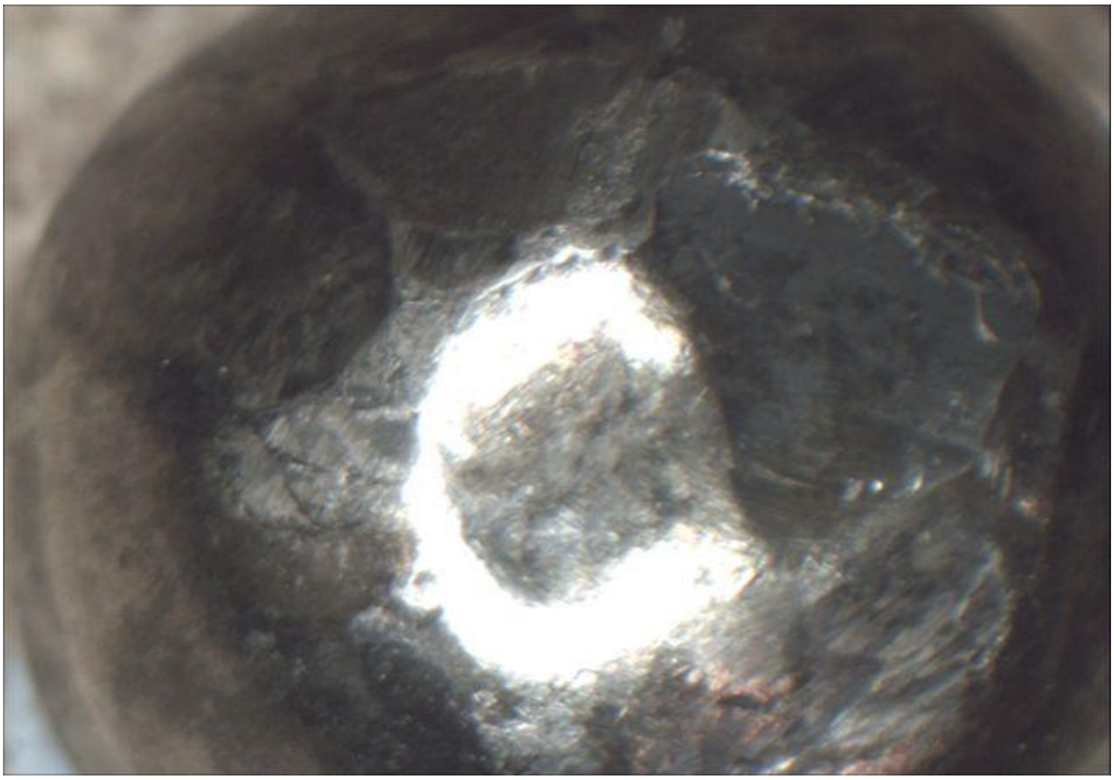


Figure 24 – *an accumulation of 'flat spots' (deformation) on rolling element*.

(2.8) (Continued)

Figure 25 – *Adhesive wear.*

2.9 Lubrication

A lubricant sample from the sump has been analysed.

(3) REAR BEARING – RHP UNKNOWN TYPE

Figure 26 – *Outer ring side face #1 'as received'.*

The bearing was received disassembled – the outer ring shown above and the inner ring (Figure 27 overleaf) split in two halves.

Twenty two rolling elements (Figure 28, overleaf) were received together with cage fragments (Figure 29, overleaf).

(3) (Continued)

Figure 27 – *Inner ring side face #1 'as received'.*

(3) (Continued)

Figure 28 – *Rolling elements 'as received'.*

(3) <u>(Continued)</u>

Figure 29 – *Some of cage fragments 'as received'.*

3.1 Inner Ring Bore

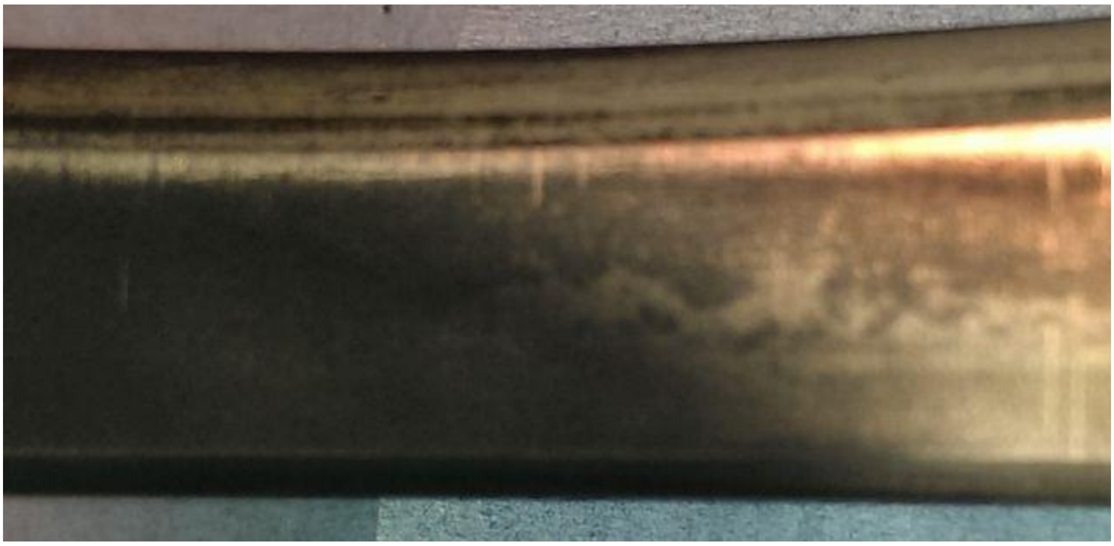


***Figure 30 –** detail of inner ring bore.*

Staining and heat damage noted.

3.2 Inner Ring Side Faces

Figure 31 – *Inner ring #1 side face 1.*

Circumferential scoring, staining and blueing noted.

(3.2) **(Continued)**

Figure 32 – *Inner ring #1 side face 2.*

Staining and bluing noted.

(3.2) **(Continued)**

Figure 33 – *Inner ring #2 side face 1.*

Heavy circumferential damage, heat damage and staining noted.

(3.2) (Continued)

Figure 34 – *Inner ring #2 side face2.*

Heat damage and staining noted.

3.3 Outer Ring Outer Diameter (OD)

***Figure 35 –** detail of outer ring OD.*

Moisture corrosion, fretting corrosion and circumferential scratches noted.

Scoring noted across OD – see Figure 36 (overleaf).

(3.3) **(Continued)**

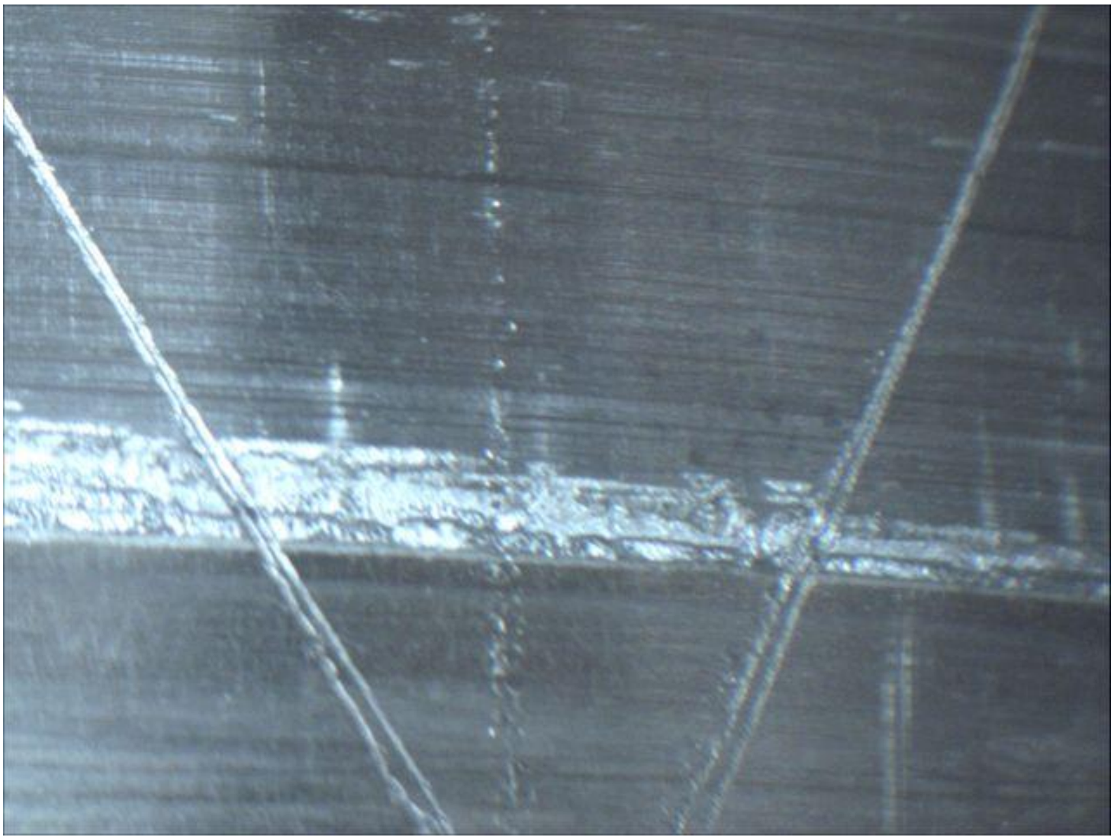


Figure 36 – *detail of outer ring OD. Note "V-shaped" marking which indicates how the matched bearing set should be mounted to obtain the proper preload in the set (see matching marks on the rear bearing shown in Figure 14).*

3.4 Outer Ring Side Faces

Figure 37 – *Outer ring side face 1.*

Circumferential scoring, staining and fractures to the inner lip noted.

(3.4) **(Continued)**

Figure 38 – *Outer ring side face 2.*

Light staining noted.

3.5 Inner Ring Raceway

Figure 39 – *Detail of inner ring raceway.*

Spalling and fractures noted.

3.6 Outer Ring Raceway

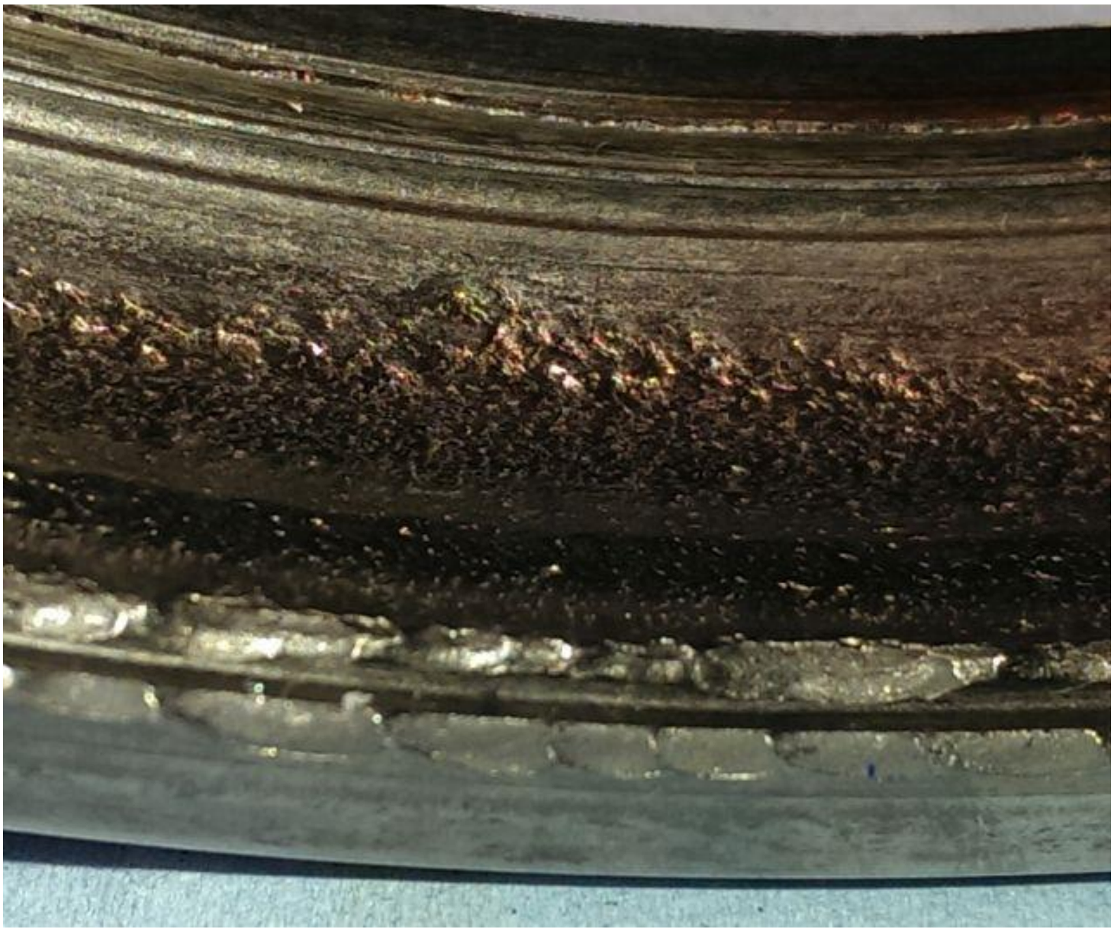


Figure 40 – *Detail of outer ring raceway.*

Heavy spalling, circumferential scoring, staining and fractures noted.

(3.6) <u>(Continued)</u>

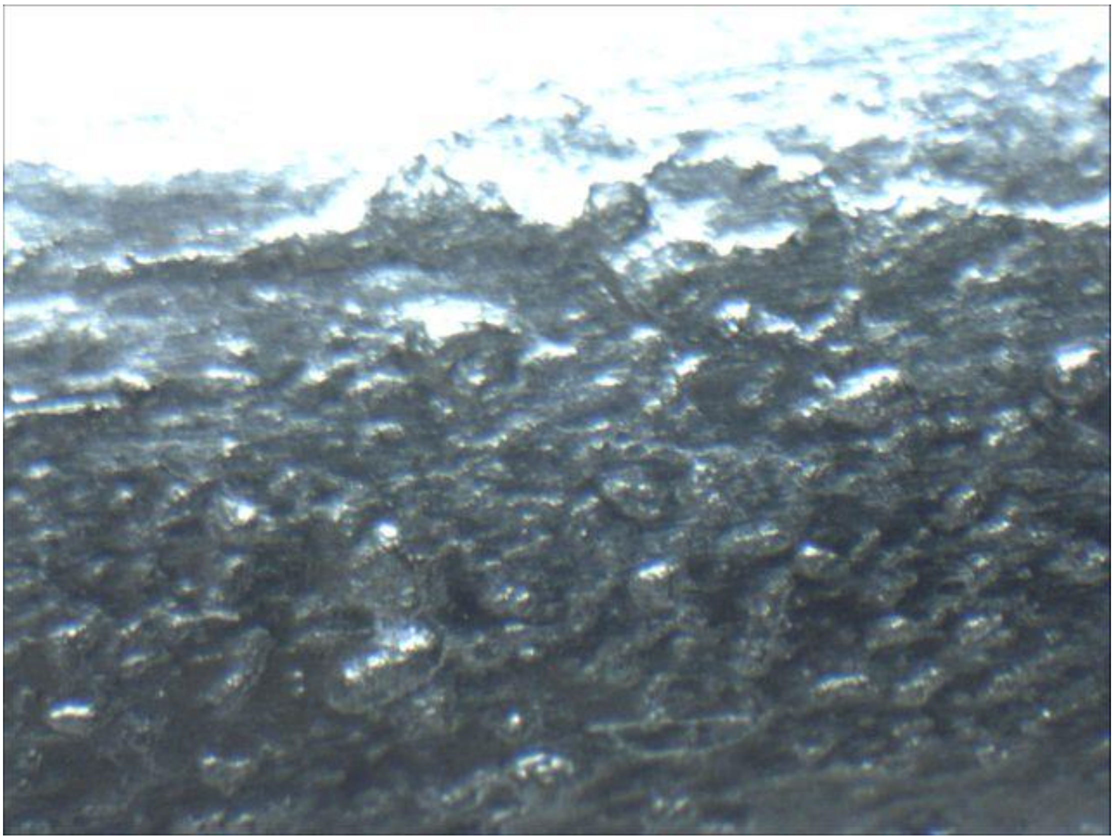


Figure 41 – *Detail of outer ring raceway damage showing heavy spalling.*

3.7 Cage

***Figure 41 –** cage fragments after cleaning.*

A quantity of the cage was found to be absent when re-construction attempted.

(3.7) **(Continued)**

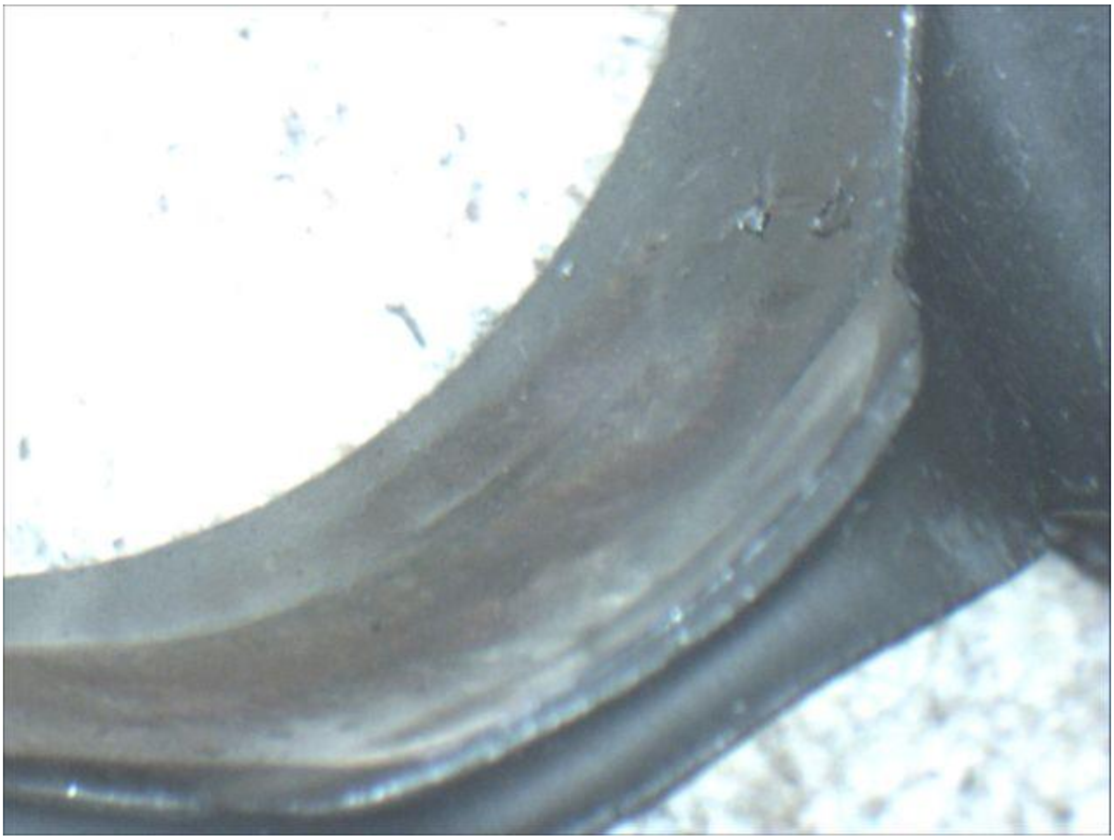


Figure 42 – *Detail of cage showing discolouration and flaring of material around the pockets.*

Heat damage, indentations and distortion of cage pockets noted.

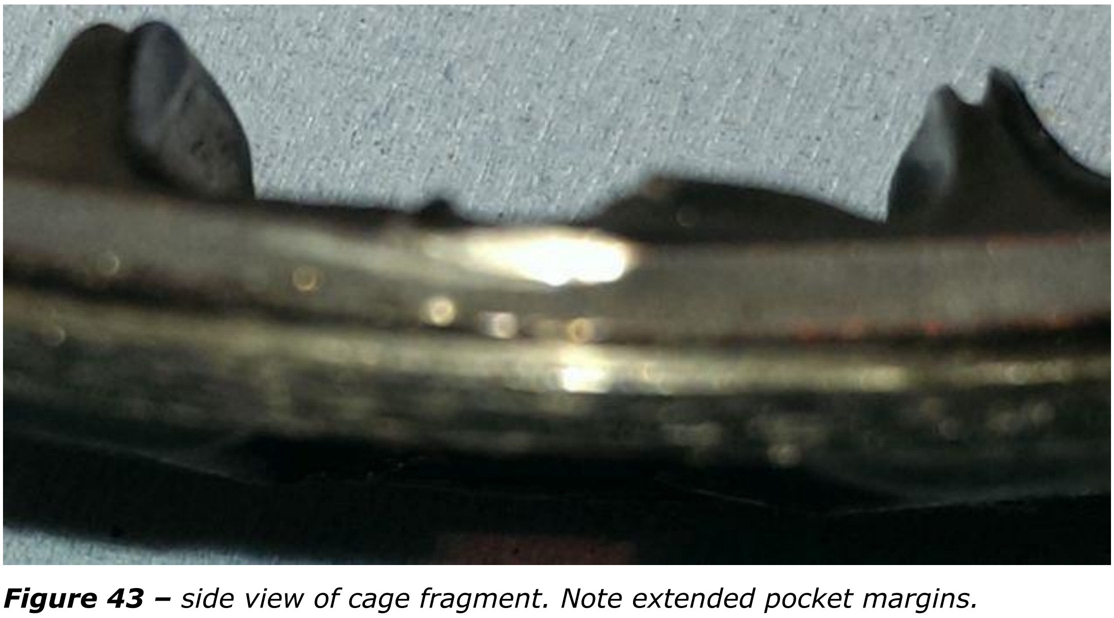


Figure 43 – *side view of cage fragment. Note extended pocket margins.*

(3.7) <u>(Continued)</u>

Figure 44 – *example of damage to exterior of cage. Also note amount of clearance around the rolling element.*

3.8 Rolling Elements

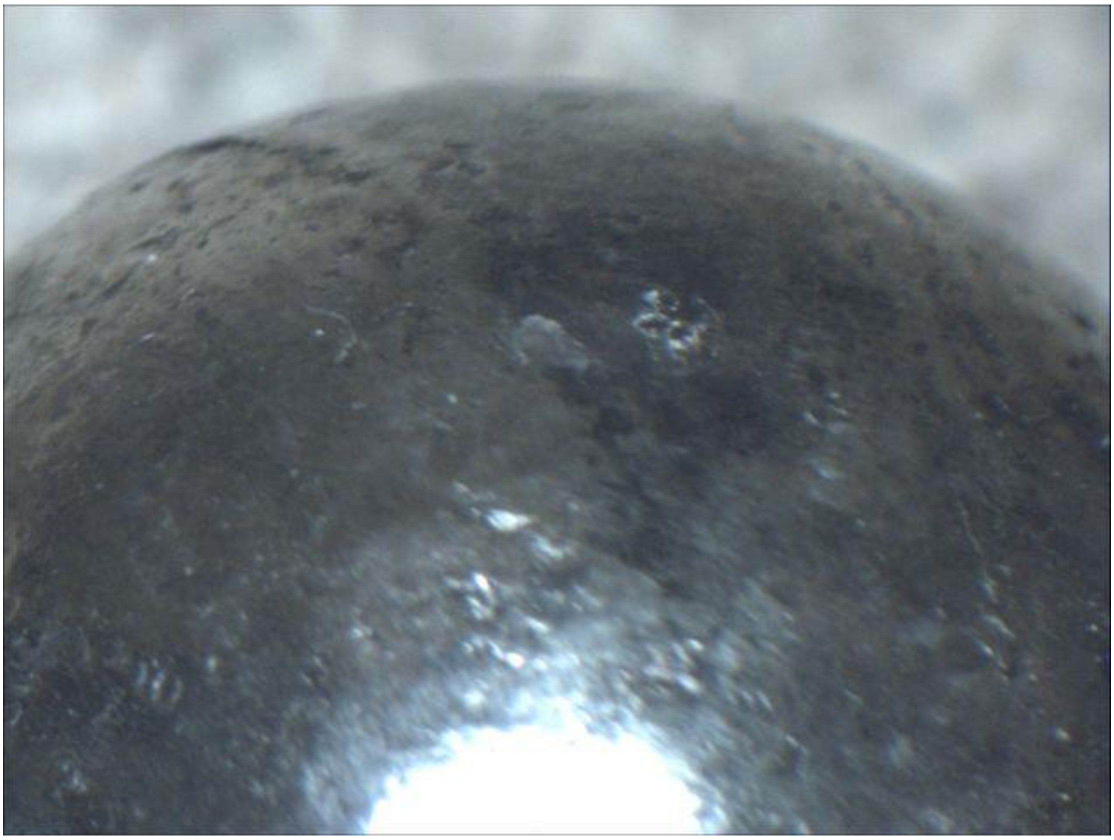


Figure 45 – example of typical ball condition.

Rolling elements were in poor condition with a variety of defects noted.

A deep gouge is illustrated in Figure 46 (overleaf).

(3.8) (Continued)

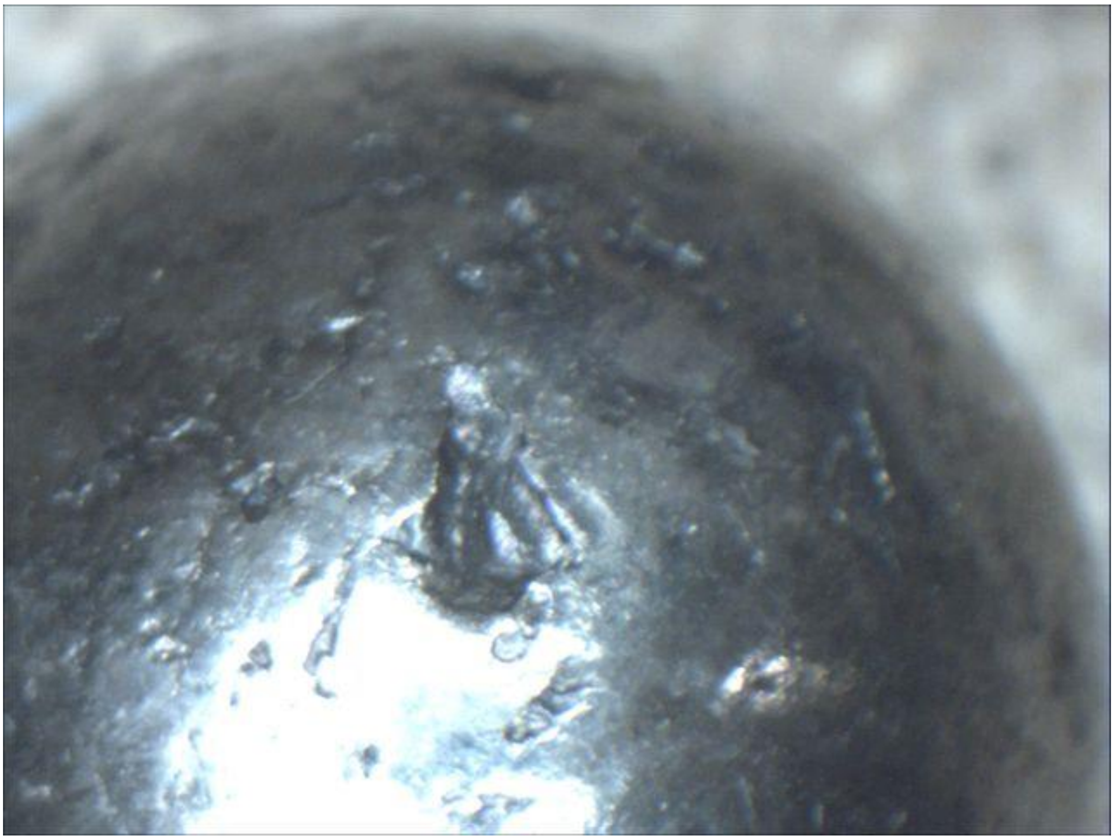


***Figure 46 –** example of deep gouge on rolling element.*

3.9 Lubrication

A lubricant sample from the sump has been analysed.

(4) BEARING HOUSING

The housing was received intact with the outer races of two bearings inside. Initial attempts to remove the bearing components were unsuccessful and after receiving confirmation from the client the housing was cut – see Figure 47.

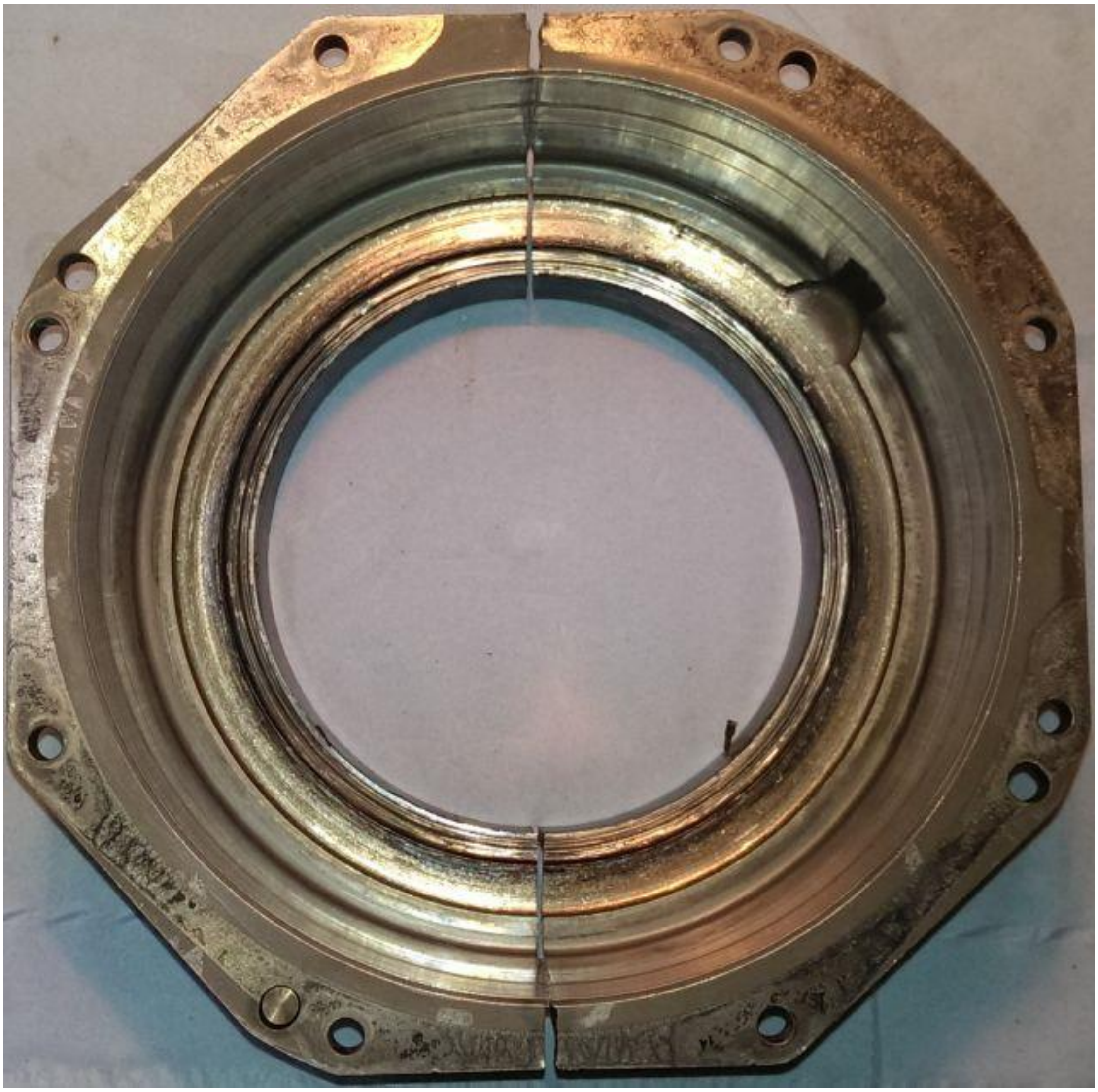


Figure 47 – *interior of housing after removal of bearing races and cleaning. Note the circumferential scoring and wear.*

A significant amount of wear was noted together with some ‘blueing’ of the surfaces adjacent to the shaft aperture.

The exterior of the housing also showed evidence of having been subjected to high localised heat – see Figure 48 (overleaf).

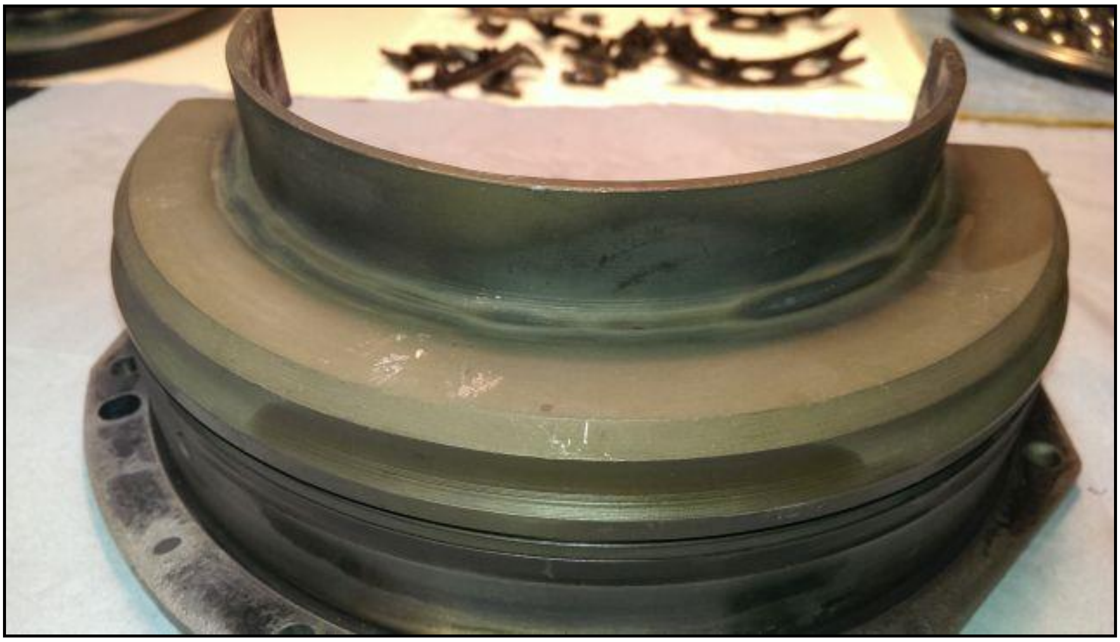


Figure 48 – *one half of housing exterior after cleaning. Note areas of 'blueing' (centre right of photo).*

Circumferential wear was noted on the housing interior – see upper section of Figure 49.

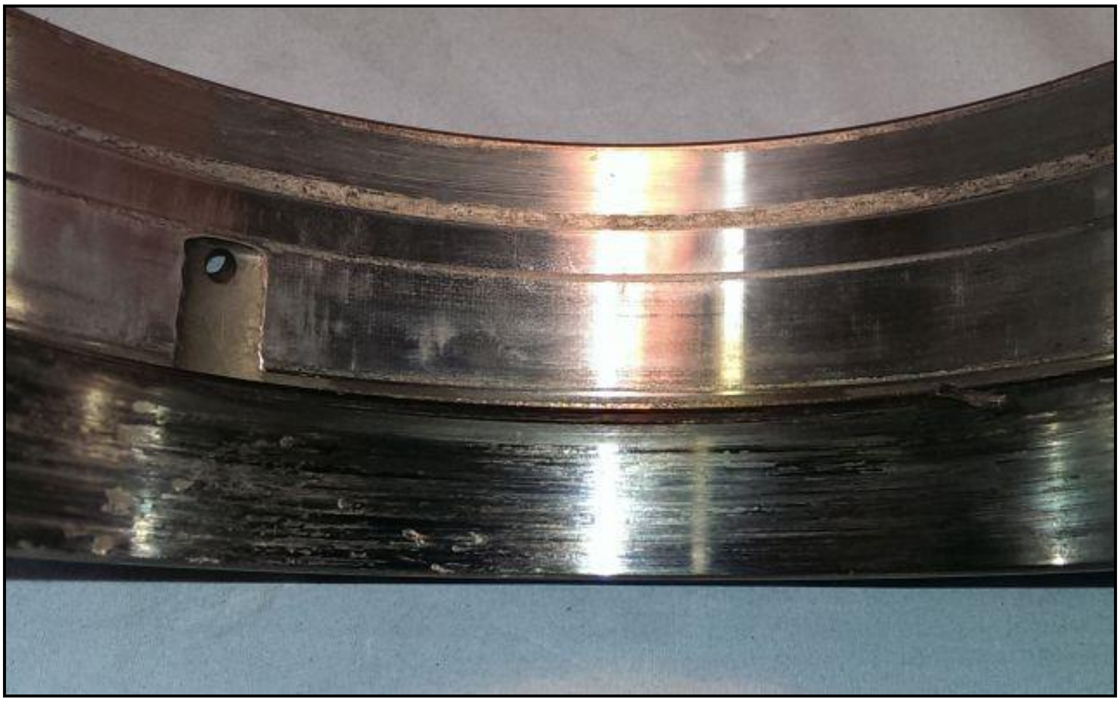


Figure 49 – *one half of housing interior.*

Significant amounts of wear noted in shaft aperture – see lower section of Figure 49.

(5) DISCUSSION

Spalling (ISO 5.1.1 – Appendix A, Table A1) was noted on both front and rear inner and outer raceways - Figure 17, Figure 18, Figure 19, Figure 39, Figure 40 & Figure 41. This type of fatigue is caused by repeated stresses between rolling elements and raceways and is often attributed to lubrication issues.

Adhesive wear (ISO 5.2.3 – Appendix A, Table A1) was noted on the front bearing inner ring #1 side face 1 (Figure 9), rear bearing inner ring #1 side face 1 (Figure 31), rear bearing inner ring #2 side face 1 (Figure 33), front bearing rolling element (Figure 25) and housing interior (Figure 49). Some causes of adhesive wear include acceleration of bearing components, skidding/smearing of rolling elements, excessive frictional heat and too light loading.

The wear and 'blueing' (Figure 47) is probably secondary damage caused by rotating contact due to increasing clearance between cage and rolling elements.

Moisture corrosion (ISO 5.3.2 – Appendix A, Table A1) was noted on front bearing outer ring OD (Figure 13) and rear bearing outer ring OD (Figure 35). For this type of corrosion to occur the component surfaces need to be exposed to moisture and oxygen when at stand-still for prolonged periods.

Fretting corrosion (ISO 5.3.3.2 – Appendix A, Table A1) was noted on front bearing inner ring #2 side face 2 (Figure 12), front bearing outer ring OD (Figure 13), the rear bearing outer ring OD (Figure 35) and interior of bearing housing (Figure 49). This type of damage is commonly caused by micro-movements between mating parts in load transmitting interfaces.

Overload (ISO 5.5.2 – Appendix A, Table A1) was noted on front bearing outer race raceway (Figure 19), front bearing cage (Figure 21), Front bearing rolling elements (Figure 22, Figure 23 & Figure 24), rear bearing cage (Figure 42 & Figure 43) and rear bearing rolling elements (Figure 45 & Figure 46). Common causes include static/shock loading of components, handling damage and surface damage caused by hard/sharp objects.

Over-rolling of steel debris often produces indentation with rounded bottoms like those seen on the rolling elements (Figures 45 and 46).

Fractures (ISO 5.6.1 – Appendix A, Table A1) were noted on front bearing outer ring side face 1 (Figure 15), front bearing outer ring raceway shoulder (Figure 18), front cage (Figure 20), rear bearing outer ring side face 1 (Figure 37), rear bearing inner ring raceway (Figure 39), rear bearing outer ring raceway (Figure 40) and rear cage (Figure 41). These are the result of the tensile strength of the material being exceeded and probably occurred following loss of bearing integrity.

The lubricant sample received from the sump was analysed and the results have been compared with Mobil Jet Oil II Material Safety Data Sheet [1] (MSDS). Elemental results are shown in Table 1. The alarm levels are for indication only but are typical for this type of gas generator – advice should always be sought from the OEM regarding lubricant cleanliness.

Element	Units	Result	Alarm
Aluminium	mg/kg	3	5
Chromium		2	5
Copper		< 1	5
Iron		21	5
Lead		< 1	5
Manganese		< 1	5
Molybdenum		< 1	5
Nickel		< 1	5
Silver		< 1	5
Titanium		< 1	5
Vanadium		< 1	5
Boron		2	5
Sodium		< 1	5
Silicon		3	5
Barium		< 1	5
Calcium		< 1	5
Magnesium		< 1	5
Phosphorous		2137	3500
Zinc		< 1	5

Table 1 – *elemental results from sump oil sample.*

PQ Index was 33 – a value of 25 or below is considered acceptable.

Viscosity at 40°C was 24.75 centiStokes versus 27.6 centiStokes on Mobil Jet Oil II MSDS [1] – 10.4% below optimum. Mobil recommend that typical viscosity ranges for turbine applications should remain within +/-5% of new oil.

Total Acidity was 0.1 mg KOH/g versus 0.03 mg KOH/g on Mobil Jet Oil II MSDS [1] – more than three times greater than 'new' oil. This typically indicates build-up of acidic by-products formed during lubricant oxidation.

The size of the sample was too small (less than 120 ml) for complete analysis to be completed – accurate determination of Flash Point.

Mobil recommend daily visual inspection for critical application turbine oils as a cloudy/hazy appearance can indicate moisture ingress.

It is not clear whether any lubricant sampling or analysis program is in place for the unit.

(5) CONCLUSION

It is apparent that the bearings ran for some time with increasingly contaminated lubricant - the source of the initial contamination has not been identified.

Both cages have fractured/separated probably as a result of excessive heat. The significant amount of separation noted between rolling element and cage pocket (Figure 44) and the distortion of pocket geometry (Figure 43) suggest running with sub-optimal lubrication conditions.

The fretting corrosion around the inside of the housing (Figures 49) suggest poor fit between components. The wear and 'blueing' (Figure 47) is probably secondary damage caused by rotating contact due to increasing clearance between cage and rolling elements.

An appropriate lubricant sampling and analysis program should have picked up trends departing from nominal – particularly important parameters such as viscosity and acidity.

(6) RECOMMENDATIONS

In order to avoid fretting corrosion, or slow the process, the tolerances (fit) should be adjusted. Some manufacturers recommend the application of an anti-fretting paste or compound. SKF, however, does not recommend the use of specially formulated adhesives to avoid fretting corrosion; a 'precision' fit should always be sought.

It would be prudent to review current oil sampling and analysis procedures to ascertain if any changes might afford earlier detection of contamination issues. It is suggested that attention should be paid to OEM and lubricant manufacturer recommended cleanliness levels perhaps through regular sampling and analysis.

Advice should be sought from the Original Equipment Manufacturer (OEM) regarding optimum lubricant selection.

A review of recent operational parameters might confirm whether significant changes in load on the engine had taken place.

A review of bearing selection criteria might be beneficial to ensure that state-of-the-art quality bearings are being utilised. Hybrid bearings (with specialist coatings) are available which can help mitigate against early wear effects and lubricant contamination.

References

[1] Exxon Mobil Corporation. Mobil Jet Oil II PDS. Exxon Mobil website - http://pds.exxonmobil.com/USA-English/Aviation/PDS/GLXXENAVIEMMobil_Jet_Oil_II.aspx

APPENDIX A

SKF BEARING DAMAGE CLASSIFICATION
(ADAPTED FROM ISO 15243:2004)

SKF BEARING DAMAGE CLASSIFICATION
(ADAPTED FROM ISO 15243:2004)

5.1.1	**Fatigue**	The change in the material structure, which is caused by the repeated stresses developed in the contacts between the rolling elements and the raceways. Fatigue is manifested visibly as ***spalling*** of particles from the surface. The time between beginning and advanced spalling varies with speed and load. In any event it is typically a condition that will not cause catastrophic failure.
5.1.2	Subsurface fatigue	The initiation of ***micro-cracks*** below the raceway surface. When these micro-cracks propagate to the surface they produce ***spalls*** (flaking).
5.1.3	Surface initiated fatigue	Distress of the surface. Failure of the rolling contact metal surface asperities (roughness) due to inadequate lubrication conditions.
5.2.1	**Wear**	The progressive removal of material resulting from the interaction of two sliding or rolling/sliding contacting surfaces during service.
5.2.2	Abrasive wear	The result of inadequate lubrication of the ingress of contaminants.
5.2.3	Adhesive wear (smearing, skidding, galling)	A material transfer from one surface to another with friction heat, sometimes with tempering or re-hardening of the surface.
5.3.1	**Corrosion**	The deterioration of a metal surface as a result of oxidation or a chemical reaction on metal surfaces.
5.3.2	Moisture corrosion	Oxidation of the surfaces in the presence of moisture.
5.3.3.1	Frictional corrosion	The chemical reaction activated by relative micro-movement between mating surfaces under certain friction conditions.
5.3.3.2	Fretting corrosion	The oxidation and wear of surface asperities under oscillating micro-movements.
5.3.3.3	False brinelling	The formation of shallow depressions resulting from micro-movements caused by cyclic vibrations when a machine is at standstill. Equally spaces depressions matching the rolling element pitch appear in the raceways.
5.4.1	**Electrical erosion**	The damage to contact surfaces (removal of material) caused by the passage of electrical currents.
5.4.2	Excessive current	Sparking and localised heating from current passage in the contact area because of ineffective insulation.
5.4.3	Current leakage	The generation of shallow craters from 9low) current passage. The crates are closely positioned

		to one another. They develop over time into flutes parallel to the rolling axis and are equally spaced.
5.5.1	**Plastic deformation**	Permanent deformation occurs whenever the yield strength of the material is exceeded.
5.5.2	Overload	Overloading by static or shock loads, leading to plastic deformation. Bearing surfaces that are dented or gouged by hard, sharp objects.
5.5.3	Indents from debris	Over-rolled particles in the contact areas from dents in the raceways and rolling elements. The size and shape of the dents depends on the nature of the particles.
5.6.1	**Fracture**	The ultimate tensile strength of a material is exceeded and complete separation of a part of a component occurs.
5.6.2	Forced fracture	A fracture resulting from a stress concentration in excess of material's tensile strength.
5.6.3	Fatigue Fracture	A fracture resulting from frequently exceeding the fatigue strength limit of the material.
5.6.4	Thermal cracking	Cracks that are generated by high frictional heating and usually occur perpendicular to the direction of the sliding motion.

Table A1 *– bearing damage classification adapted by SKF from ISO 15243:2004.*

APPENDIX 4 – AGAT Laboratories Lube Oil Analysis Report

Client: 3769512

NEWFOUNDLAND & LABRADOR HYDRO
P.O. BOX 2002
BISHOP'S FALLS, NL A0H 1C0
ATTN: JIM WHEELER/RAY ROWE/PAUL KEOUGH

Unit #: GGA LUBE SYSTEM
Unit Location: #1-GGA LUBE OIL
Component: ENGINE
Location:
Serial #: 0L-202204
Make:
Model: OLYMPUS JET ENGINE SVL GT
OAS #: #1-GGA LUBE OIL

AGAT Laboratories
Equipment Reliability and Lubricants Testing Services
3650 21st Street N.E., Calgary, AB, T2E6V6
Phone:(403)299-2000 Fax:(403)299-2105
ISO 9001
ISO 17025

Date analyzed: 05/13/16
Work order: 16C117043
Oil brand & grade: MOBIL JET II (NFLD. & LAB. HYDRO)

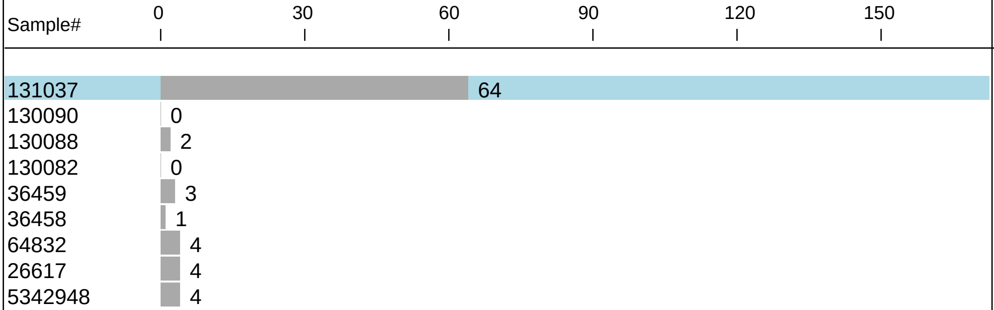
Client Ref #:

LEGEND - LC -Lower Critical LR -Lower Reportable UR -Upper Reportable UC -Upper Critical * Ital -Custom Limit

UNIT DATA					SPECTROGRAPHIC ANALYSIS (PPM)																			
Sample#	Date Sampled	Component Service	Oil Service	Oil Changed	Al Aluminum	Cr Chromium	Cu Copper	Fe Iron	Sn Tin	Pb Lead	Si Silicon	Mo Molybdenum	Ni Nickel	Ag Silver	K Potassium	Na Sodium	B Boron	Ba Barium	Ca Calcium	Mg Magnesium	Mn Manganese	P Phosphorus	Zn Zinc
New Oil					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2907	0
131037	05/06/16	450 hrs	hrs	N	7	5	1	49 UR	2	0	3	0	0	0	0	0	0	0	0	0	1	2450	0
130090	03/16/15	175.2 hrs	175.2 hrs		0	0	0	0	0	0	9	0	0	0	0	2	0	0	0	0	0	2790	0
130088	11/07/14				1	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	2690	0
130082	10/25/14			N	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2640	0
36459	03/08/13			N	0	0	1	1	0	1	2	0	0	0	1	0	0	0	5	0	0	2610	4
36458	02/07/12			N	0	0	1	0	0	0	1	0	0	0	1	1	0	0	1	0	0	2614	1
64832	02/23/10	281 hrs		N	1	0	1	1	0	1	2	0	0	0	1	0	1	0	8	0	0	2912	2
26617	04/25/08	219.2 hrs			1	0	0	0	0	3	1	0	0	0	1	0	1	0	4	0	0	2960	2
5342948	01/04/07			N	0	0	0	1	0	3	0	0	0	0	13 UR	1	0	0	7	1	0	3174	4

PHYSICAL PROPERTIES									ISO CLEANLINESS				OIL DEGRADATION								
Sample#	Glycol	H2O	% Fuel	Viscosity 40°C	Viscosity 100°C	% Solids	KF	°C Flash Point	Micron size 4	6	14	ISO Code	% SOOT	abs/cm-1 OXD	NOX	COX	SO4	ZDDP	TAN	TBN	Min. RPVOT
New Oil				25.8	5.1														0.08		
131037	N	N		26.7	5.4		344 ppm						0.0	5	0	0	0	0	0.06		
130090	N	N		28.1	5.3		189 ppm						0.0	66 UC	0	0	0	0	0.07		
130088	N	N		24.4	4.6		170 ppm						0.0	0	0	0	0	0	0.74		
130082	N	N		26.4	5.4		302 ppm						0.0	35 UC	0	0	0	0	0.01		
36459	N	N		25.8	5.4		109 ppm						0.1	118 UC	1	3	3	0	1.84 UR		
36458	N	N		23.9	5.5		136 ppm						0.0	93 UC	0	2	5	0	0.08		
64832	N	N		26.1		0.0													0.26		
26617	N	N		24.9		0..0													0.61		
5342948	N	N		26.3															1.20		

WEAR CONTROL CHART



COMMENTS

Comments:

REFER TO REVERSE FOR QUALITY CONTROL REPORT, EXPLANATION OF VARIANCE AND POSSIBLE CAUSES.

Should you wish to provide feedback to AGAT Laboratories, please access our Customer review form at www.agatlabs.com/review.htm. This input is extremely important to us because your well being and satisfaction is our number one priority.

* COMPONENT SERIAL NUMBER MUST BE GIVEN TO GENERATE HISTORY. Bold faced elements are included in Wear Control Chart.

Client: 3769512

NEWFOUNDLAND & LABRADOR HYDRO
P.O. BOX 2002
BISHOP'S FALLS, NL A0H 1C0
ATTN: JIM WHEELER/RAY ROWE/PAUL KEOUGH

Unit No.: GGA LUBE SYSTEM
Unit Location: #1-GGA LUBE OIL
Component: ENGINE
Location:
Serial No.: 0L-202204
Make:
Model: OLYMPUS JET ENGINE SVL GT
OAS No.: #1-GGA LUBE OIL

AGAT Laboratories

Quality Control Report

Date analyzed: 05/13/16
Work order: 16C117043
Oil brand & grade: MOBIL JET II (NFLD. & LAB. HYDRO)

Client Ref #:

Flagged Result	Possible Causes	Significance of Result / Recommended Action
Fe - Iron	Iron is the base element in steel and is therefore present in many lubricated components (liners, piston rings, pistons, rockers arms, cylinders, shafts, gears, valve bridges, oil pump rolling element bearings, housings and cases). Iron is also present in rust and may indicate water contamination.	Higher than expected iron levels may indicate wear or contamination. Identify and evaluate the source. Check for signs of rust, scale and corrosion. Consider filtering or changing the oil.

Client: 3769512

NEWFOUNDLAND & LABRADOR HYDRO
P.O. BOX 2002

BISHOP'S FALLS, NL A0H 1C0

ATTN: JIM WHEELER/RAY ROWE/PAUL KEOUGH

Unit #: GGA LUBE SYSTEM
Unit Location: #1-GGA LUBE OIL
Component: ENGINE
Location:
Serial #: 0L-202204
Make:
Model: OLYMPUS JET ENGINE SVL GT

Oil brand & grade: MOBIL JET II (NFLD. & LAB. HYDRO)
Sample #: C-677969
Date Sampled: 05/13/16
Date Analyzed: 05/13/16
Work order: 16C117043
Client Ref #:

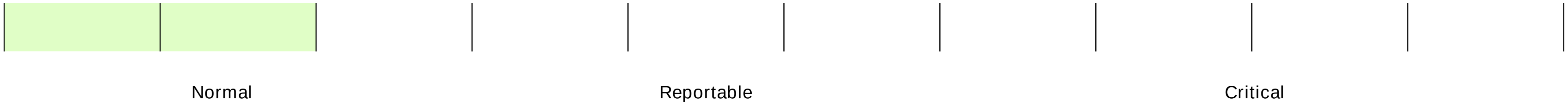
AGAT Laboratories

Sample Status and Trending

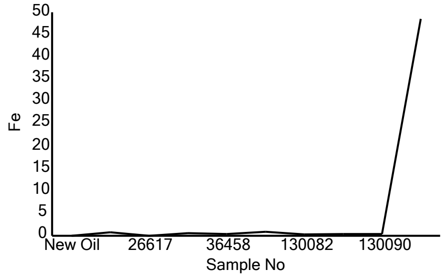
Sample Score:

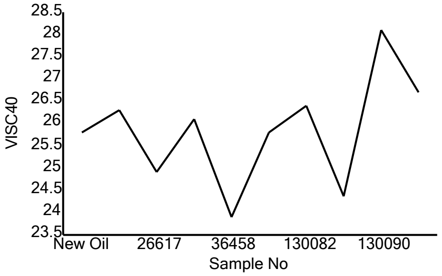
Your Sample Score: 2

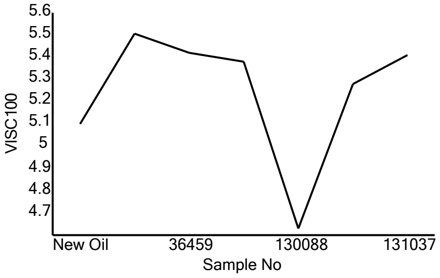
Rankings: 0-3 Normal, 4-6 Reportable, 7-10 Critical

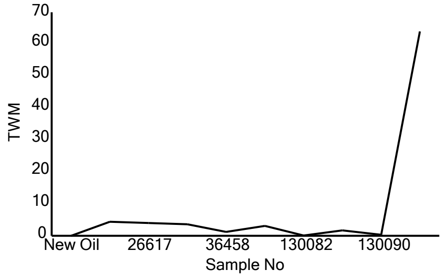


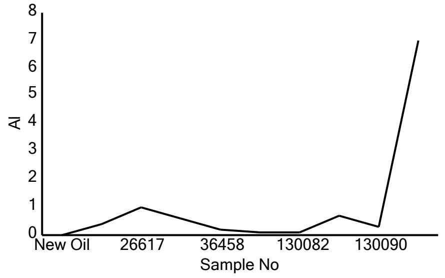
Trend Graphs

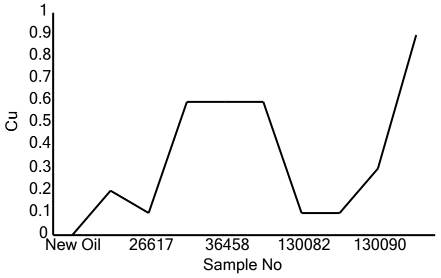


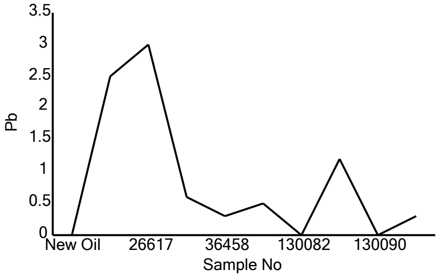


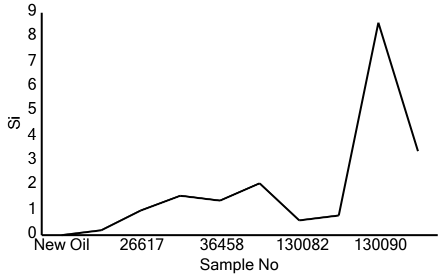












Client: 3769512

NEWFOUNDLAND & LABRADOR HYDRO
P.O. BOX 2002
BISHOP'S FALLS, NL A0H 1C0
ATTN: JIM WHEELER/RAY ROWE/PAUL KEOUGH

Date analyzed: 05/13/16
Work order: 16C117043
Oil brand & grade: MOBIL JET II (NFLD. & LAB. HYDRO)

Client Ref #:

Unit #: MOBIL JET II
Unit Location:
Component: NEW OIL
Location:
Serial #:
Make:
Model:
OAS #:

AGAT Laboratories
Equipment Reliability and Lubricants Testing Services
3650 21st Street N.E., Calgary, AB, T2E6V6
Phone:(403)299-2000 Fax:(403)299-2105
ISO 9001
ISO 17025

LEGEND - LC -Lower Critical LR -Lower Reportable UR -Upper Reportable UC -Upper Critical * Ital -Custom Limit

UNIT DATA / SPECTROGRAPHIC ANALYSIS (PPM)

Sample#	Date Sampled	Component Service	Oil Service	Oil Changed	Al Aluminum	Cr Chromium	Cu Copper	Fe Iron	Sn Tin	Pb Lead	Si Silicon	Mo Molybdenum	Ni Nickel	Ag Silver	K Potassium	Na Sodium	B Boron	Ba Barium	Ca Calcium	Mg Magnesium	Mn Manganese	P Phosphorus	Zn Zinc
New Oil					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2907	0
131038	05/06/16			N	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2770	0

PHYSICAL PROPERTIES

Sample#	Glycol	H2O	% Fuel	Viscosity 40°C	Viscosity 100°C	% Solids	KF	°C Flash Point
New Oil				25.8	5.1			
131038	N	N		26.0	5.2			

ISO CLEANLINESS

Sample#	Micron size 4	Micron size 6	Micron size 14	ISO Code
New Oil				
131038				

OIL DEGRADATION

Sample#	% SOOT	OXD	NOX	abs/cm-1 COX	SO4	ZDDP	TAN	TBN	Min. RPVOT
New Oil							0.08		
131038							0.04	1.7	

WEAR CONTROL CHART

Sample#	0 30 60 90 120 150
131038	0

COMMENTS

Comments:

Should you wish to provide feedback to AGAT Laboratories, please access our Customer review form at www.agatlabs.com/review.htm. This input is extremely important to us because your well being and satisfaction is our number one priority.

* COMPONENT SERIAL NUMBER MUST BE GIVEN TO GENERATE HISTORY. Bold faced elements are included in Wear Control Chart.

AGAT Laboratories Liability Shall Not Exceed The Cost Of Analysis. *Results relate only to the items tested

Client: 3769512

NEWFOUNDLAND & LABRADOR HYDRO
P.O. BOX 2002
BISHOP'S FALLS, NL A0H 1C0
ATTN: JIM WHEELER/RAY ROWE/PAUL KEOUGH

Unit #: GGB LUBE SYSTEM
Unit Location:
Component: ENGINE
Location:
Serial #: 202223
Make:
Model: OLYMPUS SVL GT
OAS #:

AGAT Laboratories
Equipment Reliability and Lubricants Testing Services
3650 21st Street N.E., Calgary, AB, T2E6V6
Phone:(403)299-2000 Fax:(403)299-2105

Date analyzed: 05/13/16
Work order: 16C117043
Oil brand & grade: MOBIL JET II (NFLD. & LAB. HYDRO)

Client Ref #:

LEGEND - LC -Lower Critical LR -Lower Reportable UR -Upper Reportable UC -Upper Critical * Ital -Custom Limit

UNIT DATA

Sample#	Date Sampled	Component Service	Oil Service	Oil Changed
New Oil				
131039	05/06/16	hrs	hrs	N
130091	03/16/15	122.9 hrs	122.9 hrs	
130081	10/25/14			N

SPECTROGRAPHIC ANALYSIS (PPM)

Sample#	Al Aluminum	Cr Chromium	Cu Copper	Fe Iron	Sn Tin	Pb Lead	Si Silicon	Mo Molybdenum	Ni Nickel	Ag Silver	K Potassium	Na Sodium	B Boron	Ba Barium	Ca Calcium	Mg Magnesium	Mn Manganese	P Phosphorus	Zn Zinc
New Oil	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2907	0
131039	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2630	0
130091	0	0	0	0	0	0	7	0	0	0	1	2	1	0	0	0	0	2800	0
130081	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2440	0

PHYSICAL PROPERTIES

Sample#	Glycol	H2O	% Fuel	Viscosity 40°C	Viscosity 100°C	% Solids	KF	°C Flash Point
New Oil				25.8	5.1			
131039	N	N		26.2	5.6		327 ppm	
130091	N	N		26.1	5.6		375 ppm	
130081	N	N		26.1	5.5		341 ppm	

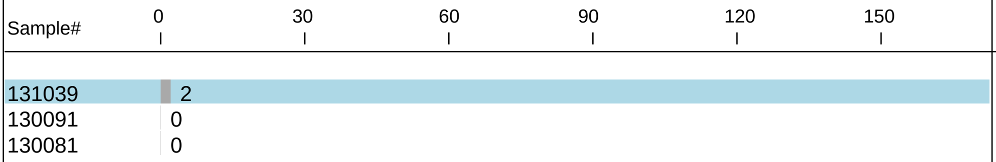
ISO CLEANLINESS

Micron size 4	6	14	ISO Code

OIL DEGRADATION

Sample#	% SOOT	OXD (abs/cm-1)	NOX (abs/cm-1)	COX (abs/cm-1)	SO4 (abs/cm-1)	ZDDP	TAN	TBN	Min. RPVOT
New Oil							0.08		
131039	0.0	8	0	0	0	0	0.11		
130091	0.0	48 UC	0	1	0	0	0.12		
130081	0.0	37 UC	0	0	0	0	0.09		

WEAR CONTROL CHART



COMMENTS

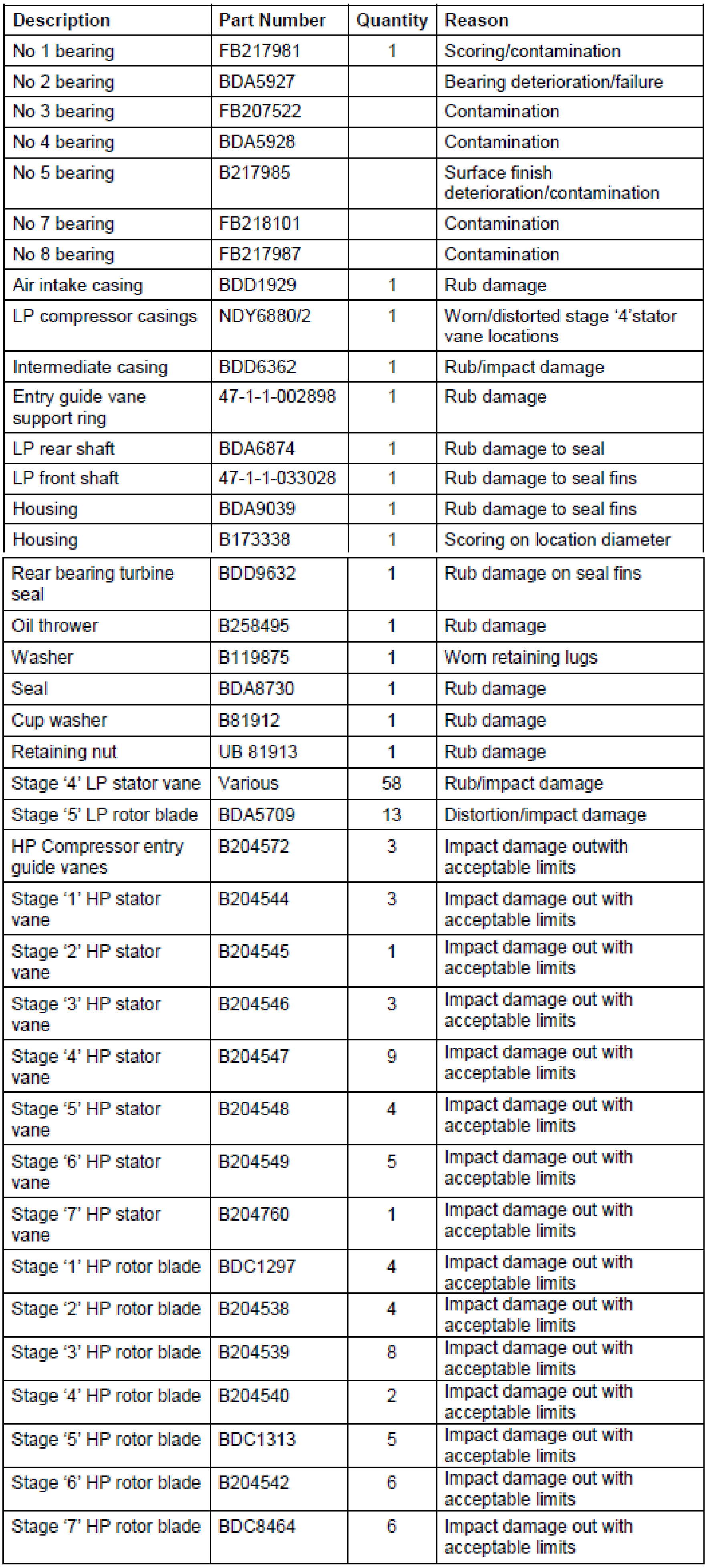
Comments:

Should you wish to provide feedback to AGAT Laboratories, please access our Customer review form at www.agatlabs.com/review.htm. This input is extremely important to us because your well being and satisfaction is our number one priority.

* COMPONENT SERIAL NUMBER MUST BE GIVEN TO GENERATE HISTORY. Bold faced elements are included in Wear Control Chart.
AGAT Laboratories Liability Shall Not Exceed The Cost Of Analysis. *Results relate only to the items tested

APPENDIX 5 – Rejected Components List

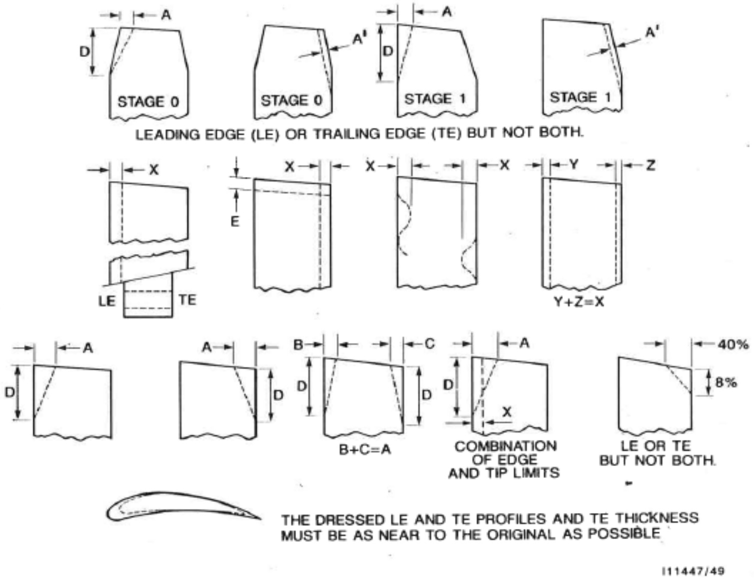
Olympus 202204 Rejected Components List



Description	Part Number	Quantity	Reason
No 1 bearing	FB217981	1	Scoring/contamination
No 2 bearing	BDA5927		Bearing deterioration/failure
No 3 bearing	FB207522		Contamination
No 4 bearing	BDA5928		Contamination
No 5 bearing	B217985		Surface finish deterioration/contamination
No 7 bearing	FB218101		Contamination
No 8 bearing	FB217987		Contamination
Air intake casing	BDD1929	1	Rub damage
LP compressor casings	NDY6880/2	1	Worn/distorted stage '4'stator vane locations
Intermediate casing	BDD6362	1	Rub/impact damage
Entry guide vane support ring	47-1-1-002898	1	Rub damage
LP rear shaft	BDA6874	1	Rub damage to seal
LP front shaft	47-1-1-033028	1	Rub damage to seal fins
Housing	BDA9039	1	Rub damage to seal fins
Housing	B173338	1	Scoring on location diameter
Rear bearing turbine seal	BDD9632	1	Rub damage on seal fins
Oil thrower	B258495	1	Rub damage
Washer	B119875	1	Worn retaining lugs
Seal	BDA8730	1	Rub damage
Cup washer	B81912	1	Rub damage
Retaining nut	UB 81913	1	Rub damage
Stage '4' LP stator vane	Various	58	Rub/impact damage
Stage '5' LP rotor blade	BDA5709	13	Distortion/impact damage
HP Compressor entry guide vanes	B204572	3	Impact damage outwith acceptable limits
Stage '1' HP stator vane	B204544	3	Impact damage out with acceptable limits
Stage '2' HP stator vane	B204545	1	Impact damage out with acceptable limits
Stage '3' HP stator vane	B204546	3	Impact damage out with acceptable limits
Stage '4' HP stator vane	B204547	9	Impact damage out with acceptable limits
Stage '5' HP stator vane	B204548	4	Impact damage out with acceptable limits
Stage '6' HP stator vane	B204549	5	Impact damage out with acceptable limits
Stage '7' HP stator vane	B204760	1	Impact damage out with acceptable limits
Stage '1' HP rotor blade	BDC1297	4	Impact damage out with acceptable limits
Stage '2' HP rotor blade	B204538	4	Impact damage out with acceptable limits
Stage '3' HP rotor blade	B204539	8	Impact damage out with acceptable limits
Stage '4' HP rotor blade	B204540	2	Impact damage out with acceptable limits
Stage '5' HP rotor blade	BDC1313	5	Impact damage out with acceptable limits
Stage '6' HP rotor blade	B204542	6	Impact damage out with acceptable limits
Stage '7' HP rotor blade	BDC8464	6	Impact damage out with acceptable limits

(courtesy of Alba Power)

APPENDIX 6 – OEM Acceptance Limits for Blade Damage



LEADING EDGE (LE) OR TRAILING EDGE (TE) BUT NOT BOTH.

THE DRESSED LE AND TE PROFILES AND TE THICKNESS MUST BE AS NEAR TO THE ORIGINAL AS POSSIBLE

DIMENSIONS IN INCHES

Stage	x	a	d	a'	e	f
00	0.200	0.300	3.750	0.300	0.020	0.050
0	0.182	0.250	3.000	0.250	0.020	0.045
1	0.165	0.200	1.550	0.200	0.020	0.040
2	0.122	0.333	1.165		0.020	0.030
3	0.140	0.300	1.050		0.020	0.035
4	0.075	0.260	0.910		0.010	0.020
5 Pre-Mod.3187	0.055	0.260	0.770		0.010	0.020
5 Mod.3187	0.055	0.120	0.770	0.120	0.010	0.020
6	0.100	0.200	0.725		0.010	0.020
7	0.075	0.200	0.725		0.010	0.020
8	0.075	0.200	0.725		0.010	0.020
9	0.075	0.200	0.700		0.005	0.020
10	0.075	0.200	0.700		0.005	0.020
11	0.075	0.200	0.700		0.005	0.020
12	0.065	0.180	0.650		0.005	0.020
13	0.065	0.180	0.650		0.005	0.020
14	0.065	0.180	0.650		0.005	0.020
15	0.065	0.180	0.650		0.005	0.020

Blades which have been repaired to the dimensions shown in the table, can be grouped into complete sets for fitting to the respective discs provided that not more than 50 per cent of the blades in a stage have had the chordal width reduced by the amount (or more) shown in column 'f'.

Acceptance Limits for Blending Rotor Blades
(Dimensions in Inches)
Figure 5128/1

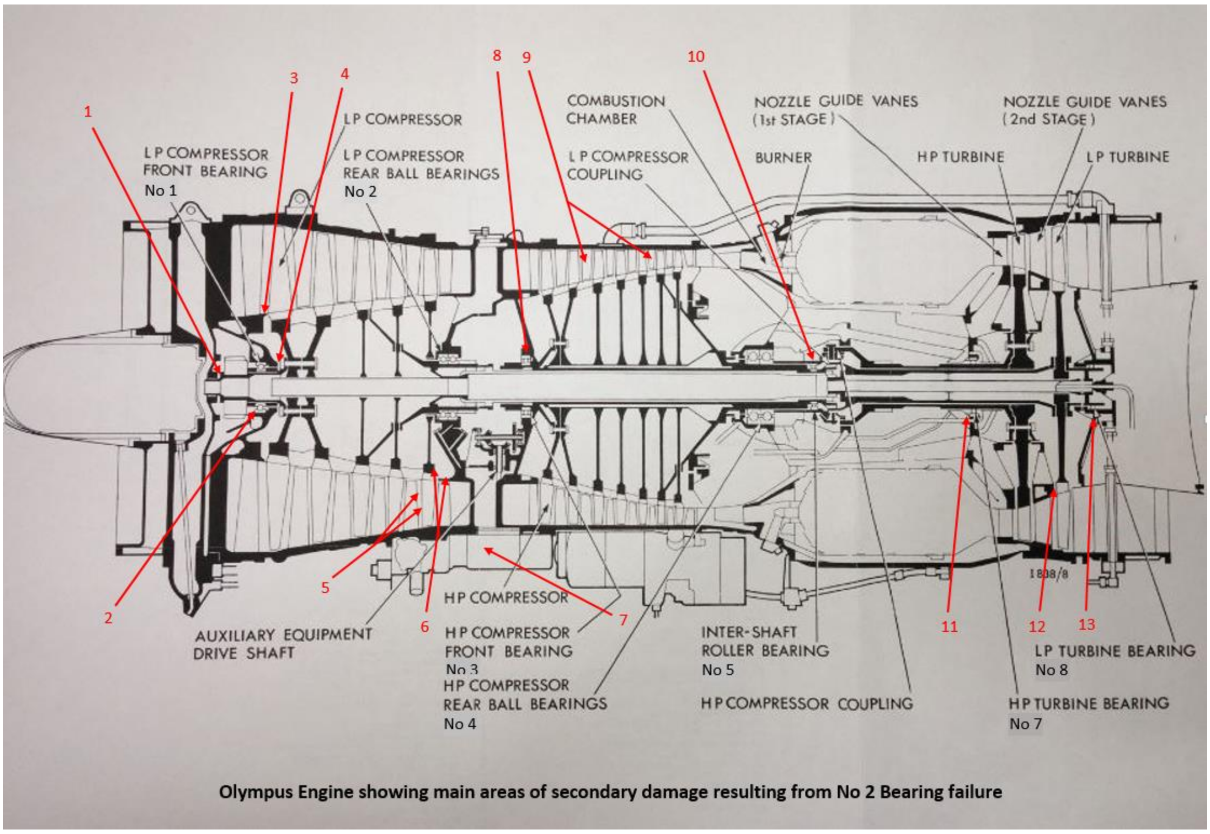
APPENDIX 7 – Secondary Damage Report

Olympus GG 202204 Secondary Damage Report

This photo report describes the main areas of secondary damage found throughout the GG resulting from the No 2 bearing failure. In accordance with turbine reporting convention the areas are described in sequence from front to rear of the GG.

Photos of Secondary Damage Areas

Photo numbers refer to damage area numbers shown in the Olympus sectional illustration below. Illustrations of the damage areas, numbered as per respective photos, showing the location and sectional details of the areas are contained in the Illustrations Section, starting on page 13.



Olympus Engine showing main areas of secondary damage resulting from No 2 Bearing failure

Photo 1 below: shows LP Compressor shaft front end labyrinth seal bush damage from running contact with the shaft lock nut.

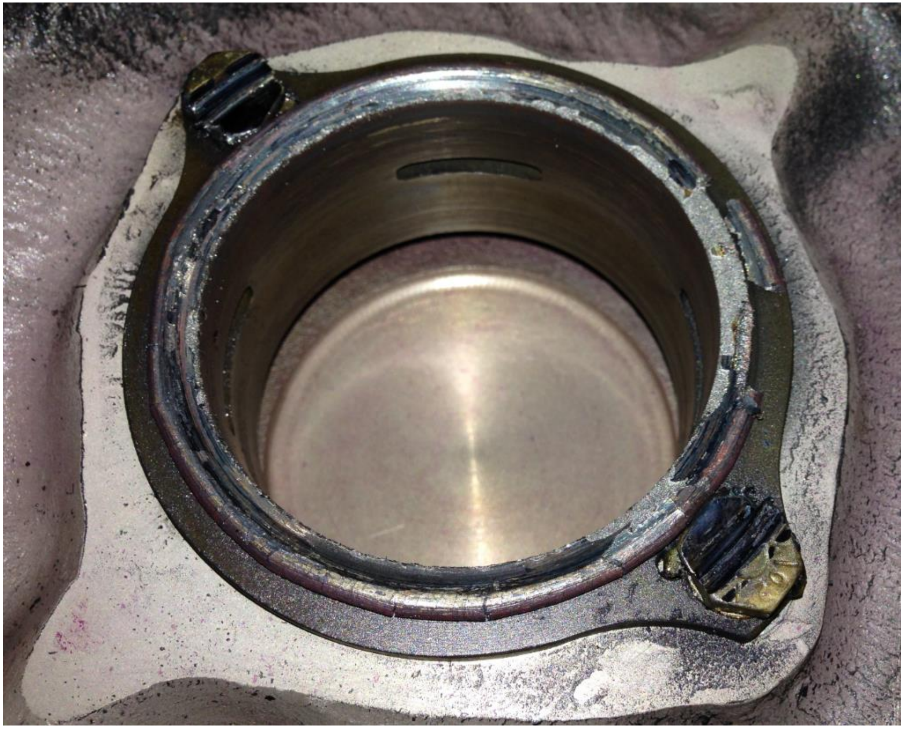


Photo 2 below: shows matt micro pitted surfaces of No 1 bearing rollers caused by lube oil system contamination. Also shows larger corrosion pitting.

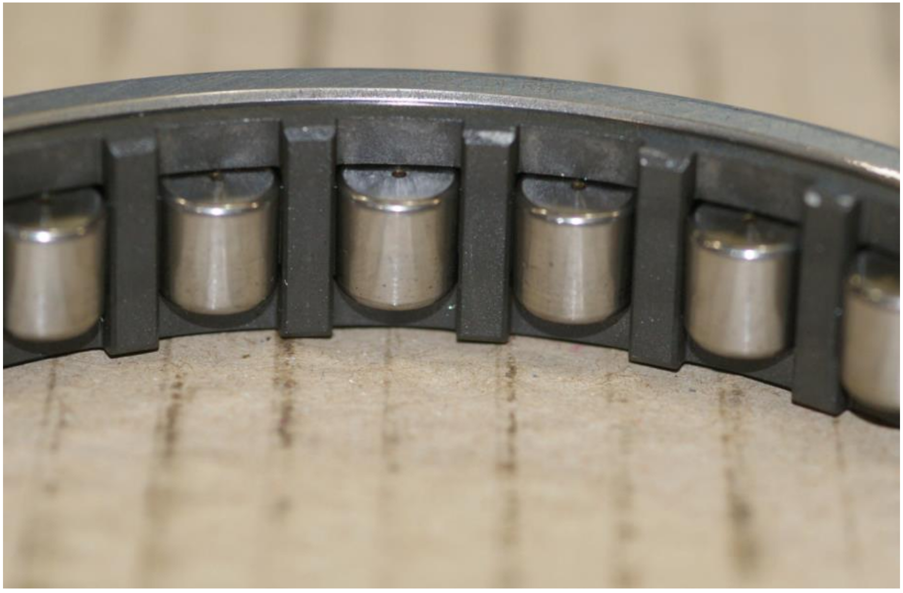


Photo 3 below: shows LP Compressor 1st stage blades platforms front edge deep abrasion metal loss (to flush with disc) from running contact with Inlet Guide Vanes platform segments.

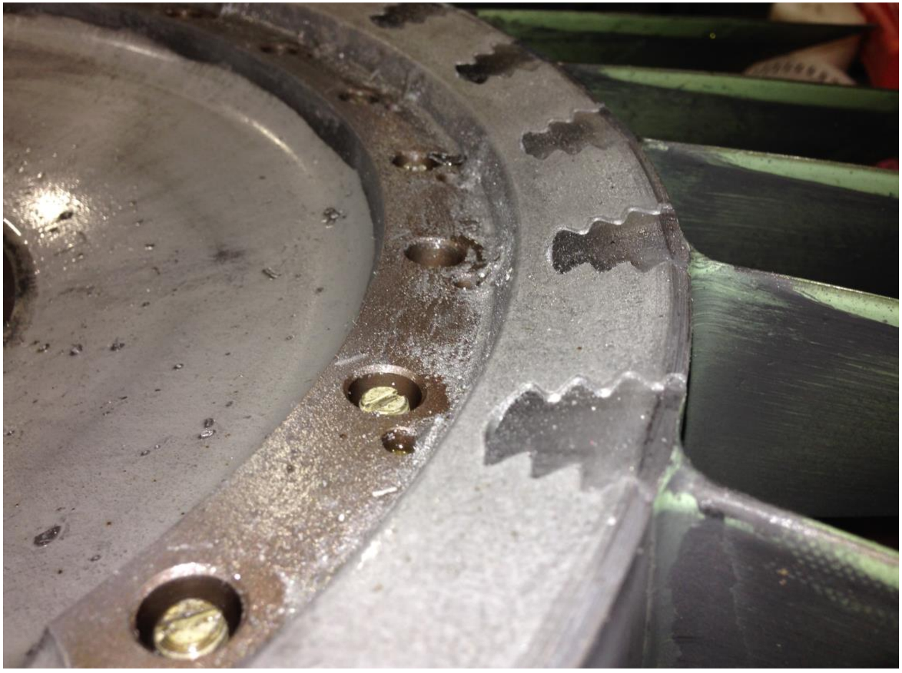


Photo 4a below: shows No 1 bearing housing rear face deep abrasion metal loss from running contact with the LP Compressor Rotor 1st/2nd stage discs retaining bolts.

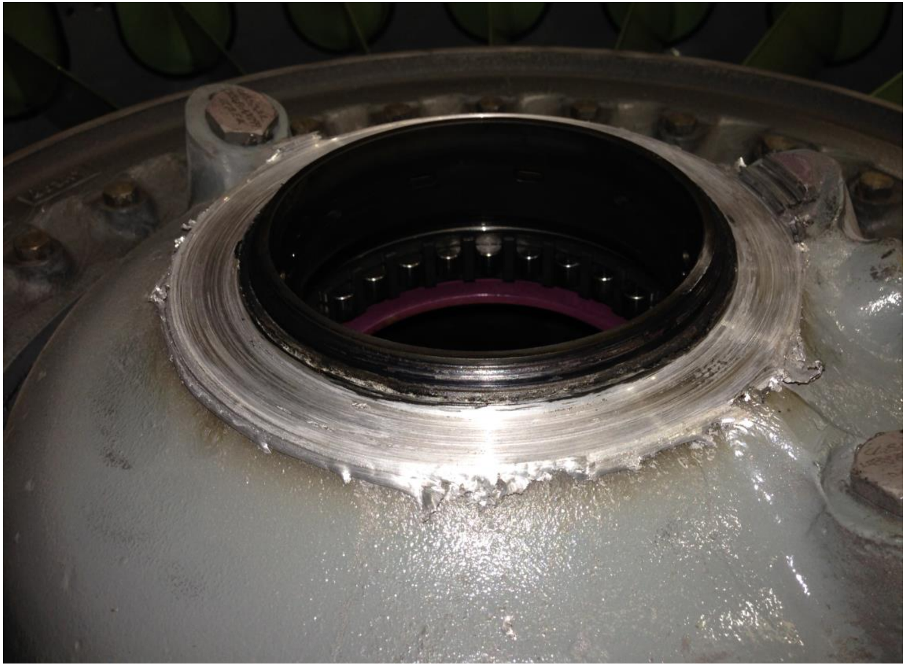


Photo 4b below: shows the LP Rotor 1st/2nd stage discs retaining bolts that caused the bearing housing damage in the photo above. Aluminium pick-up shows on two prominent bolts.

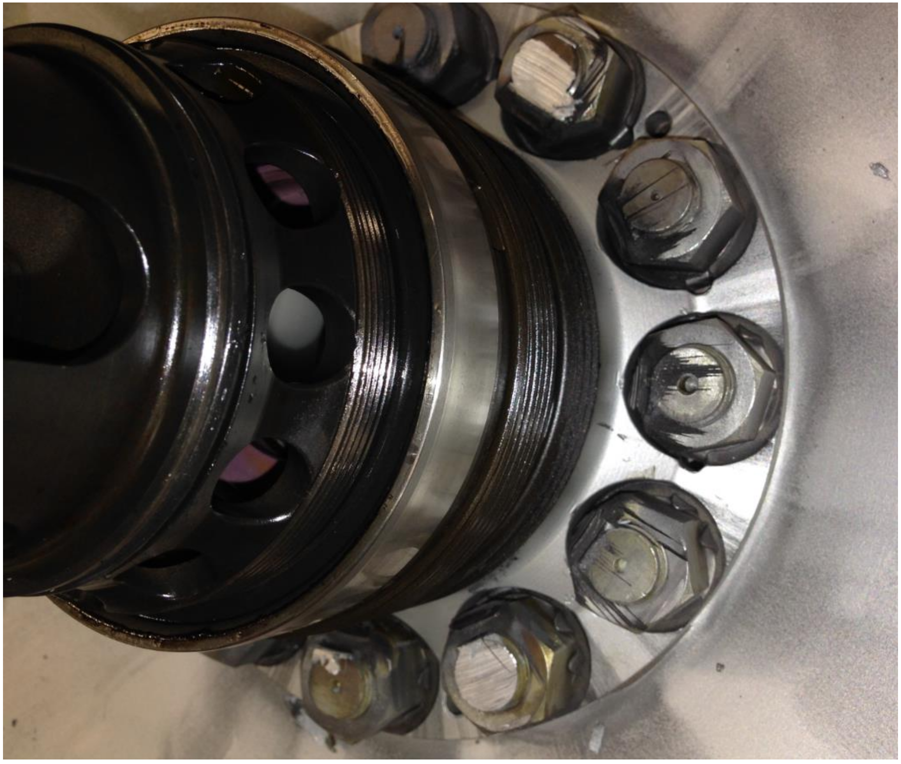


Photo 5a below: shows LP Compressor Rotor 5th stage blades heavy damage from running contact with stator guide vanes. Deep rotational scoring is also seen on the inter-stage disc from running contact with the IGV’s tips due to the rotor having dropped as a result of the No 2 bearing damage.

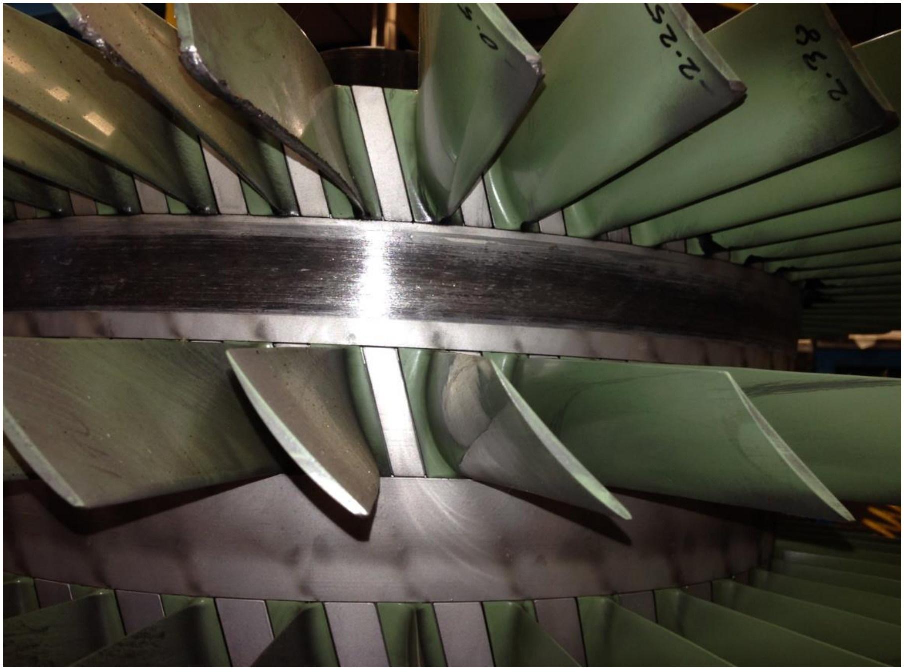


Photo 5b below: shows LP Compressor 5th stage stator vanes damage corresponding with the blades damage shown in the photo above. The open gap at the top of the vanes slot shows that the LP Compressor casing has distorted at that area due to running contact force.

Photo 6a below: shows LP Compressor 5th stage disc rear side & bolting damage caused by two released stud/nut heads that had snapped off due to stress at the No 2 bearing housing resulting from the bearing failure.

Photo 6b below: shows Intermediate Casing damage also caused by two the two released stud heads. The two broken studs can be seen just above the removed cover at bottom.

Photo 6c below: shows a close-up of the two broken studs.

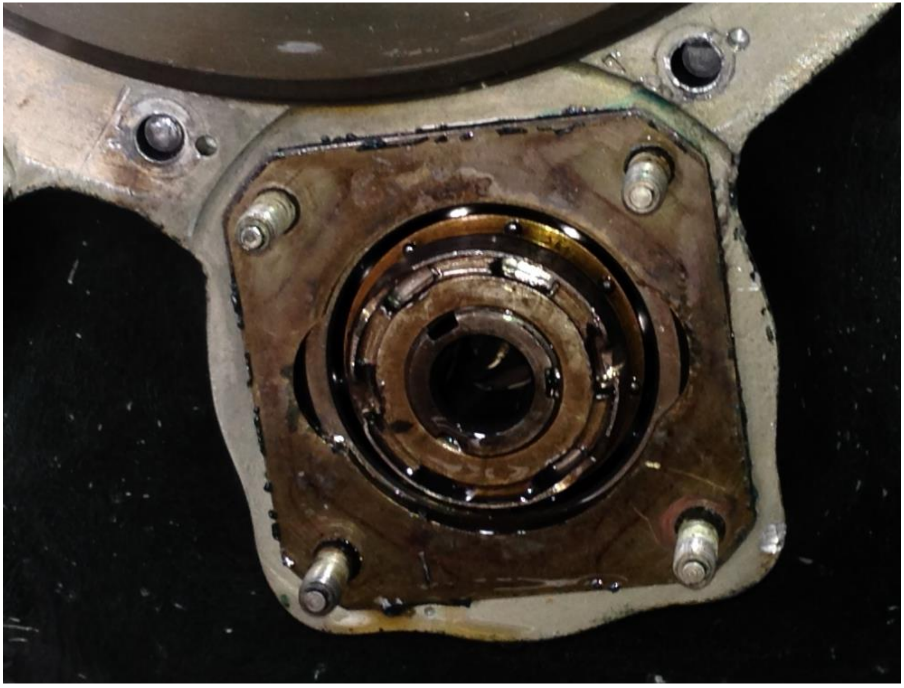


Photo 7 below: shows scavenge lube oil pump gears housing diameter deep abrasion metal loss caused by debris from No 2 bearing damage. (The pump was still operational.)

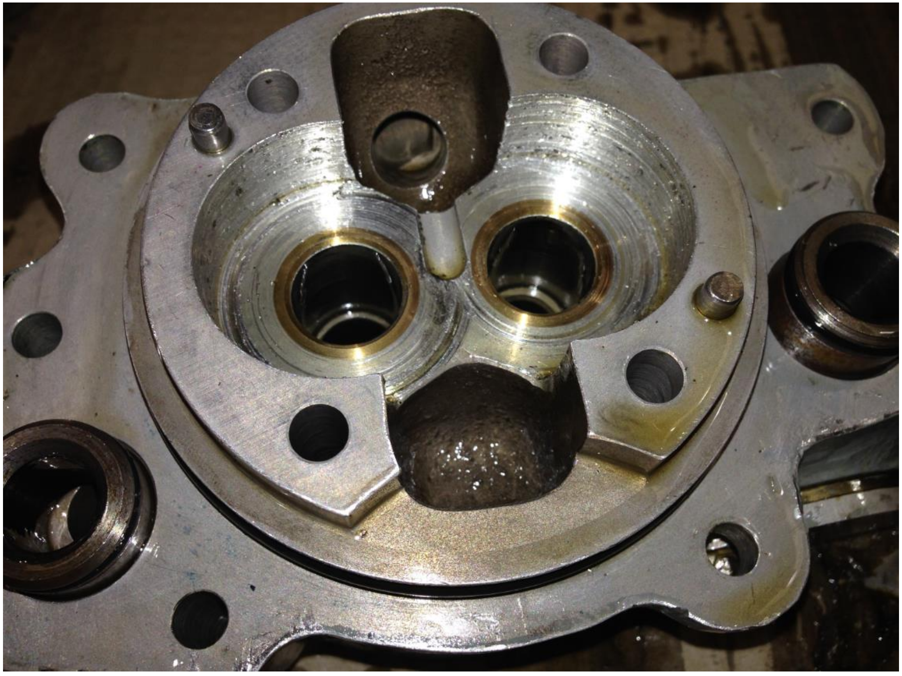


Photo 8 below: shows matt micro pitted surfaces of No 3 bearing rollers caused by lube oil system contamination, also visible.

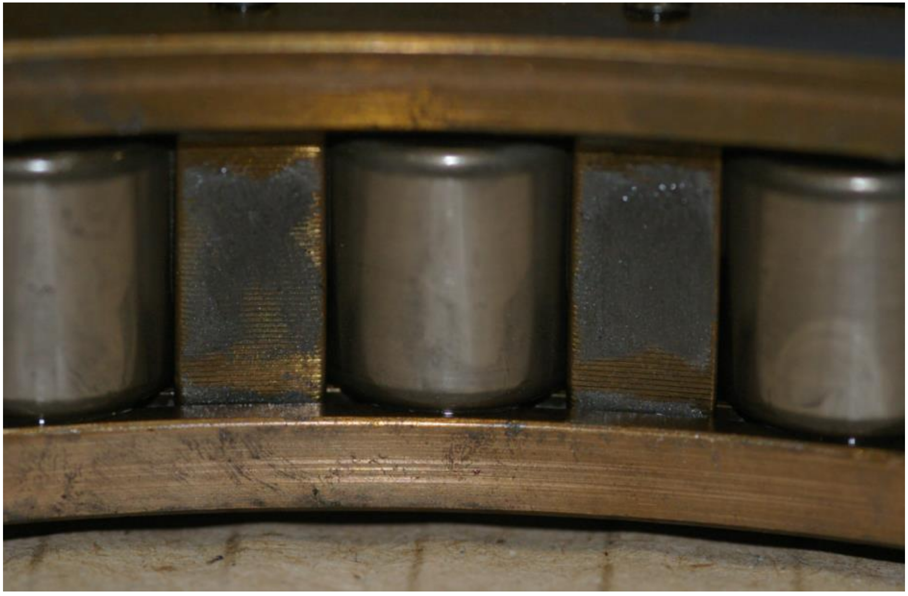


Photo 9 below: shows HP Compressor Rotor blades impact damage caused by debris from LP Compressor front end damage released into the compressor air stream. The damage is typical of that seen throughout the HP Compressor stages.

Photo 10a below: shows matt micro pitted surfaces of No 5 bearing rollers caused by lube oil system contamination. Also shows larger corrosion pitting, along with metal flake fragments from oil thrower damage.

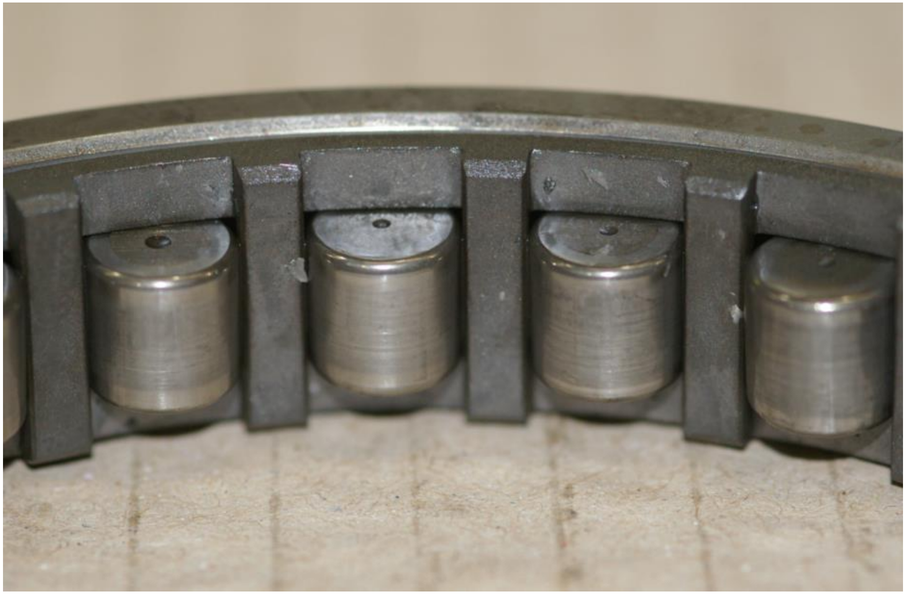


Photo 10b below: shows No 5 bearing oil thrower high friction/heat and crack initiation damage from running contact with the LP Compressor Rotor drive coupling hub.

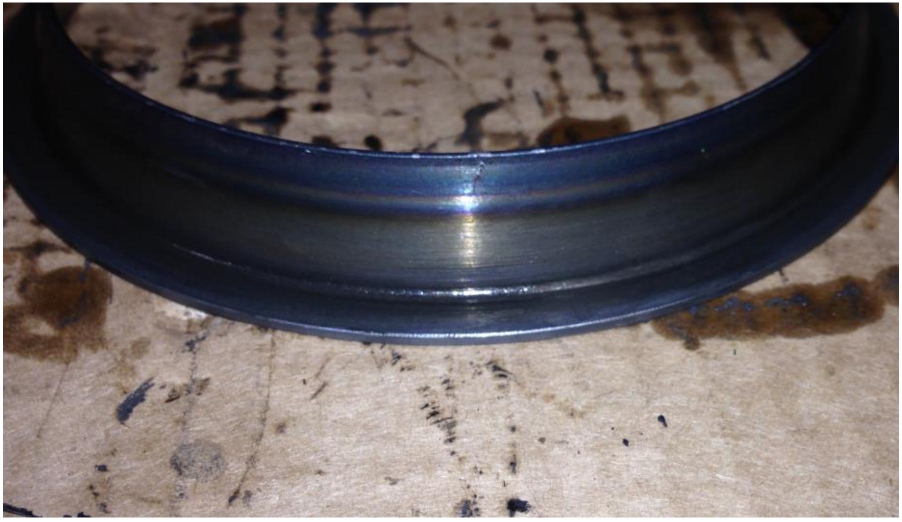


Photo 10c below: shows LP Compressor Rotor drive coupling hub damage corresponding with the damage shown in the photo above.

Photo 11 below: shows matt micro pitted surfaces of No 7 bearing rollers caused by lube oil system contamination. Also shows larger corrosion pitting.

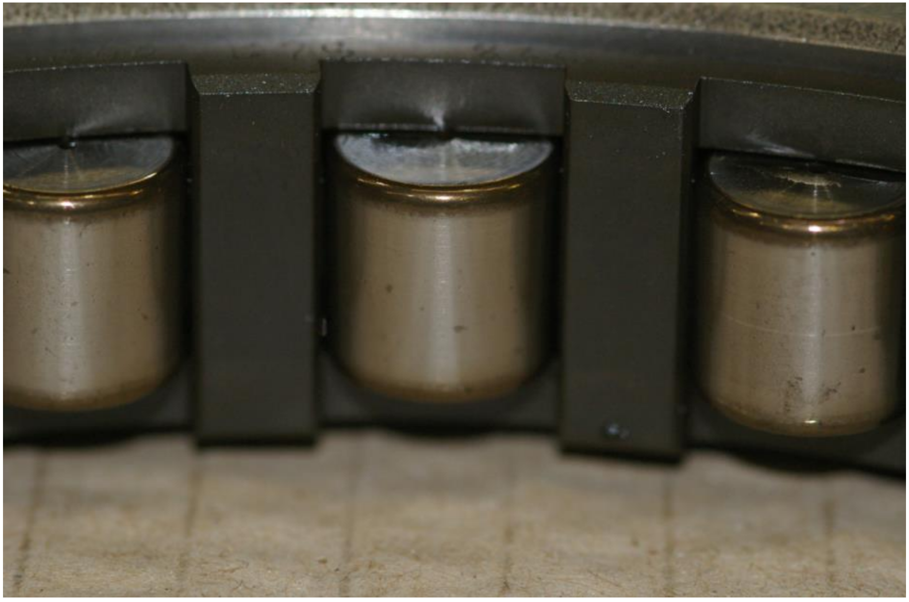


Photo 12a below: shows LP Turbine Nozzle Guide Vanes segments retaining bolts heads damage from running contact with Turbine Rotor blades fir tree roots lock tabs. Also shows examples of minor aluminium melt spatter impingement on the vanes.

Photo 12b below: shows LP Turbine Rotor blades fir tree roots lock tabs damage corresponding with the damage shown in the photo above.

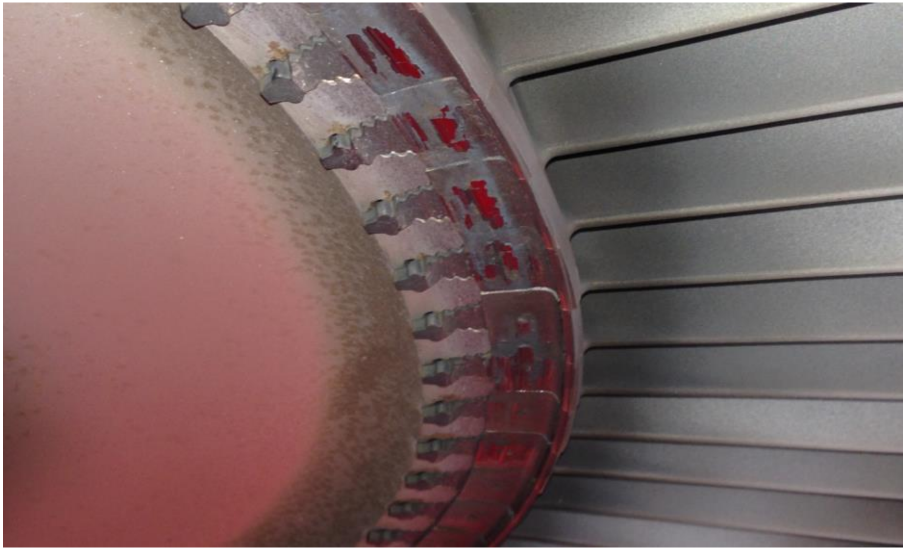
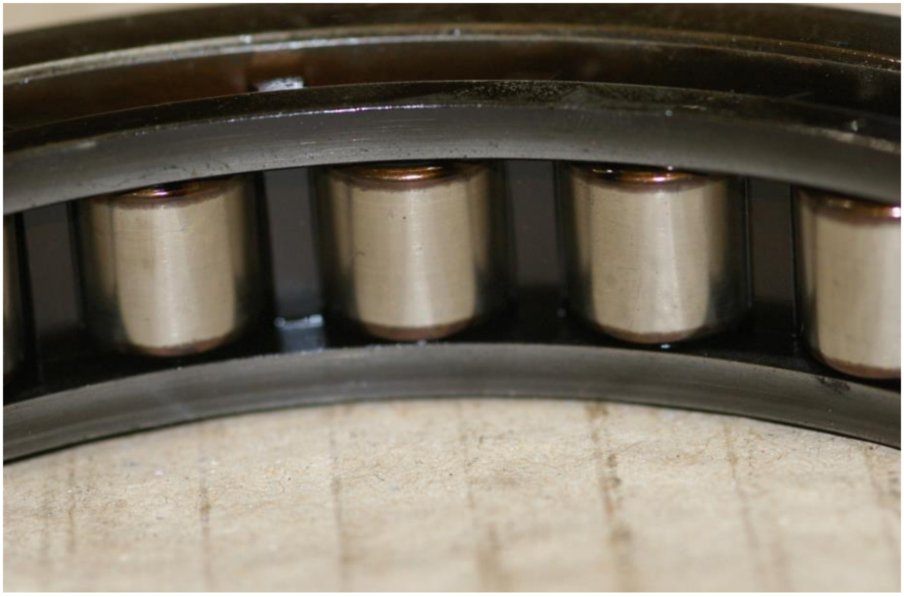


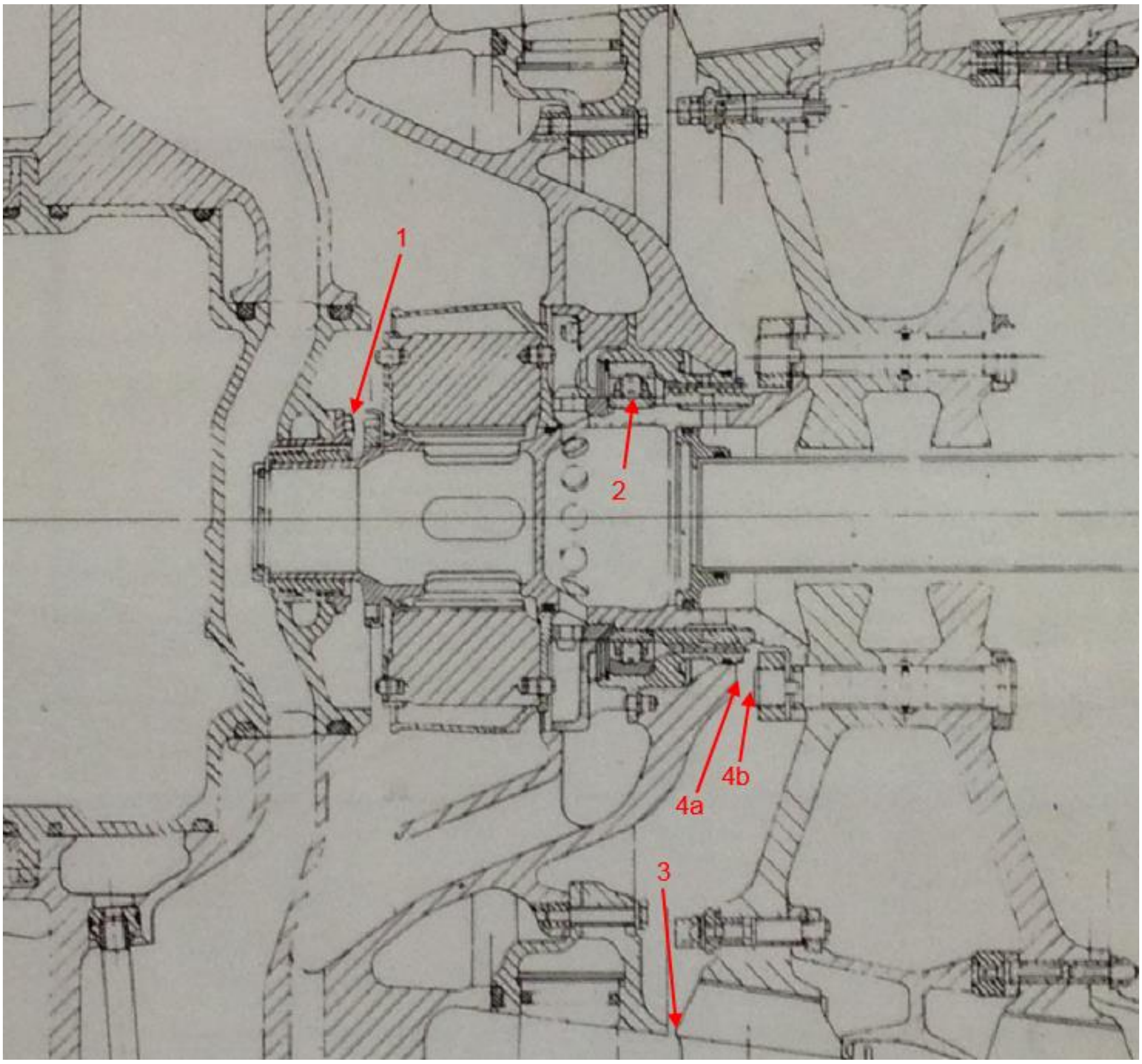
Photo 13 below: shows matt micro pitted surfaces of No 8 bearing rollers caused by lube oil system contamination. Also shows larger corrosion pitting.



It was also observed during strip inspections that re-solidified aluminium melt spatter had impinged on the turbine section nozzle guide vanes and rotor blades. This had resulted from LP Compressor front end damage debris released into the compressor air stream and carried through the combustion system.

Photo 14 below shows a typical example of the aluminium melt spatter found on the turbine blades.

GG Illustrations Showing Secondary Damage Areas in Detail



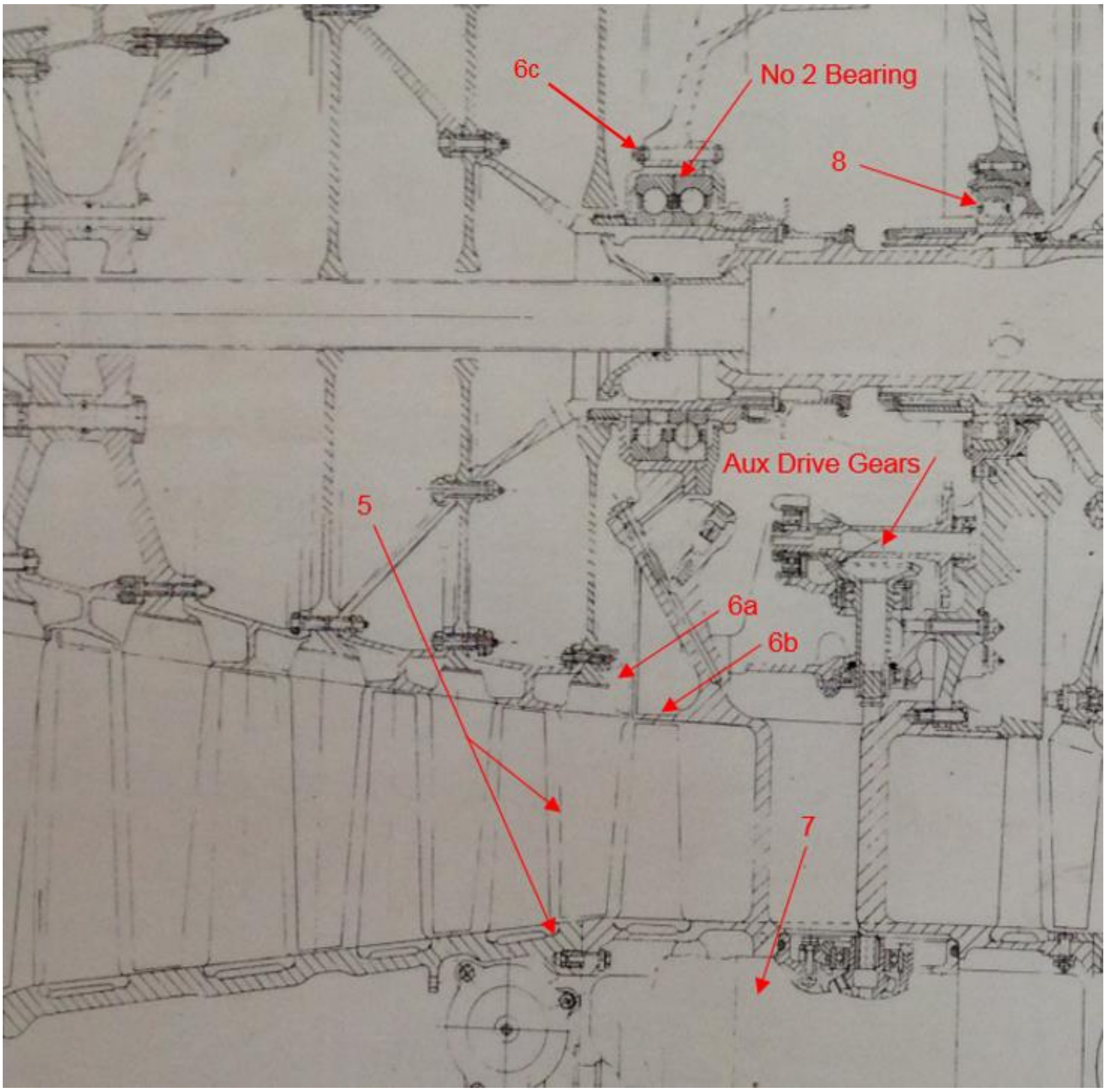
1 LP Compressor Rotor shaft front labyrinth seal bush retaining bolts.

2 No 1 Bearing (roller type).

3 LP Compressor Rotor 1st stage blades platforms.

4a No 1 Bearing Housing (part of Intake Casing) rear face

4b LP Compressor Rotor 1st/2nd stages discs retaining bolts.



5a LP Compressor Rotor 5th stage blades (and 4th/5th inter-stage disc)

5b LP Compressor Stator 5th stage vanes and dovetail slot/compressor casing)

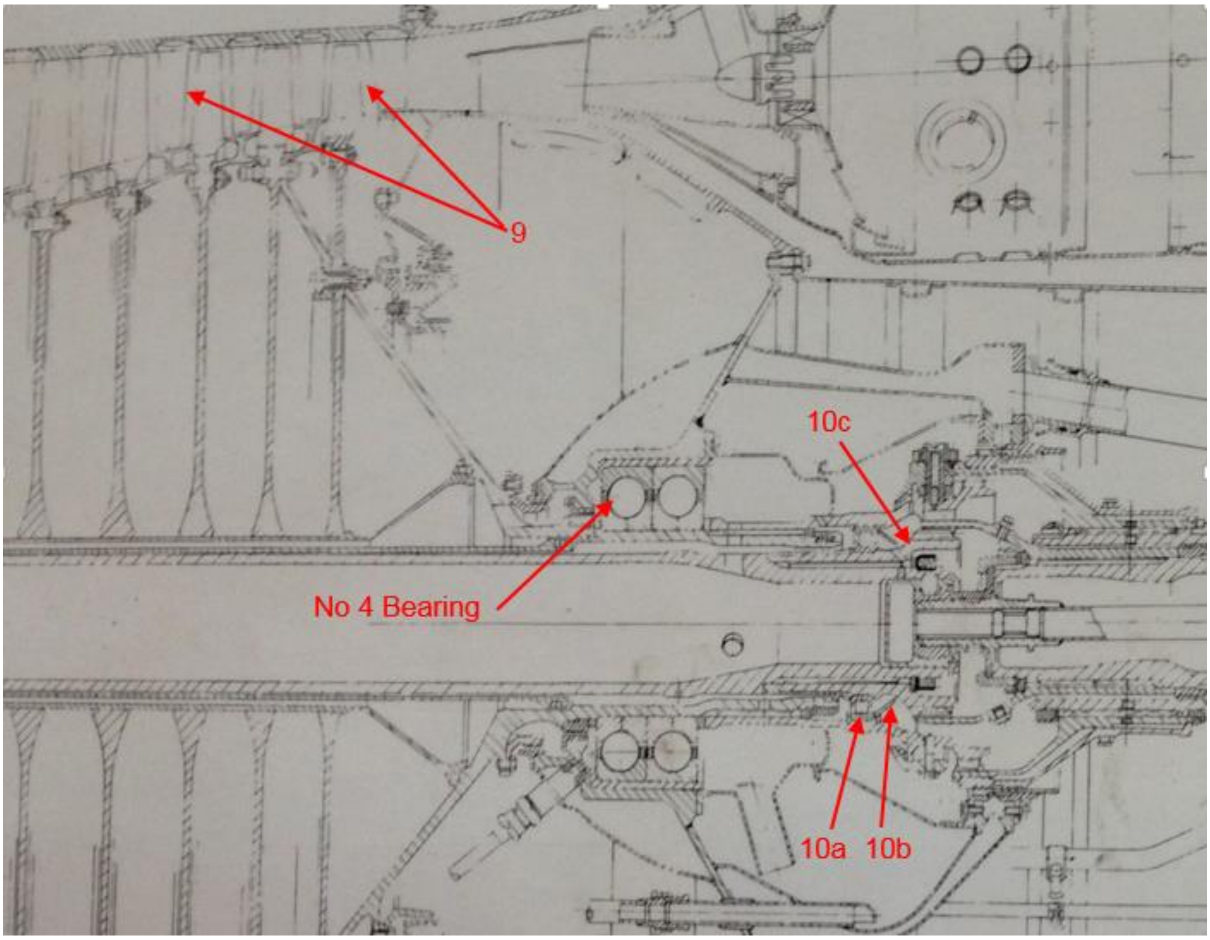
6a LP Compressor Rotor 5th stage disc and retaining bolts.

6b Intermediate Casing.

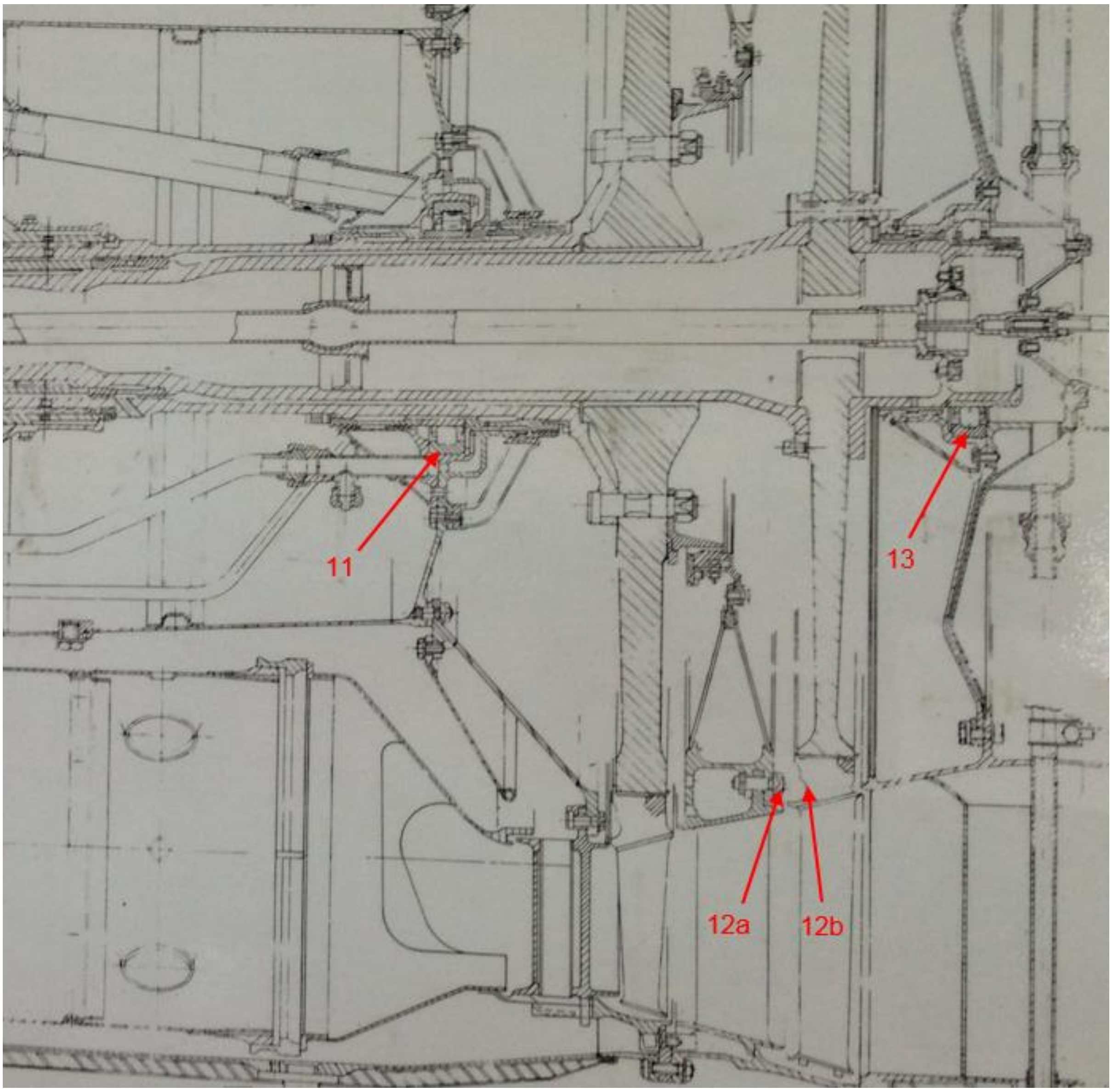
6c No 2 Bearing Housing studs (two broken).

7 Scavenge lube oil pump gears housing.

8 No 8 Bearing (roller type)



9	HP Compressor Rotor blades.
10a	No 5 Bearing (roller type)
10b	No 5 Bearing oil thrower.
10c	LP Compressor Rotor drive coupling hub.



11 No 7 Bearing (roller type).

12a LP Turbine nozzle guide vanes disc/retaining bolts.

12b LP Turbine Rotor disc fir tree roots lock tabs.

13 No 8 Bearing (roller type)

APPENDIX 8 – Progress Update Project Notes

Project Note 07/07/2016

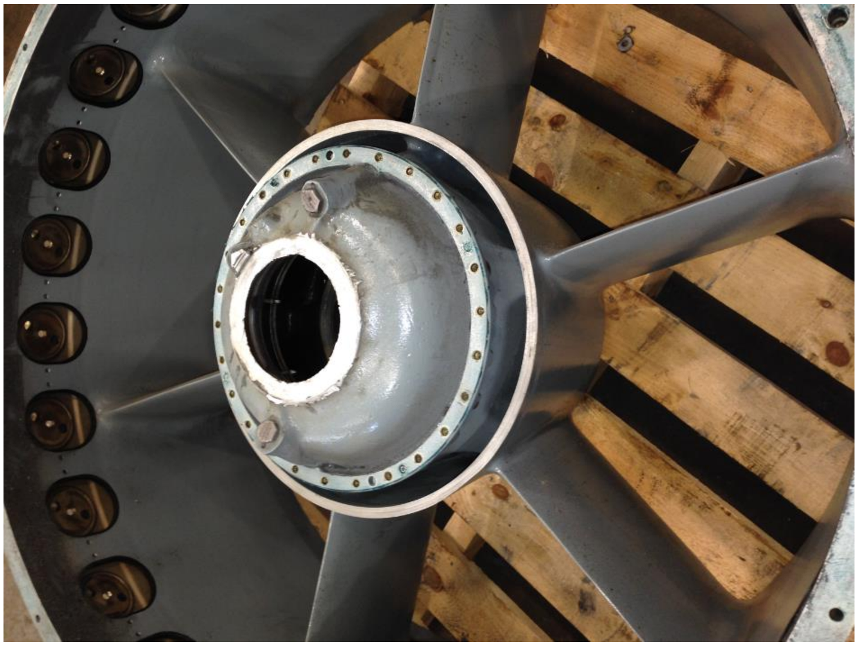
To: From: Ryan Cooper
Doug Eynon / Gavin Smith
Reference: Nalcor Olympus C Turbine site inspection P10854
Date: 07/07/2016
RE: Summary Report (No. 11)

Detail Strip commenced at Alba today. Intake Casing and LP Compressor Rotor have now been completely stripped.

The following are summary notes from today's inspections on the main points of secondary damage and reparability/cost implications.

1. **Intake Casing:** previous updates have already reported the deep running contact damage at the LP Compressor front bearing (GG No 1 bearing) housing rear face, where the face had to be treated with a hand grinder to remove the bearing. In discussion with Alba, it is apparently more cost effective and a quicker turnaround to replace the casing with a spare unit that Alba have available in stock, rather than assign to a repair scheme. (Alba/Hydro need to review the unit "exchange" commercial arrangement.)

   Photo below shows the stripped casing and the deeply damaged face. (It was established today by measurements that the LP Rotor had moved forward by approx. 5.5 mm.)



Project Note 07/07/2016

Below is close-up of damaged face in process of hand grinding to free the bearing (as previously reported).

2. **LP Compressor:** as previously reported, the LP Rotor moving forward resulted in the leading edges of the 5th stage blades coming into very heavy running contact with the stator vanes trailing edges causing serious damage to both sets. Therefore, we can expect Alba to declare all 5th stage blades and vanes as scrap.

   Additionally, detail inspection today revealed that the force of the running contact between the 5th stage blades and vanes caused the stator vanes dovetail slot to distort open, causing the vanes to become extremely loose in the slot (normally a snug fit), which also means the casing itself at that area has flared out. This damage has no repair scheme and so it is expected that Alba will declare the LP Compressor Casing as scrap, to be replaced by a spare unit they have available in stock.

Project Note 07/07/2016

Photo below shows typical rotor blades leading edge damage. Also shows scoring of the 4th/5th inter-stage spacer from contact with the stator vanes tips due to No 2 bearing failure abrasion wear.

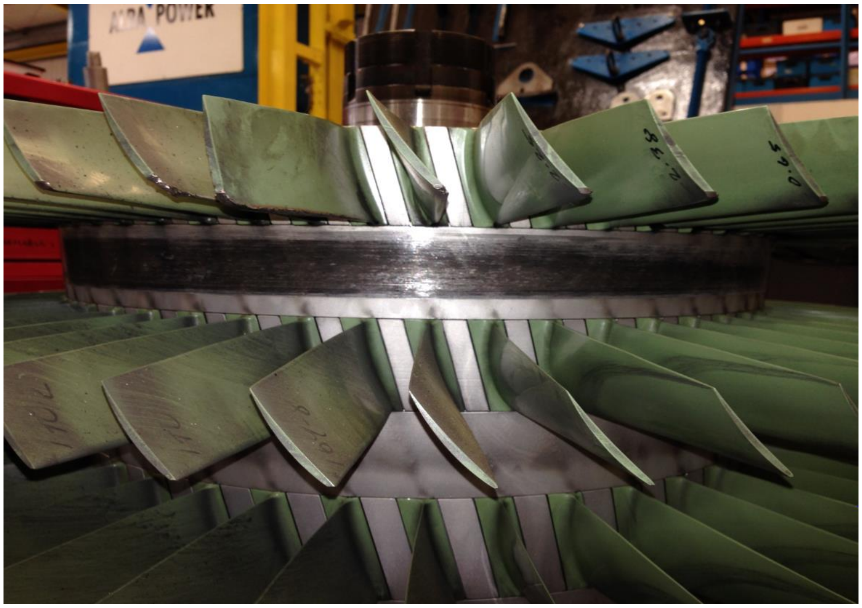
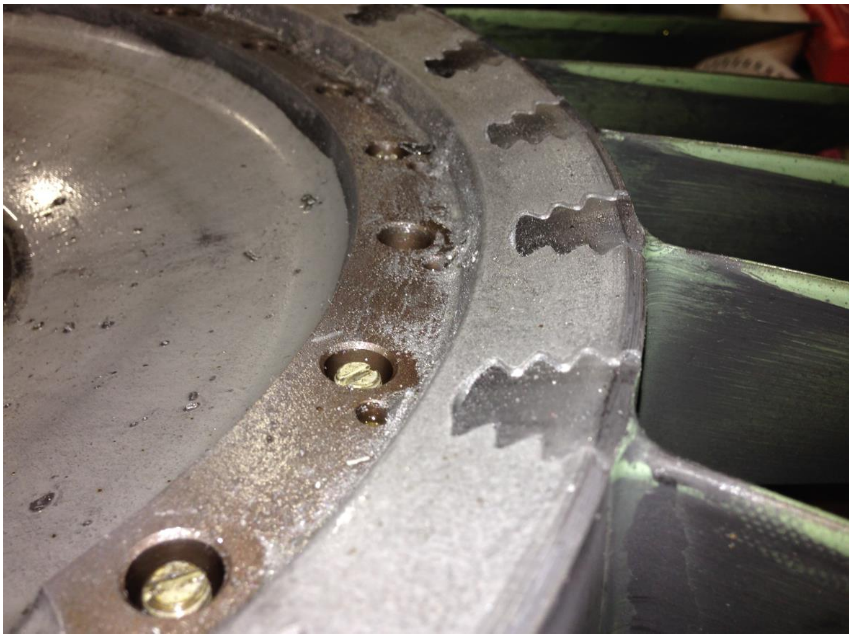


Photo below shows typical stator vanes trailing edge damage. Also note the distortion gap at the top of the dovetail slot.

Project Note 07/07/2016

Photo below shows how the stator vane originally sat in the dovetail slot – i.e. no gap. Compare with above photo.

Photo below shows abrasion wear at the 1st stage rotor blades forward platform edges from running contact with the Inlet Guide Vanes platform. It is thought that a repair scheme is perhaps not available for this damage - Alba to confirm. Note also the debris from the No 1 bearing housing rear face damage, caught on the disc shoulder from being centrifuged out into the compressor air path.



Project Note 08/07/2016

To:	Ryan Cooper
From:	Doug Eynon / Gavin Smith
Reference:	Nalcor Olympus C Turbine site inspection P10854
Date:	08/07/2016
RE:	Summary Report (No. 12)

The Intermediate Casing and Delivery Casing assemblies were detail stripped today. The Intermediate strip was completed and the Delivery strip is ongoing with completion expected Monday.

A notable reporting point is that the Intermediate Casing is expected to be rejected for reuse due to the secondary damage incurred.

Photos below show the Intermediate casing with secondary damage resulting from the No 2 bearing failure. Also, a few guide vane aerofoils exhibited light impact damage which appears repairable for reuse.

Project Note 08/07/2016

In view of the likely components rejection rate for the Olympus failure repair job, PI raised a formal request for Alba to consider means of presenting major value components repair vs exchange vs scrap replacement comparative costs & turnaround options, with reasoned recommendations for Hydro's visibility and decision on the best suited options. We await Alba response, albeit the suite of options with costs etc. will of course be presented to Nalcor, not PI.

Performance
Improvements (PI)

Project Note 12/07/2016

To: Ryan Cooper
From: Doug Eynon / Chris Smith
Reference: Nalcor Olympus C Turbine site inspection P10854
Date: 12/07/2016
RE: Summary Report (No. 13)

The Delivery Casing and LP Compressor Casing assemblies detail strips were completed today.

Delivery Casing:

Components appeared to be undamaged on initial visual inspection. Detail inspection and NDT check routines remain to be carried out. Casing is shown below.

Project Note 12/07/2016

LP Compressor Casing:

No additional damage was evident on initial inspection further to the damage previously reported – ie 4th stage stator vanes from running contact with LP Comp Rotor 5th stage blades, and casing local distortion at the vanes dovetail slots.

The removed stator vanes were too dirty for close inspection but no obvious damage was apparent on the samples checked. The vanes are to be cleaned for detail inspection and review for repair. Photos below show the stripped half-casings and vanes stages set out.

Project Note 12/07/2016

Project Note 12/07/2016

To: Ryan Cooper
From: Doug Eynon / Gavin Smith
Reference: Nalcor Olympus C Turbine site inspection P10854
Date: 18/07/2016
RE: Summary Report (No. 14)

Summary

The Detail Strip was completed Friday 15/7/16. Alba in-house detailed inspection of stripped components starts today with completion expected Friday 22nd and Alba report to follow. Inspection and repair of some component parts such as blades, discs, main line bearings and auxiliary pumps are out-sourced to specialist companies. The turnaround for out-sourced parts is typically 3-4 weeks.

Alba hold a large stock of spares which they use to expedite repair/replacement of certain components, discounted to customers in accordance with the cost of repair for restocking as spares.

From discussion with Alba, it is PI's understanding that in view of the extent of damage requiring repair throughout the engine, Alba intend to make an overall fixed price repair offer to Hydro as the most expedient cost/time effective and least risk option for Hydro in light of the ongoing operational exposure.

Progress Updates –

Wednesday 13/7/16

HP and LP Turbine Rotors detail strips were completed today. No additional damage further to that reported previously was evident from initial visual inspection. The aluminium spatter impingement on the blades aerofoils is not considered to have had any damaging effect on the blades or chemical reaction with the blade coating. Regardless, all turbine (and compressor) blades are anyway sent to Alba's specialist contractor for NDT inspection, repair and recoating as standard practice. (PI will review with Alba.

HP Compressor Rotor strip was also started today, with completion expected tomorrow.

The photo below shows the LP Turbine Rotor blades being removed from the disc fir tree roots, with the stripped HP Turbine Rotor showing in the background.

Project Note 12/07/2016

Thursday 14/7/16

The HP Compressor Rotor and Casing detail strips were completed today. Although uncertain due to the generally dirty condition of the blades, initial visual inspection indicated that approx. 50% of the rotor blades have impact damage penetrating the protective coating through to the core material. Regardless, as mentioned above, all the blades are sent for inspection, repair and recoat as standard practice.

The photo below shows a removed compressor stage disc and blades with typical impact damage through the protective coating. The blades are suitable for reuse in this condition but their service life would be drastically reduced by corrosion undermining at the coating break-through points.

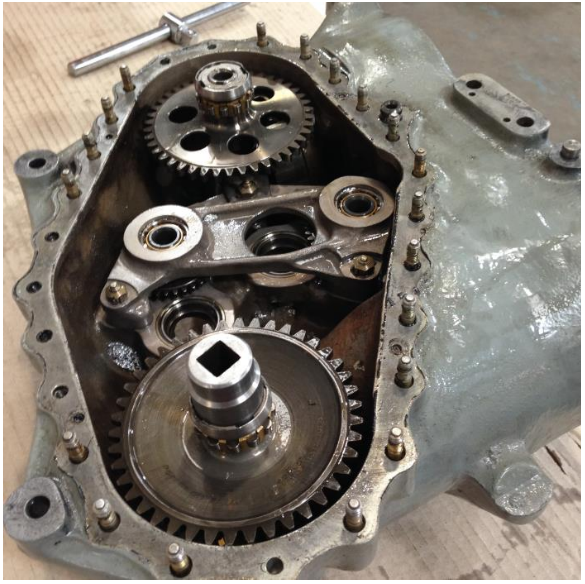
Friday 15/7/16

HP and LP Turbine Stators and Fuel Pumps Gearbox detail strips were completed today. No additional damage further to that reported previously was noted on initial visual inspection.

The photo below shows the HP stator in process of detail strip.

Project Note 12/07/2016

The photos below show the HP and LP fuel pumps unit split from their drive gearbox.



Project Note 27/07/2016

To:	Ryan Cooper
From:	Doug Eynon / Gavin Smith
Reference:	Nalcor Olympus C Turbine site inspection P10854
Date:	27/07/2016
RE:	Summary Report (No. 15)

Summary

In view of the failure investigation project recently being in a hiatus/reporting phase, this update summarises over the period Monday 18 July to Monday 25 July.

Cost Tracking

Update of costs to date against budget is as follows -

Current Project Spend to 24 July 2106:

Total Assigned Budget:	UK £81,134.00
Budget Spend to date:	UK £60,100.09
Remaining Budget:	UK £21,033.91

Breakdown:

Doug Eynon:	369 hours	(£47,309.49)	
Gavin Smith:	86 hours	(£11,026.06)	
Scott Buchard:	18 hours	(£1,764.54)	(site for w/e 5 June 2016)

Progress Updates

Monday 18/7/16
PI completed, QA checked and issued our Bulk Strip & Inspection Report Rev 0 to Hydro for review and comment, on return of which the Report amended per comment will be re-issued at Rev 1 as Final.

Tuesday 19/7/16 to Monday 25/7/16
Started collation of information for development of Detail Strip & Inspection Report on Tuesday, and subject to our arranging with Alba for PI to visit their workshop to verify detail inspections of stripped components for any further findings or information potentially relevant for input to the Report.

Work on the Report was stopped when Hydro requested PI to bring forward our RCA Report for delivery Friday 22/7 to fit their immediate purposes. Due to the short notice this wasn't possible, but PI proposed an abbreviated report which Hydro agreed to. Development started 21/7 and a Preliminary RCA Report Rev 0 was issued to Hydro 25/7.

Issue of our full RCA Report is expected after completion of the failure investigations (and of the Detail Strip & Inspection Report as Hydro requires).

APPENDIX 2 – Alba Post Failure Field Service Report

Field Service Report
For
Investigation of High Vibration
Olympus Serial No: 202204

Customer: Newfoundland Hydro Stephenville

Date: 29th March 2016

Project Number: Alba 5269

Alba Power Ltd
Tel: (44) 01569 730088
Fax: (44) 01569 730099
sales@albapower.com
www.albapower.com

Quality Certification
ISO 9001:2008
ISO 14001:2004
OHSAS 18001:2007
Scotland

Table of Contents

Note:

The information contained within this documentation is Alba Power proprietary information and shall remain so at all times, no reproduction or passing to third parties shall be permissible

1 Introduction

Mr. Symon Hanna arrived at the Newfoundland Hydro site in Stephenville to investigate a high vibration trip and debris found on number 2 and 3 magnetic chip detector.

Date of works: Tuesday 29th March 2016 – Friday 1st April 2016.

Alba Power on site personnel: Mr. Symon Hanna.

2 Daily Report

2.1 Tuesday 29th March 2016

Symon checked in at Aberdeen airport and travelled to Deer Lake Newfoundland via London Heathrow and Toronto airports. Symon stayed overnight in Deer Lake.

2.2 Wednesday 30th March 2016

Symon travelled from Deer Lake to the Newfoundland Hydro Stephenville site. On arrival Symon was given a tailboard safety brief and the work scope of the job was discussed.

Both lube oil feed and return oil pipes were removed from the Olympus and the main oil tank. On removal of these pipes the oil contained fine black and metallic particles and also was discoloured with a burnt smell apparent.

The inlet oil strainer was removed and inspected for debris and found to be clean.

All magnetic chip detectors were removed and debris samples taken. All magnetic chip detector baskets were removed and debris samples were taken. There was severe bearing material debris in the green (Nos: 2 and 3) magnetic chip detector basket.

The air starter motor was removed and the HP rotor was rotated by hand. No abnormal noises or tightness was noted. The turning gear caps were removed from the fuel pump gear box and the LP rotor was attempted to be turned by hand. The LP rotor would not rotate.

The access was gained to the inlet plenum and the front of the LP rotor was inspected. On inspection a sizeable piece of debris was found between the LP rotor and the inlet casing stuck to the base of one of the first stage rotor blades. The LP rotor was rotated in an anti-clockwise direction and was tight to rotate. The LP rotor was then rotated in a clockwise direction and was very tight to turn with scraping noises noted.

2.3 Thursday 31st March 2016

Symon arrived on site and was given a tailboard safety brief before starting work.

All magnetic chip detector baskets were cleaned and replaced along with all corresponding magnetic chip detectors. All removed pipe-work was re-fitted along with the turning gear caps.

The oil used in the Olympus gas turbines was inspected and found to be in date in an adequate storage environment.

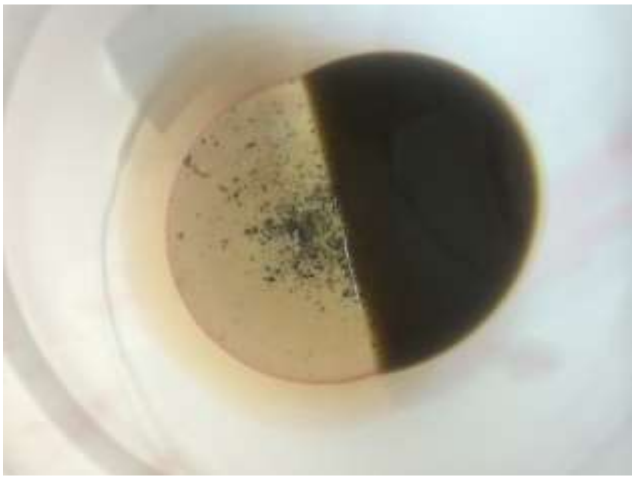
Symon left site and travelled to Dear Lake for his return flight to Aberdeen via Halifax and London Heathrow airports.

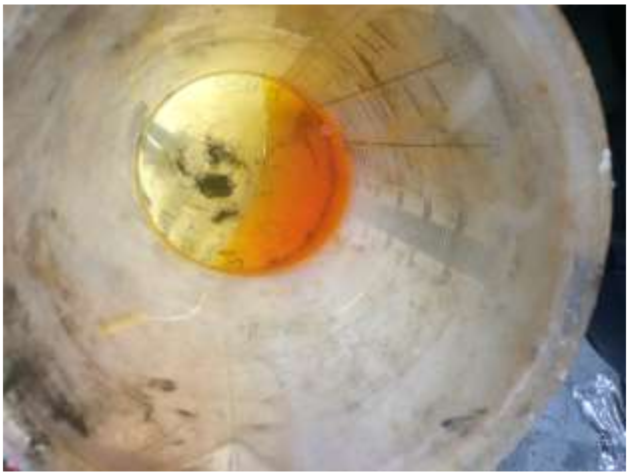
2.4 Friday 1st April 2016

Symon arrived back in Aberdeen.

3 Photographic Images

<table>
<tr><td></td><td></td></tr>
<tr><td>No.1 (Blue) Bearing magnetic chip detector and basket.</td><td>No.2 and 3 (Green) Bearing magnetic chip detector basket showing excessive debris.</td></tr>
<tr><td></td><td></td></tr>
<tr><td>No. 4 and 5 (Aluminium) Bearing magnetic chip detector and basket</td><td>No. 7 (White) Bearing magnetic chip detector and basket showing several large pieces of debris.</td></tr>
</table>

	
No. 8 (Yellow) Bearing magnetic chip detector and basket.	Oil and debris drained from the removal of the No. 2 and 3 (Green) Bearings magnetic chip detector basket showing contaminated burnt oil and excessive debris.
	
Oil Tank scavenge filter showing large quantities of metallic debris.	Oil feed pipe from the oil tank to the Olympus showing contaminated and discoloured oil through excessive heat.

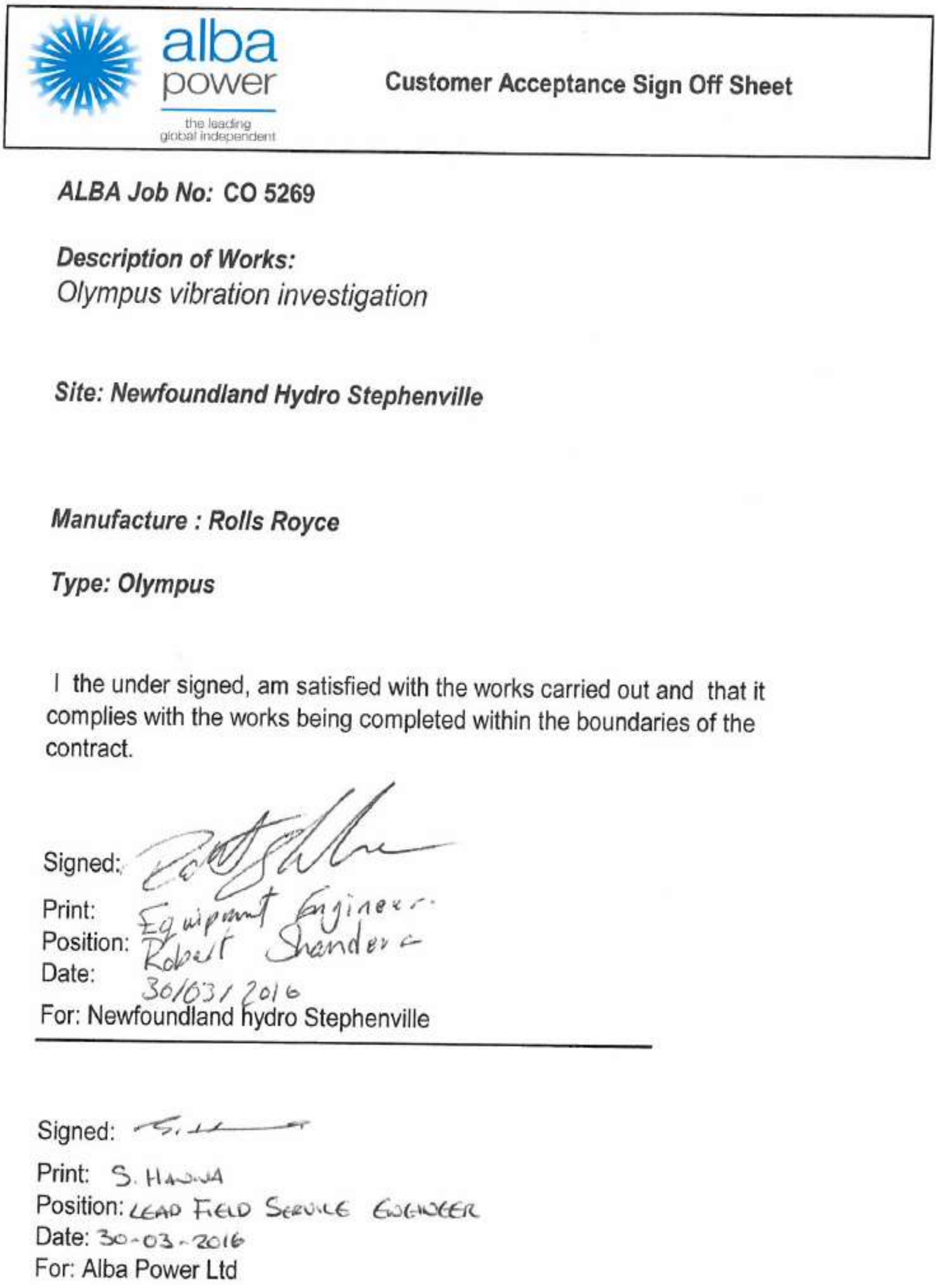
	
Oil scavenge pump filter removed. No signs of debris.	Mobil Jet 2 Oil tank showing that the oil is in date.
	
Fresh oil pumped from the oil drum used for the Olympus gas turbines showing its colour and cleanliness.	Piece of debris removed from between the LP compressor rotor and the intake casing.

4 Summary

All oil filters and magnetic chip detectors have been examined and excessive amounts of debris found in the No. 2 and 3 (Green) magnetic chip detector basket. This debris appears to be bearing material.

The lubricating oil for the Olympus gas turbine appears to be burnt and as a result Gas Turbine s/n: 202204 has suffered front end LP rotor main line bearing failure. The reason behind the excessive heat within the oil system could be due to the heating element within the oil tank becoming too hot or the way in which the gas turbines are shut down and not having a cool down period of at least 5 minutes at LP idle speed of 2000rpm.

5 Customer Acceptance



Customer Acceptance Sign Off Sheet

ALBA Job No: CO 5269

Description of Works:
Olympus vibration investigation

Site: Newfoundland Hydro Stephenville

Manufacture : Rolls Royce

Type: Olympus

I the under signed, am satisfied with the works carried out and that it complies with the works being completed within the boundaries of the contract.

Signed:
Print: Equipment Engineer.
Position: Robert Shandera
Date: 30/03/2016
For: Newfoundland hydro Stephenville

Signed:
Print: S. HANNA
Position: LEAD FIELD SERVICE ENGINEER
Date: 30-03-2016
For: Alba Power Ltd

6 Report Compilation

On site personnel:	Symon Hanna	Date:	29th March – 1st April 2016
Report compiled by:	Symon Hanna	Date:	1st April 2016
Reviewed by:	Alan Watson	Date:	1st April 2016

APPENDIX 3 – AGAT Lube Oil Analysis Report

Client: **3769512**

NEWFOUNDLAND & LABRADOR HYDRO
P.O. BOX 2002
BISHOP'S FALLS, NL A0H 1C0
ATTN: JIM WHEELER/RAY ROWE/PAUL KEOUGH

Date analyzed: **05/13/16**
Work order: **16C117043**
Oil brand & grade: **MOBIL JET II (NFLD. & LAB. HYDRO)**
Client Ref #:

Unit #: **GGA LUBE SYSTEM**
Unit Location: **#1-GGA LUBE OIL**
Component: **ENGINE**
Location:
Serial #: **0L-202204**
Make:
Model: **OLYMPUS JET ENGINE SVL GT**
OAS #: **#1-GGA LUBE OIL**

AGAT Laboratories
Equipment Reliability and Lubricants Testing Services
3650 21st Street N.E., Calgary, AB, T2E6V6
Phone:(403)299-2000 Fax:(403)299-2105

LEGEND - LC -Lower Critical LR -Lower Reportable UR -Upper Reportable UC -Upper Critical * *Ital* -Custom Limit

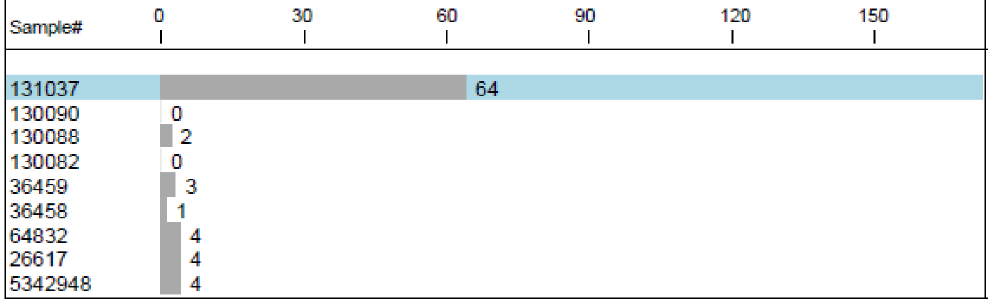
UNIT DATA / SPECTROGRAPHIC ANALYSIS (PPM)

Sample#	Date Sampled	Component Service	Oil Service	Oil Changed	Al Aluminum	Cr Chromium	Cu Copper	Fe Iron	Sn Tin	Pb Lead	Si Silicon	Mo Molybdenum	Ni Nickel	Ag Silver	K Potassium	Na Sodium	B Boron	Ba Barium	Ca Calcium	Mg Magnesium	Mn Manganese	P Phosphorus	Zn Zinc
New Oil					0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2907	0
131037	05/06/16	450 hrs	hrs	N	7	5	1	49 UR	2	0	3	0	0	0	0	0	0	0	0	0	1	2450	0
130090	03/16/15	175.2 hrs	175.2 hrs		0	0	0	0	0	0	9	0	0	0	0	2	0	0	0	0	0	2790	0
130088	11/07/14				1	0	0	0	0	1	1	0	0	0	0	1	0	0	0	0	0	2690	0
130082	10/25/14			N	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2640	0
36459	03/08/13			N	0	0	1	1	0	1	2	0	0	0	1	0	0	0	5	0	0	2610	4
36458	02/07/12			N	0	0	1	0	0	0	1	0	0	0	1	1	0	0	1	0	0	2614	1
64832	02/23/10	281 hrs		N	1	0	1	1	0	1	2	0	0	0	1	0	1	0	8	0	0	2912	2
26617	04/25/08	219.2 hrs			1	0	0	0	0	3	1	0	0	0	1	0	1	0	4	0	0	2960	2
5342948	01/04/07			N	0	0	0	1	0	3	0	0	0	0	13 UR	1	0	0	7	1	0	3174	4

PHYSICAL PROPERTIES / ISO CLEANLINESS / OIL DEGRADATION

Sample#	Glycol	H2O	% Fuel	Viscosity 40°C	Viscosity 100°C	% Solids	KF	°C Flash Point	Micron size 4	Micron size 6	Micron size 14	ISO Code	% SOOT	abs/cm-1 OXD	NOX	COX	SO4	ZDDP	TAN	TBN	Min. RPVOT
New Oil				25.8	5.1														0.08		
131037	N	N		26.7	5.4		344 ppm						0.0	5	0	0	0	0	0.06		
130090	N	N		28.1	5.3		189 ppm						0.0	66 UC	0	0	0	0	0.07		
130088	N	N		24.4	4.6		170 ppm						0.0	0	0	0	0	0	0.74		
130082	N	N		26.4	5.4		302 ppm						0.0	35 UC	0	0	0	0	0.01		
36459	N	N		25.8	5.4		109 ppm						0.1	118 UC	1	3	3	0	1.84 UR		
36458	N	N		23.9	5.5		136 ppm						0.0	93 UC	0	2	5	0	0.08		
64832	N	N		26.1		0.0													0.26		
26617	N	N		24.9		0..0													0.61		
5342948	N	N		26.3															1.20		

WEAR CONTROL CHART



COMMENTS

Comments:

REFER TO REVERSE FOR QUALITY CONTROL REPORT, EXPLANATION OF VARIANCE AND POSSIBLE CAUSES.

Should you wish to provide feedback to AGAT Laboratories, please access our Customer review form at www.agatlabs.com/review.htm. This input is extremely important to us because your well being and satisfaction is our number one priority.

* COMPONENT SERIAL NUMBER MUST BE GIVEN TO GENERATE HISTORY. Bold faced elements are included in Wear Control Chart.

AGAT Laboratories

Quality Control Report

Client: **3769512**

NEWFOUNDLAND & LABRADOR HYDRO
P.O. BOX 2002
BISHOP'S FALLS, NL A0H 1C0
ATTN: JIM WHEELER/RAY ROWE/PAUL KEOUGH

Date analyzed: **05/13/16**
Work order: **16C117043**
Oil brand & grade: **MOBIL JET II (NFLD. & LAB. HYDRO)**
Client Ref #:

Unit No.: **GGA LUBE SYSTEM**
Unit Location: **#1-GGA LUBE OIL**
Component: **ENGINE**
Location:
Serial No.: **0L-202204**
Make:
Model: **OLYMPUS JET ENGINE SVL GT**
OAS No.: **#1-GGA LUBE OIL**

Flagged Result	Possible Causes	Significance of Result / Recommended Action
Fe - Iron	Iron is the base element in steel and is therefore present in many lubricated components (liners, piston rings, pistons, rockers arms, cylinders, shafts, gears, valve bridges, oil pump rolling element bearings, housings and cases). Iron is also present in rust and may indicate water contamination.	Higher than expected iron levels may indicate wear or contamination. Identify and evaluate the source. Check for signs of rust, scale and corrosion. Consider filtering or changing the oil.

Client: 3769512

NEWFOUNDLAND & LABRADOR HYDRO
P.O. BOX 2002

BISHOP'S FALLS, NL A0H 1C0

ATTN: JIM WHEELER/RAY ROWE/PAUL KEOUGH

Unit #: **GGA LUBE SYSTEM**
Unit Location: **#1-GGA LUBE OIL**
Component: **ENGINE**
Location:
Serial #: **0L-202204**
Make:
Model: **OLYMPUS JET ENGINE SVL GT**

Oil brand & grade: MOBIL JET II (NFLD. & LAB. HYDRO)
Sample #: **C-677969**
Date Sampled: 05/13/16
Date Analyzed: 05/13/16
Work order: 16C117043
Client Ref #:

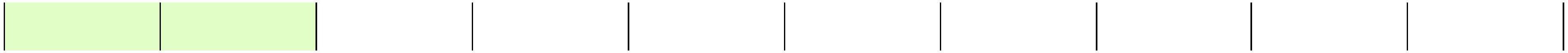
AGAT Laboratories

Sample Status and Trending

Sample Score:

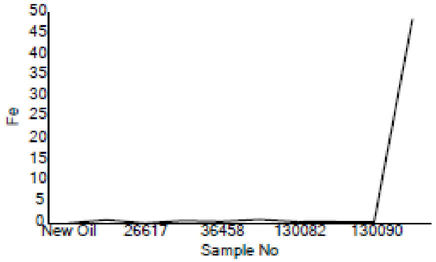
Your Sample Score: 2

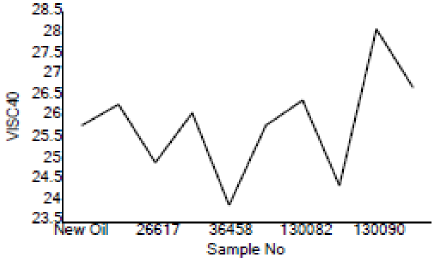
Rankings: 0-3 Normal, 4-6 Reportable, 7-10 Critical

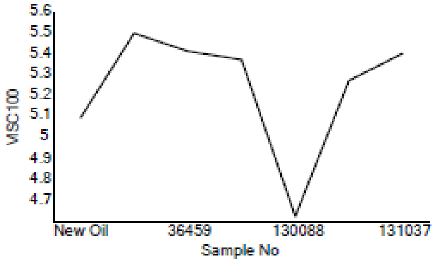


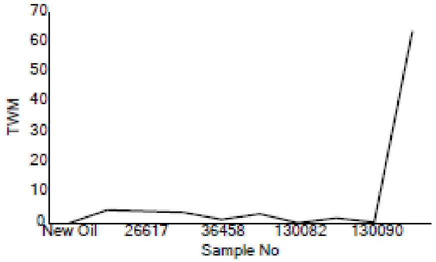
Normal **Reportable** **Critical**

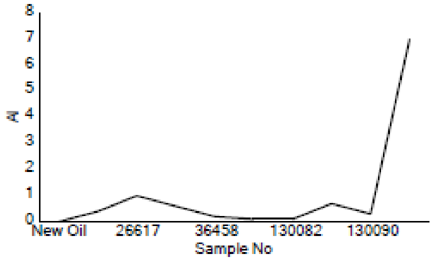
Trend Graphs

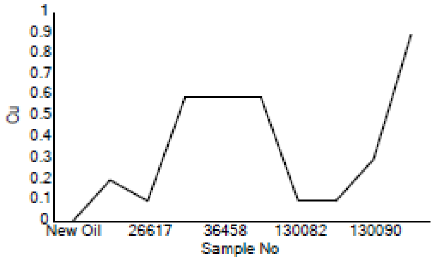


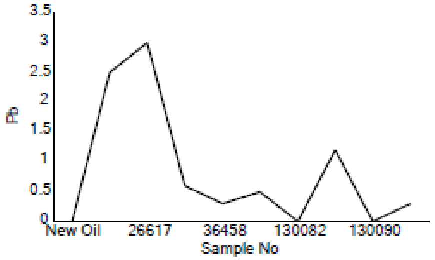


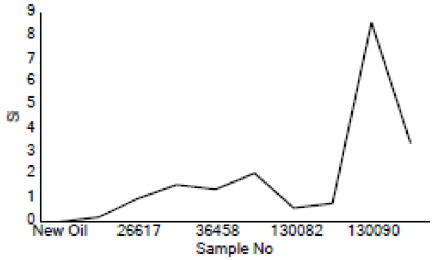












APPENDIX 4 – SKF Failure Analysis Report

ALBA POWER
ROLLS-ROYCE OLYMPUS
BEARING FAILURE ANALYSIS

DUNCAN FALLOW 17/06/2016
CONSULTANT (RELIABILITY ENGINEERING)

Distribution:

To:- Martin Cruickshank
cc:-

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Industrial Market, Wellheads Road, Farburn Industrial Estate, Dyce, Aberdeen, AB21 7HG
Tel. +44 (0) 1224 723321 Fax: +44 (0) 1224 723341 aberdeen.marketing@skf.com www.skf.co.uk

REPORT NUMBER: SKF REPORT RPCM507_ALBA POWER_160617_DF	
TITLE: ALBA POWER ROLLS-ROYCE OLYMPUS BEARING FAILURE ANALYSIS	
WRITTEN BY: D FALLOW **DESIGNATION: CONSULTANT**	**AUTHORISED BY: D ARMSTRONG** **DESIGNATION: TEAM MANAGER**

SUMMARY:

No root cause has been found for the bearing failures; however poor fit, moisture ingress, lubricant condition, cage integrity and loading appear contributing factors.

A review of monitoring and maintenance procedures might be beneficial to ensure they align with current best practices.

Advice on bearing selection and precision fit/mounting should be sought from a specialist.

Advice on lubricant selection, cleanliness, sampling frequency and analysis should be sought from specialist such as the Original Equipment Manufacturer (OEM) and lubricant supplier.

KEYWORDS: Lubricant contamination, load, fretting corrosion, poor fit, spalling, cage separation, temperature.

Project Quality Assurance

Carried out in accordance with SKF Quality Work Instructions as referenced. Accredited to ISO 9001:2008.

ALBA POWER
ROLLS-ROYCE OLYMPUS
BEARING FAILURE ANALYSIS

CONTENTS

(1) INTRODUCTION

A bearing housing containing two bearings from a Rolls-Royce Olympus gas turbine was received for analysis. The turbine had done approximately 90 hours of start/stop duty as a stand-by unit before removal of the housing.

An oil sample, taken from the engine sump, was received and sent for analysis – there was visible debris in the container on receipt.

1.1 Motor Unit Details

Rolls-Royce Olympus – no model designated.

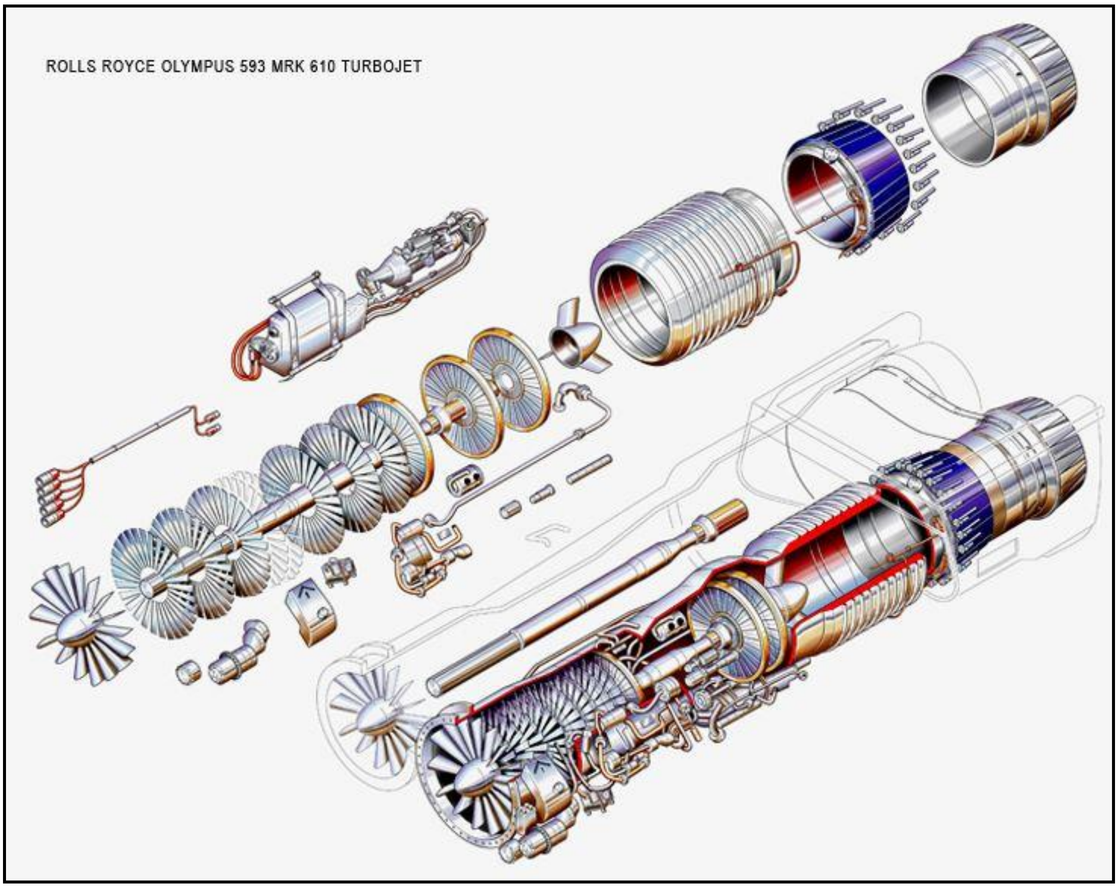
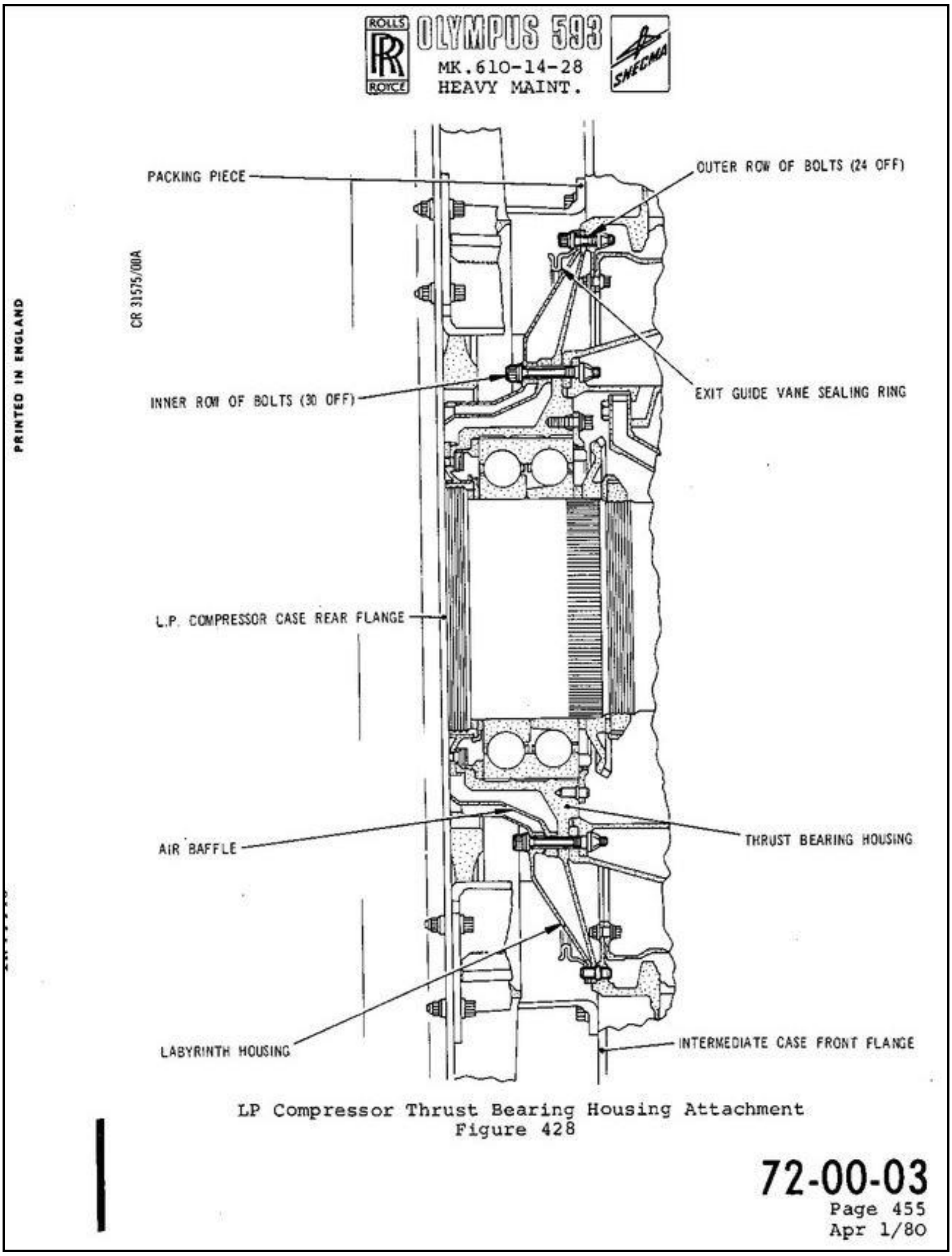


***Figure 1 –** Exploded diagram of Olympus 593 engine.*

1.2 General Arrangement



LP Compressor Thrust Bearing Housing Attachment
Figure 428

Figure 2 – *excerpt from Rolls-Royce Heavy Maintenance manual for Olympus 593 Mk-610, from the website www.Avialogs.com.*

1.3 Bearing Nomenclature

It has been impossible to positively identify the bearings due to the amount of wear on the side faces – where manufacturing marks and designations are normally situated.

1.4 Housing

Figure 3 – *Housing 'as received' with both outer rings in place. The Front bearing is uppermost in the photo.*

(2) FRONT BEARING – RHP UNKNOWN TYPE

Figure 4 – *Outer ring side face #1 'as received'.*

The bearing was received disassembled – the outer ring shown above and the inner ring (Figure 5 overleaf) split in two halves.

Twenty two rolling elements (Figure 6, overleaf) were received together with cage fragments (Figure 7, overleaf).

(2) (Continued)

Figure 5 – *Inner ring side face #1 ‘as received’.*

(2) **(Continued)**

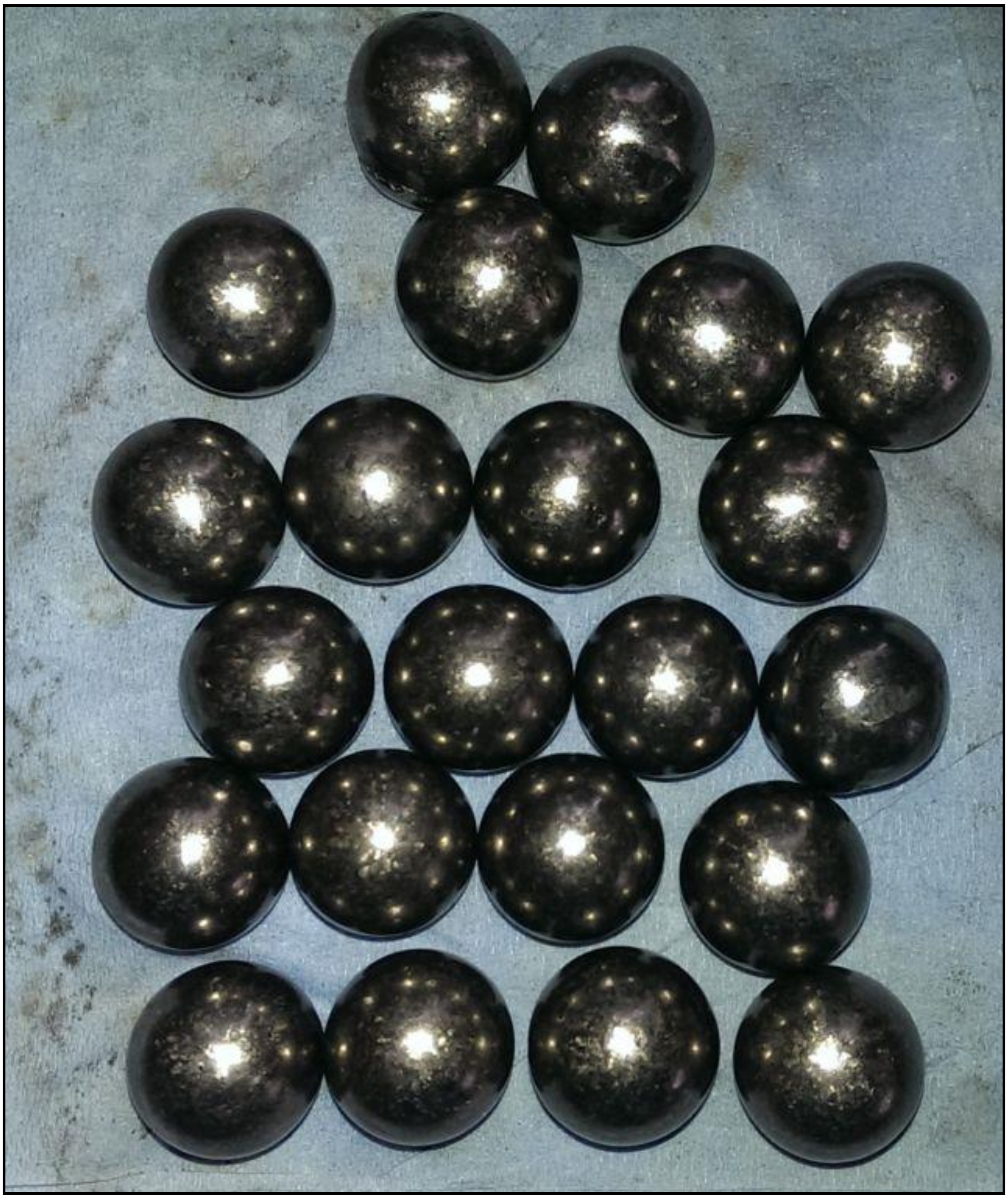


Figure 6 – *Rolling elements 'as received'.*

(2) (Continued)

Figure 7 – *Cage fragments 'as received'.*

2.1 Inner Ring Bore

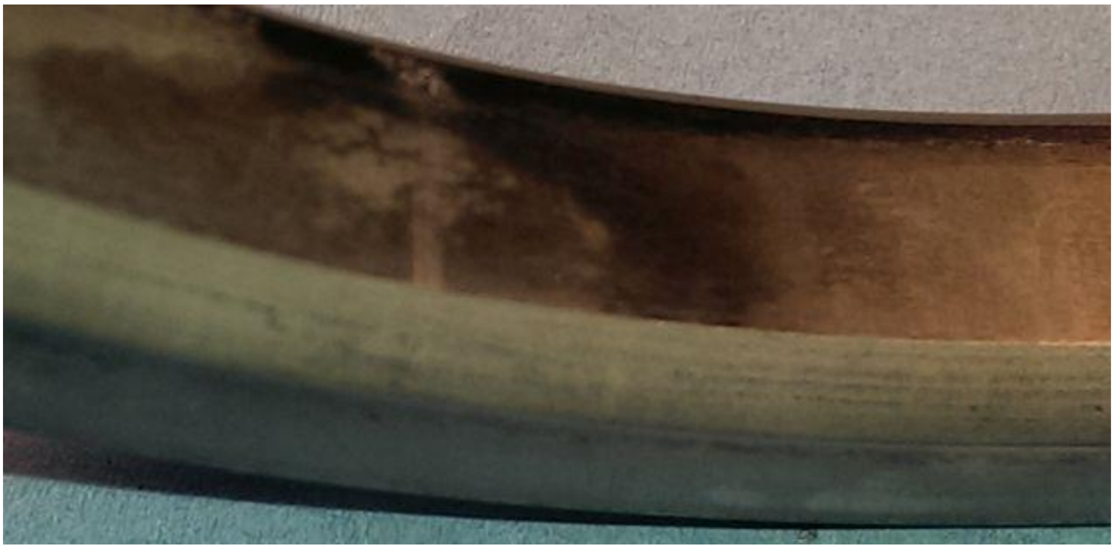


Figure 8 – *detail of inner ring bore.*

Staining and heat damage noted.

2.2 Inner Ring Side Faces

Figure 9 – *Inner ring #1 side face 1.*

Circumferential scoring, staining and blueing noted.

(2.2) (Continued)

Figure 10 – *Inner ring #1 side face 2.*

Staining and bluing noted.

(2.2) **(Continued)**

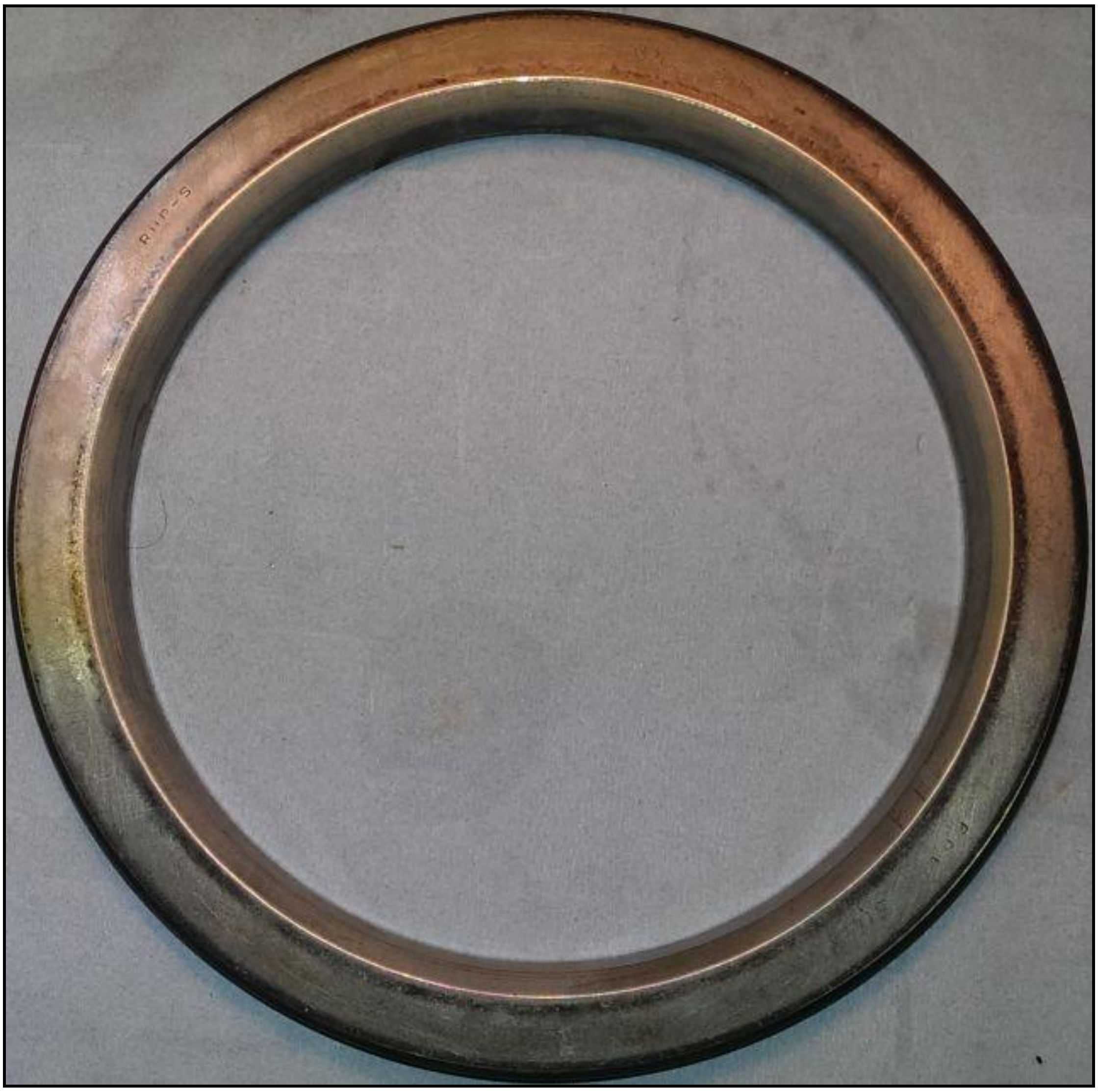


Figure 11 – *Inner ring #2 side face 1.*

Light staining noted.

(2.2) **(Continued)**

Figure 12 – *Inner ring #2 side face2.*

Fretting corrosion and surface damage noted. The surface damage (lower left of photo) appears relatively fresh and may have occurred during dismounting.

2.3 Outer Ring Outer Diameter (OD)

Figure 13 – *detail of outer ring OD.*

Moisture corrosion, fretting corrosion and circumferential scratches noted.

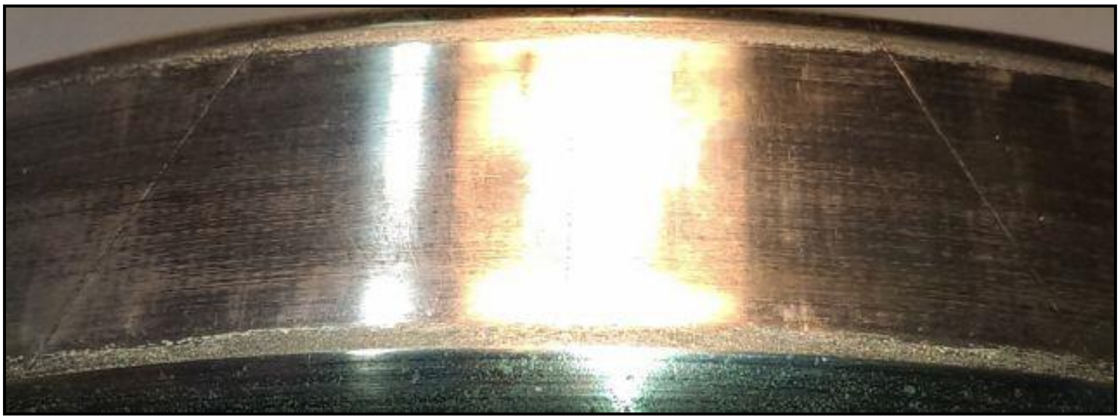


Figure 14 – *detail of outer ring OD. Note "V-shaped" marking which indicates how the matched bearing set should be mounted to obtain the proper preload in the set (see matching marks on the rear bearing shown in Figure 36).*

2.4 Outer Ring Side Faces

Figure 15 – *Outer ring side face 1.*

Circumferential scoring, staining and fractures to the inner lip noted.

(2.4) (Continued)

Figure 16 – *Outer ring side face 2.*

Light staining noted.

2.5 Inner Ring Raceway

Figure 17 – *Detail of inner ring raceway (colour corrected).*

Spalling and staining noted.

2.6 Outer Ring Raceway

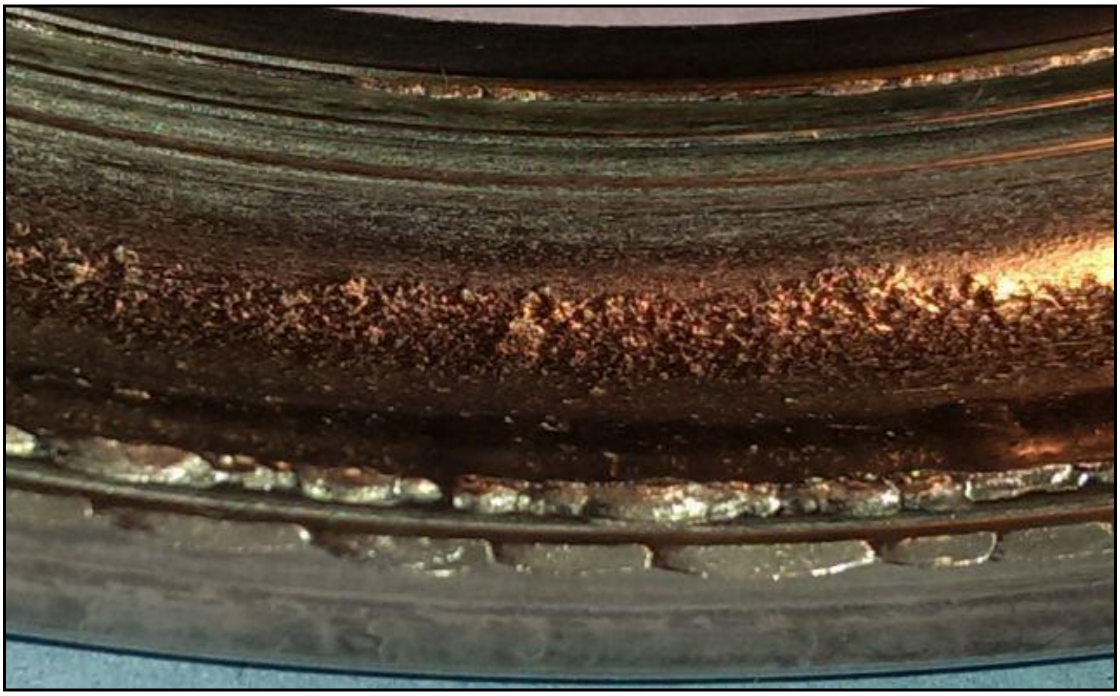


Figure 18 – *Detail of outer ring raceway.*

Heavy spalling, circumferential scoring, staining and fractures noted.

(2.6) (Continued)

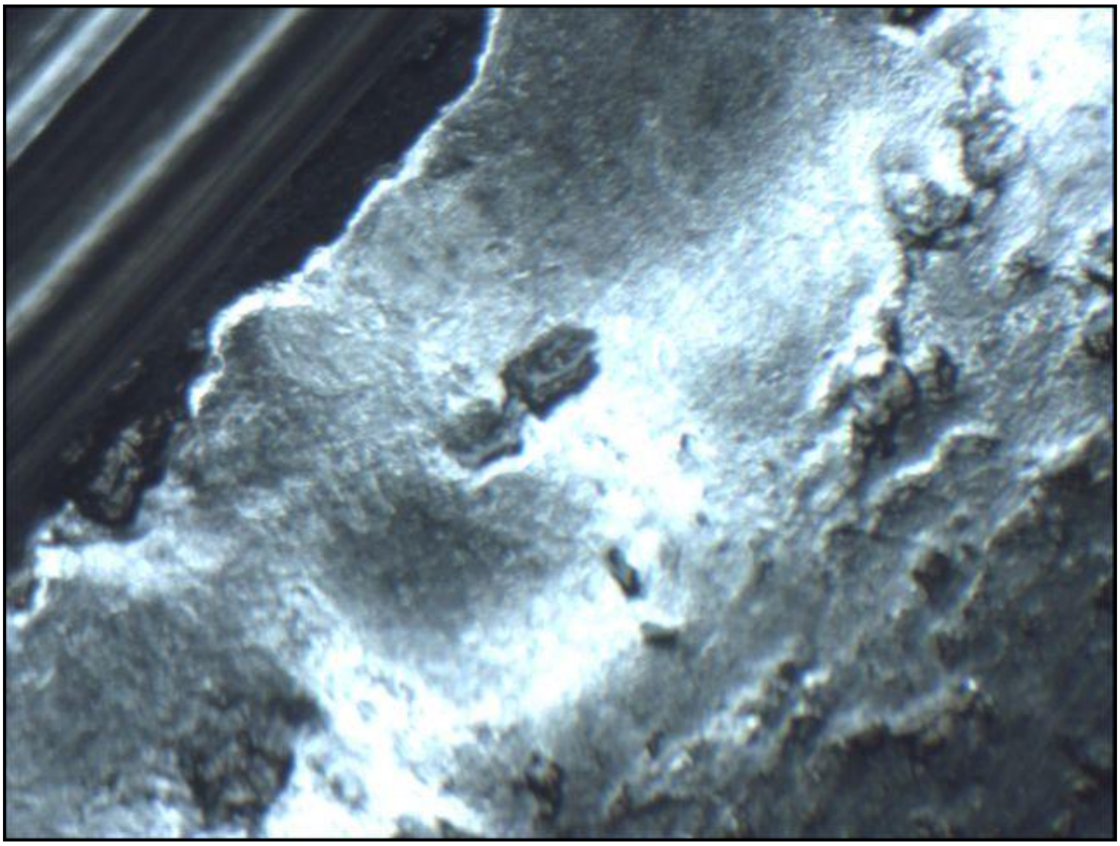


Figure 19 – *Detail of outer ring raceway damage showing heavy spalling and large indentations (deformation) at edge of raceway.*

2.7 Cage

***Figure 20 –** cage fragments after cleaning.*

A quantity of the cage was found to be absent when re-construction attempted.

(2.7) **(Continued)**

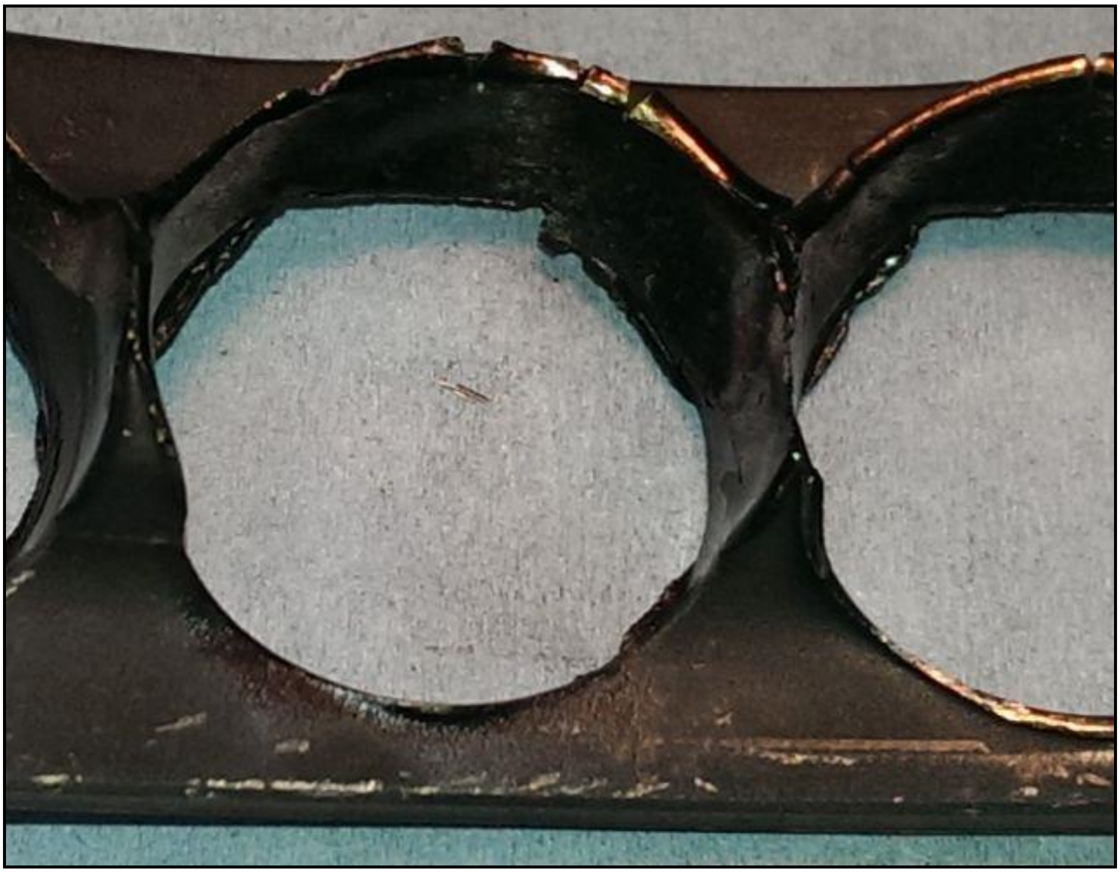


Figure 21 – *Detail of cage showing flaring of material around the pockets.*

Significant distortion of cage pockets noted.

2.8 Rolling Elements

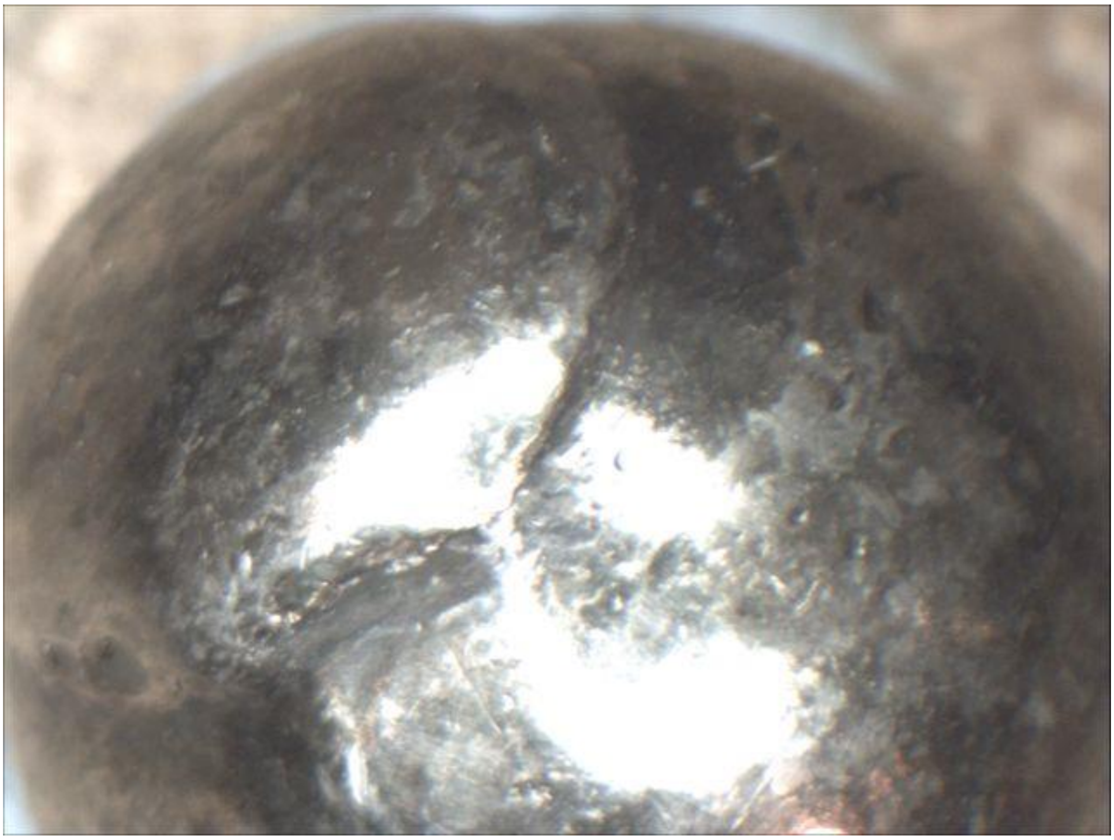


Figure 22 – example of typical ball condition. Note dents (deformation) and heavy surface damage.

Rolling elements were in very poor condition with a variety of defects noted.

A deep gouge is illustrated in Figure 23 (overleaf).

An accumulation of ‘flat spots’ are illustrated in Figure 24 (overleaf).

An instance of large scale adhesive wear is shown in Figure 25 (overleaf).

(2.8) <u>(Continued)</u>

***Figure 23** – example of deep gouge (deformation) on rolling element.*

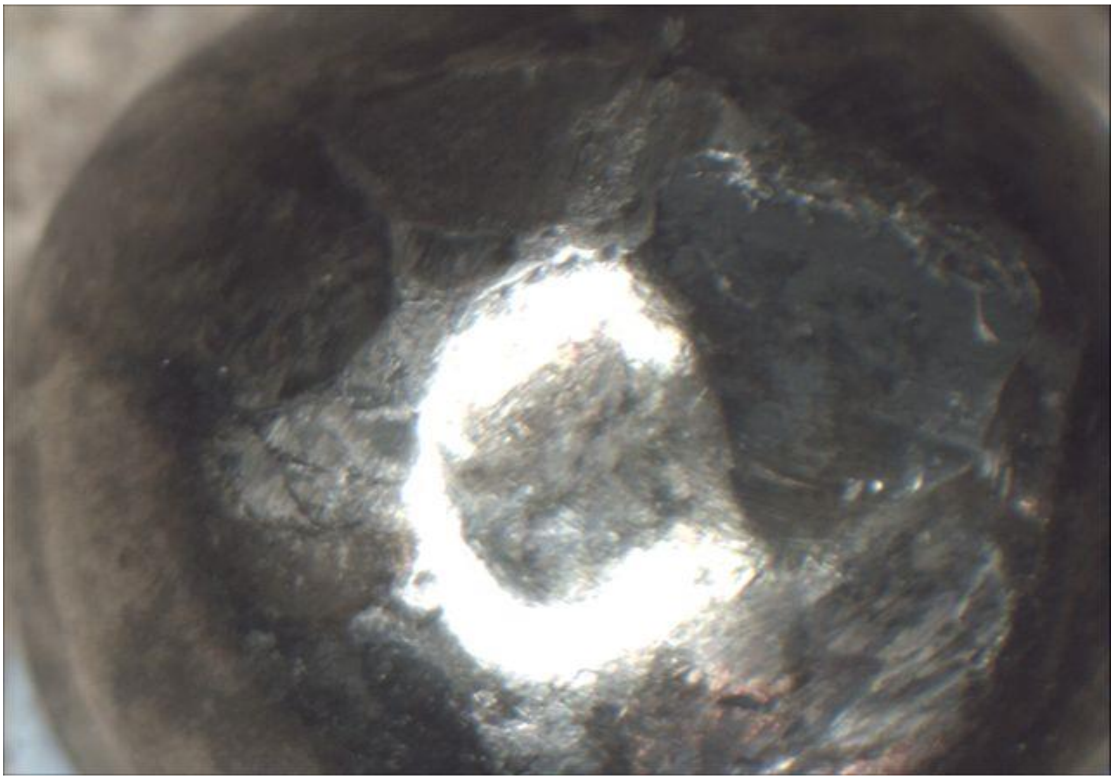


***Figure 24** – an accumulation of 'flat spots' (deformation) on rolling element.*

(2.8) **(Continued)**

Figure 25 – *Adhesive wear.*

2.9 Lubrication

A lubricant sample from the sump has been analysed.

(3) REAR BEARING – RHP UNKNOWN TYPE

***Figure 26 –** Outer ring side face #1 'as received'.*

The bearing was received disassembled – the outer ring shown above and the inner ring (Figure 27 overleaf) split in two halves.

Twenty two rolling elements (Figure 28, overleaf) were received together with cage fragments (Figure 29, overleaf).

(3) (Continued)

Figure 27 – *Inner ring side face #1 'as received'.*

(3) <u>(Continued)</u>

Figure 28 – *Rolling elements 'as received'.*

(3) (Continued)

Figure 29 – *Some of cage fragments 'as received'.*

3.1 Inner Ring Bore

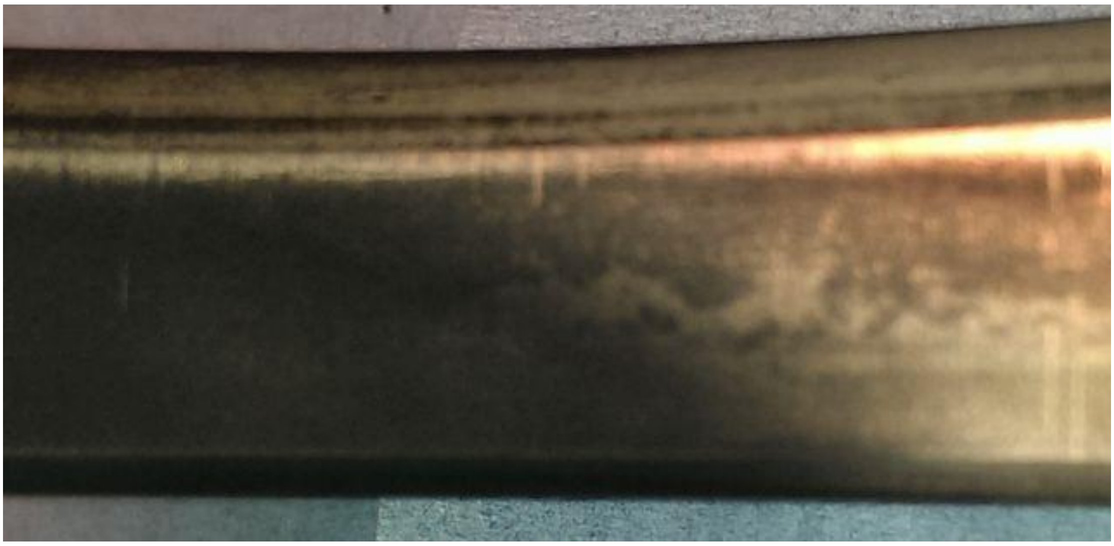


***Figure 30 –** detail of inner ring bore.*

Staining and heat damage noted.

3.2 Inner Ring Side Faces

***Figure 31** – Inner ring #1 side face 1.*

Circumferential scoring, staining and blueing noted.

(3.2) **(Continued)**

Figure 32 – *Inner ring #1 side face 2.*

Staining and bluing noted.

(3.2) (Continued)

Figure 33 – *Inner ring #2 side face 1.*

Heavy circumferential damage, heat damage and staining noted.

(3.2) **(Continued)**

Figure 34 – *Inner ring #2 side face2.*

Heat damage and staining noted.

3.3 Outer Ring Outer Diameter (OD)

Figure 35 – *detail of outer ring OD.*

Moisture corrosion, fretting corrosion and circumferential scratches noted.

Scoring noted across OD – see Figure 36 (overleaf).

(3.3) **(Continued)**

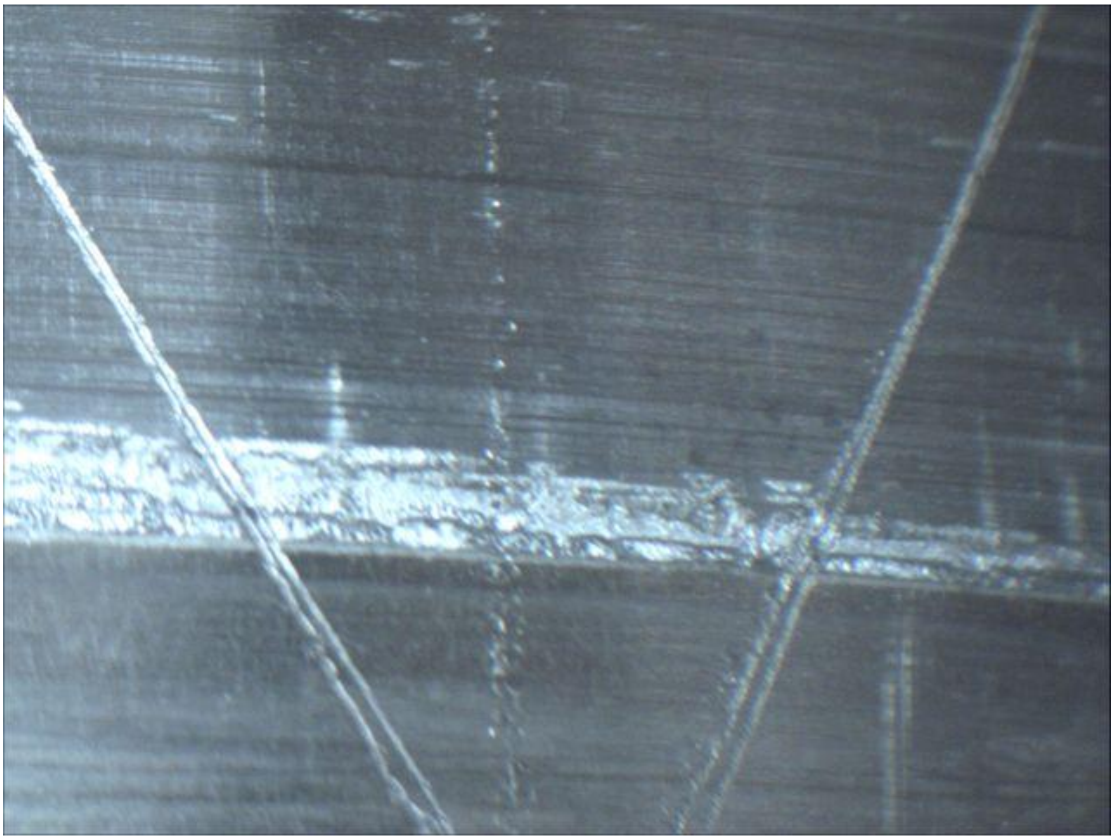


Figure 36 – *detail of outer ring OD. Note "V-shaped" marking which indicates how the matched bearing set should be mounted to obtain the proper preload in the set (see matching marks on the rear bearing shown in Figure 14).*

3.4 Outer Ring Side Faces

Figure 37 – *Outer ring side face 1.*

Circumferential scoring, staining and fractures to the inner lip noted.

(3.4) **(Continued)**

Figure 38 – *Outer ring side face 2.*

Light staining noted.

3.5 Inner Ring Raceway

Figure 39 – *Detail of inner ring raceway.*

Spalling and fractures noted.

3.6 Outer Ring Raceway

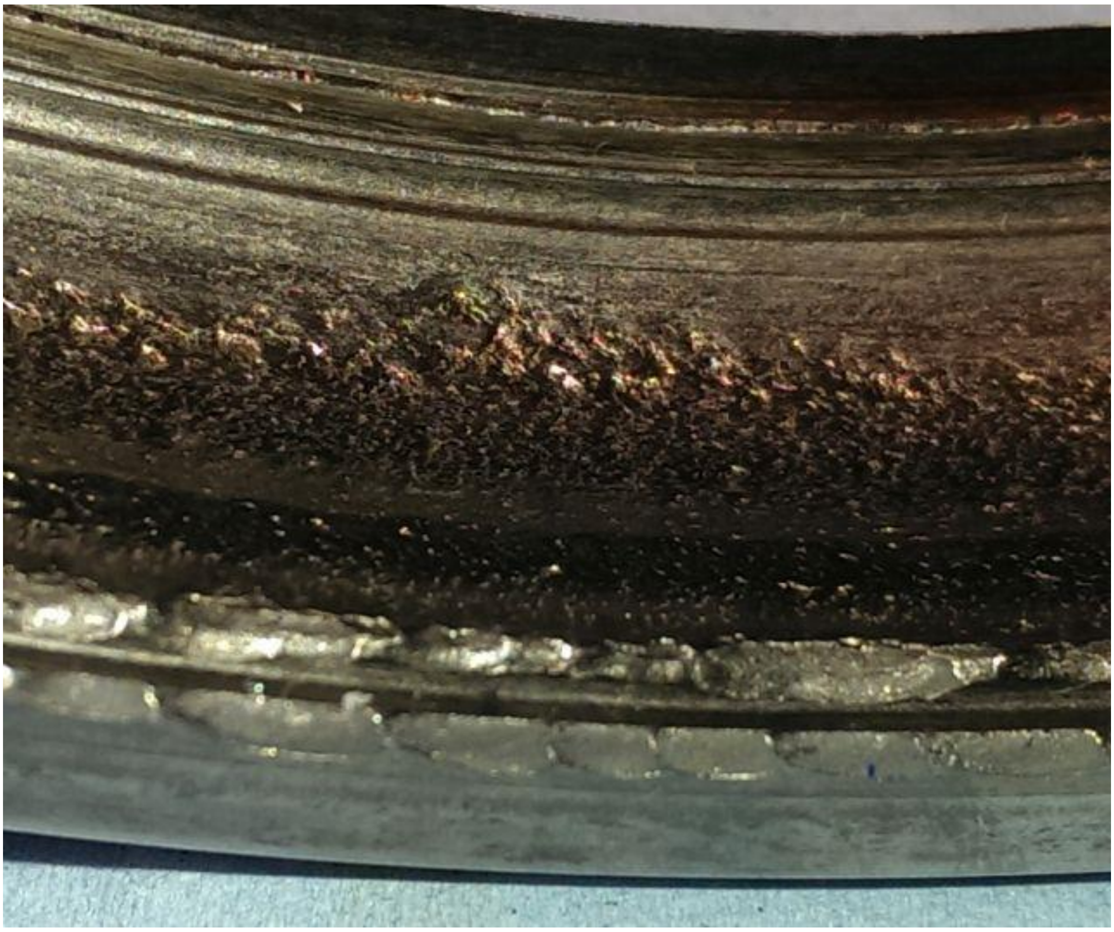


Figure 40 – *Detail of outer ring raceway.*

Heavy spalling, circumferential scoring, staining and fractures noted.

(3.6) <u>(Continued)</u>

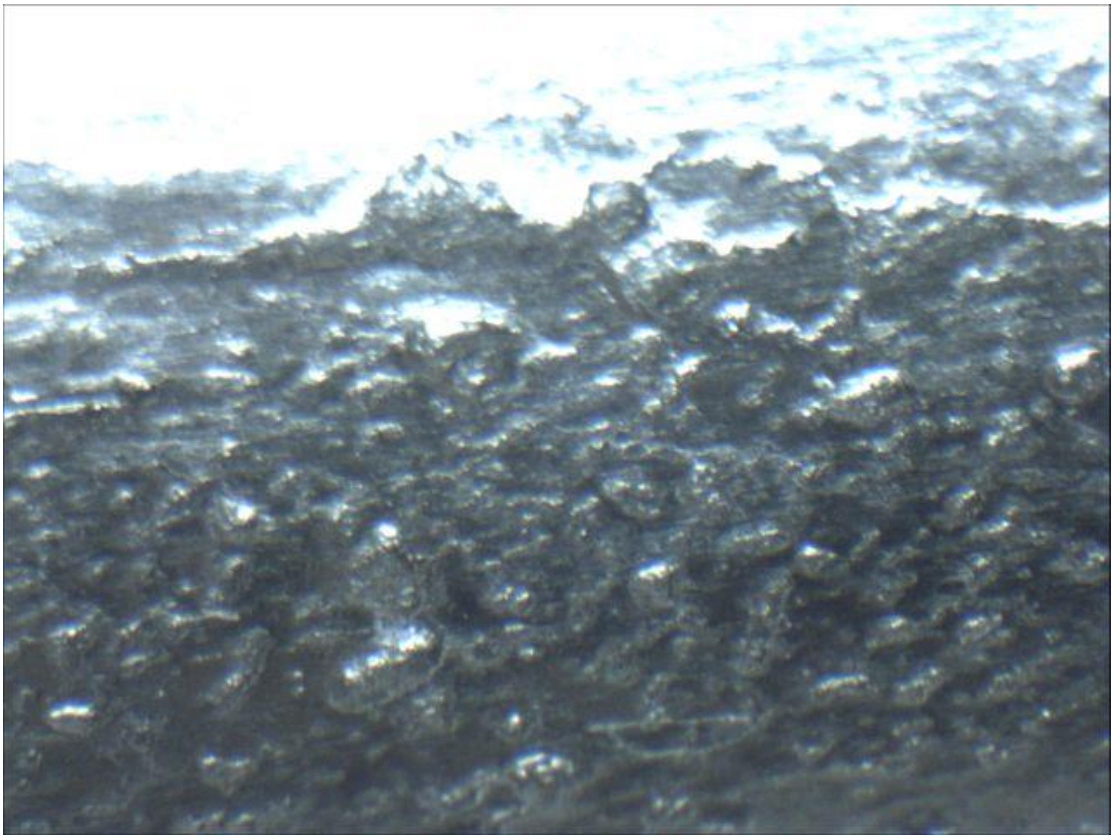


Figure 41 – *Detail of outer ring raceway damage showing heavy spalling.*

3.7 Cage

Figure 41 – *cage fragments after cleaning.*

A quantity of the cage was found to be absent when re-construction attempted.

(3.7) **(Continued)**

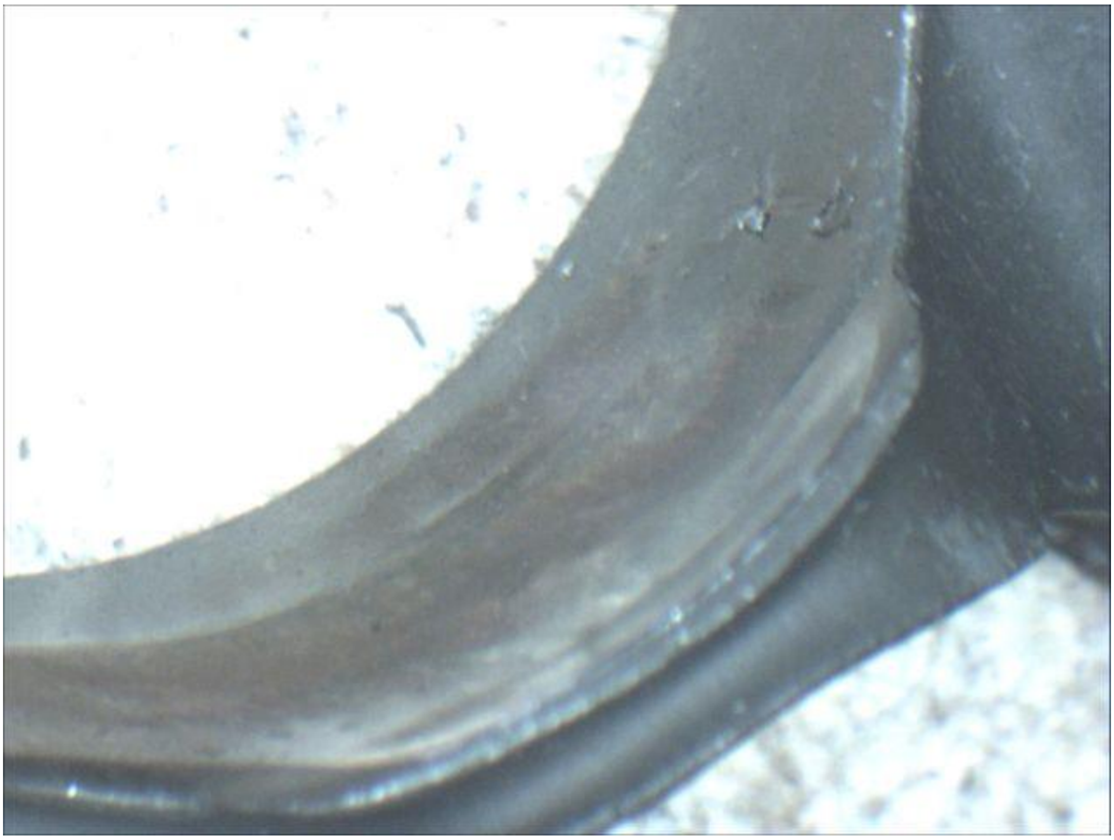


Figure 42 – *Detail of cage showing discolouration and flaring of material around the pockets.*

Heat damage, indentations and distortion of cage pockets noted.

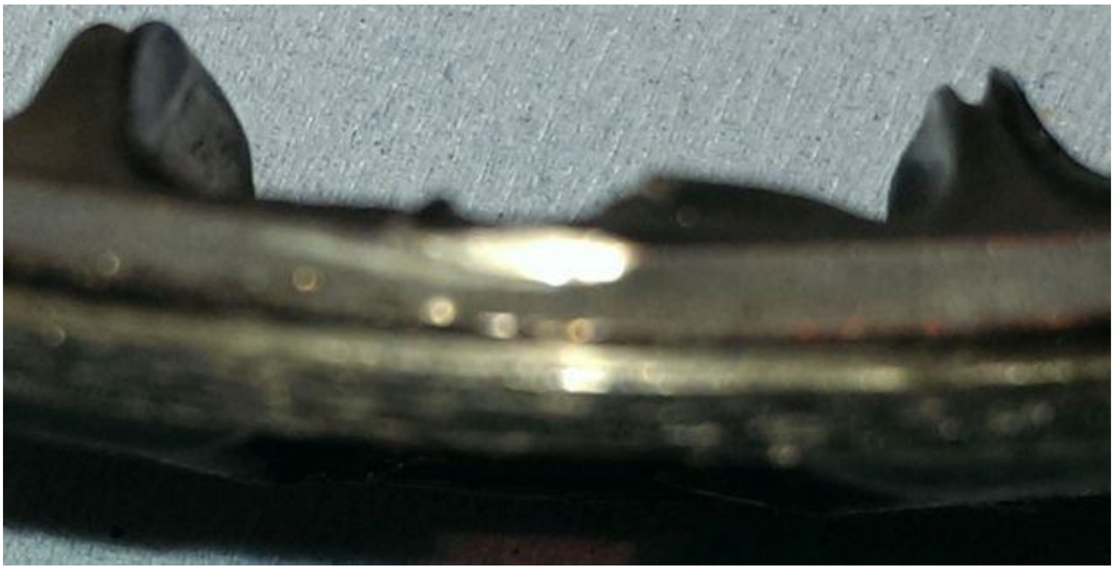


Figure 43 – *side view of cage fragment. Note extended pocket margins.*

(3.7) **(Continued)**

Figure 44 – *example of damage to exterior of cage. Also note amount of clearance around the rolling element.*

3.8 Rolling Elements

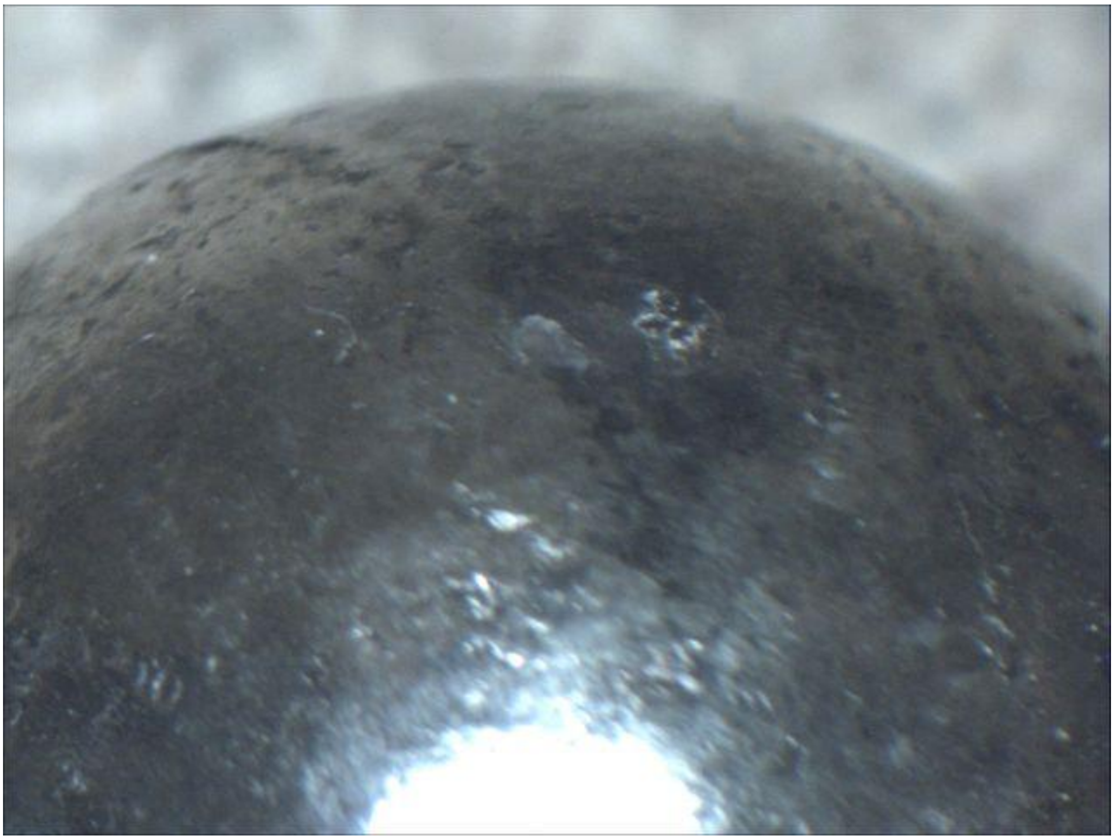


Figure 45 – example of typical ball condition.

Rolling elements were in poor condition with a variety of defects noted.

A deep gouge is illustrated in Figure 46 (overleaf).

(3.8) **(Continued)**

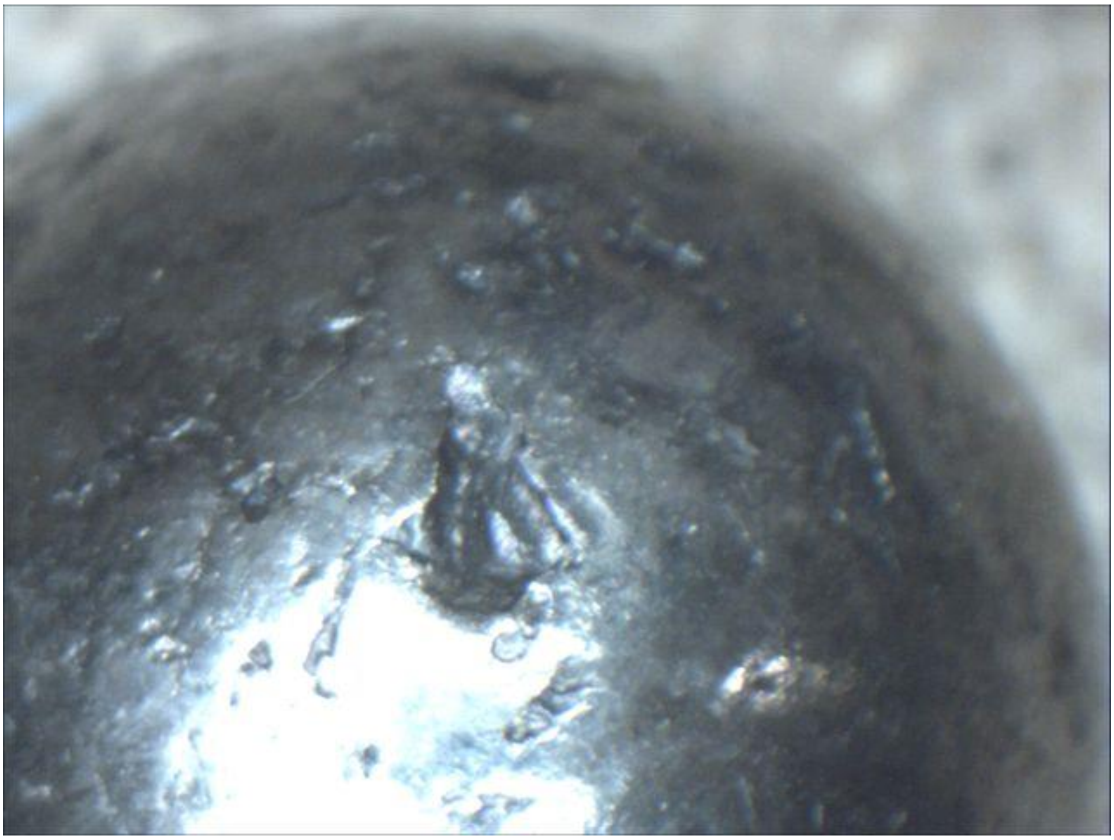


Figure 46 – *example of deep gouge on rolling element.*

3.9 Lubrication

A lubricant sample from the sump has been analysed.

(4) BEARING HOUSING

The housing was received intact with the outer races of two bearings inside. Initial attempts to remove the bearing components were unsuccessful and after receiving confirmation from the client the housing was cut – see Figure 47.

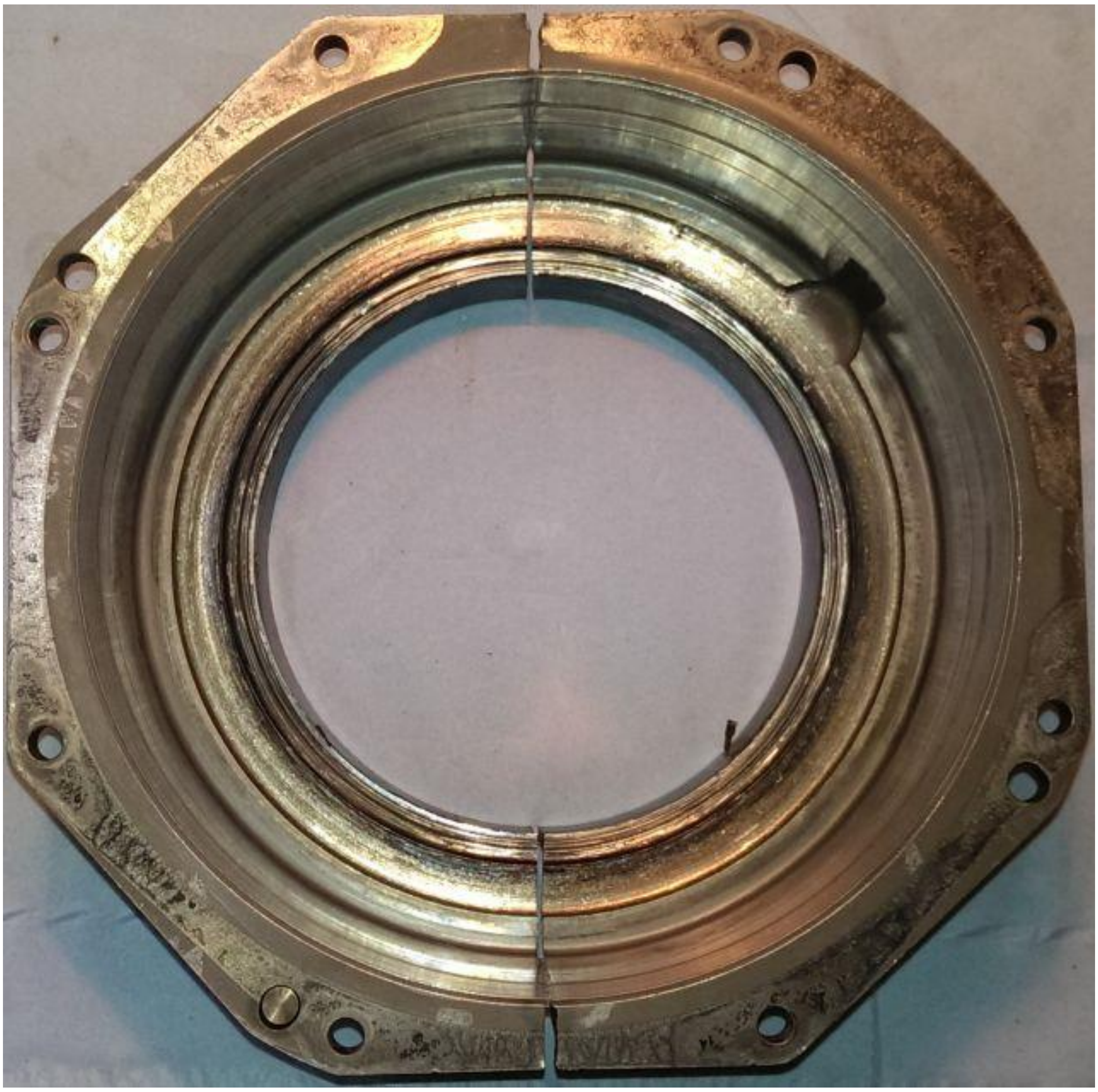


Figure 47 – *interior of housing after removal of bearing races and cleaning. Note the circumferential scoring and wear.*

A significant amount of wear was noted together with some 'blueing' of the surfaces adjacent to the shaft aperture.

The exterior of the housing also showed evidence of having been subjected to high localised heat – see Figure 48 (overleaf).

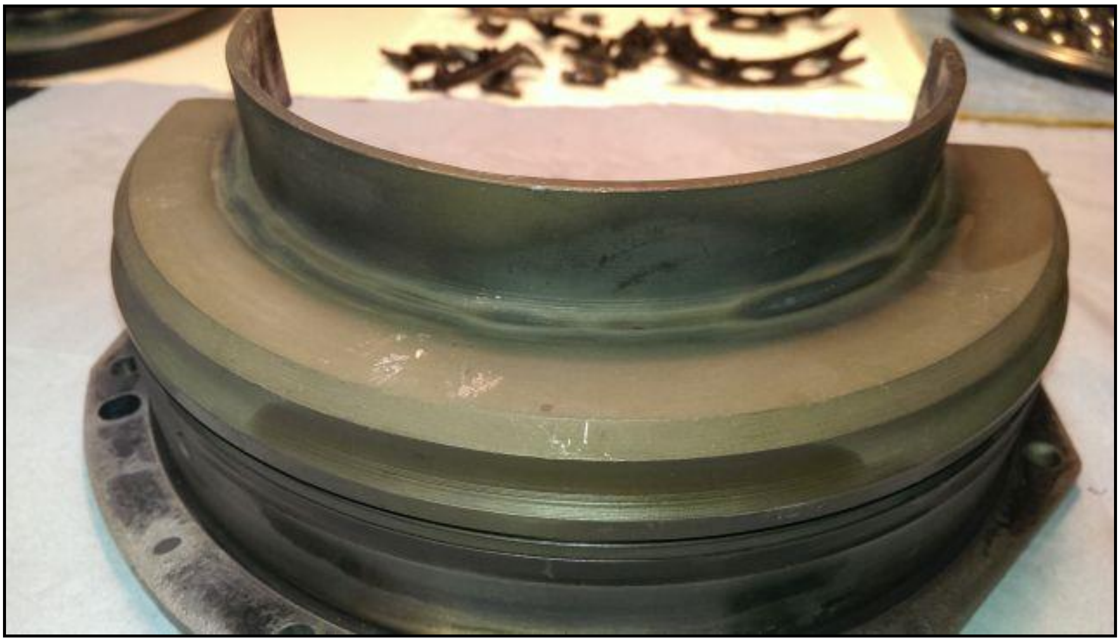


***Figure 48 –** one half of housing exterior after cleaning. Note areas of 'blueing' (centre right of photo).*

Circumferential wear was noted on the housing interior – see upper section of Figure 49.

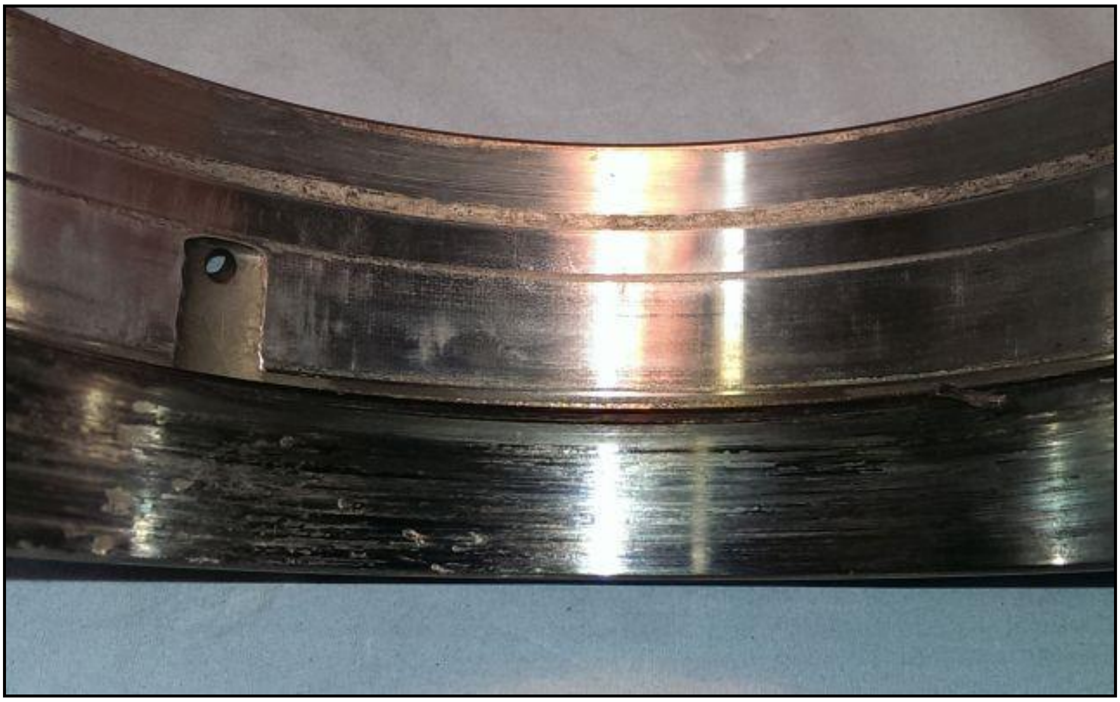


***Figure 49 –** one half of housing interior.*

Significant amounts of wear noted in shaft aperture – see lower section of Figure 49.

(5) DISCUSSION

Spalling (ISO 5.1.1 – Appendix A, Table A1) was noted on both front and rear inner and outer raceways - Figure 17, Figure 18, Figure 19, Figure 39, Figure 40 & Figure 41. This type of fatigue is caused by repeated stresses between rolling elements and raceways and is often attributed to lubrication issues.

Adhesive wear (ISO 5.2.3 – Appendix A, Table A1) was noted on the front bearing inner ring #1 side face 1 (Figure 9), rear bearing inner ring #1 side face 1 (Figure 31), rear bearing inner ring #2 side face 1 (Figure 33), front bearing rolling element (Figure 25) and housing interior (Figure 49). Some causes of adhesive wear include acceleration of bearing components, skidding/smearing of rolling elements, excessive frictional heat and too light loading.

The wear and 'blueing' (Figure 47) is probably secondary damage caused by rotating contact due to increasing clearance between cage and rolling elements.

Moisture corrosion (ISO 5.3.2 – Appendix A, Table A1) was noted on front bearing outer ring OD (Figure 13) and rear bearing outer ring OD (Figure 35). For this type of corrosion to occur the component surfaces need to be exposed to moisture and oxygen when at stand-still for prolonged periods.

Fretting corrosion (ISO 5.3.3.2 – Appendix A, Table A1) was noted on front bearing inner ring #2 side face 2 (Figure 12), front bearing outer ring OD (Figure 13), the rear bearing outer ring OD (Figure 35) and interior of bearing housing (Figure 49). This type of damage is commonly caused by micro-movements between mating parts in load transmitting interfaces.

Overload (ISO 5.5.2 – Appendix A, Table A1) was noted on front bearing outer race raceway (Figure 19), front bearing cage (Figure 21), Front bearing rolling elements (Figure 22, Figure 23 & Figure 24), rear bearing cage (Figure 42 & Figure 43) and rear bearing rolling elements (Figure 45 & Figure 46). Common causes include static/shock loading of components, handling damage and surface damage caused by hard/sharp objects.

Over-rolling of steel debris often produces indentation with rounded bottoms like those seen on the rolling elements (Figures 45 and 46).

Fractures (ISO 5.6.1 – Appendix A, Table A1) were noted on front bearing outer ring side face 1 (Figure 15), front bearing outer ring raceway shoulder (Figure 18), front cage (Figure 20), rear bearing outer ring side face 1 (Figure 37), rear bearing inner ring raceway (Figure 39), rear bearing outer ring raceway (Figure 40) and rear cage (Figure 41). These are the result of the tensile strength of the material being exceeded and probably occurred following loss of bearing integrity.

The lubricant sample received from the sump was analysed and the results have been compared with Mobil Jet Oil II Material Safety Data Sheet [1] (MSDS). Elemental results are shown in Table 1. The alarm levels are for indication only but are typical for this type of gas generator – advice should always be sought from the OEM regarding lubricant cleanliness.

Element	Units	Result	Alarm
Aluminium	mg/kg	3	5
Chromium		2	5
Copper		< 1	5
Iron		21	5
Lead		< 1	5
Manganese		< 1	5
Molybdenum		< 1	5
Nickel		< 1	5
Silver		< 1	5
Titanium		< 1	5
Vanadium		< 1	5
Boron		2	5
Sodium		< 1	5
Silicon		3	5
Barium		< 1	5
Calcium		< 1	5
Magnesium		< 1	5
Phosphorous		2137	3500
Zinc		< 1	5

Table 1 – *elemental results from sump oil sample.*

PQ Index was 33 – a value of 25 or below is considered acceptable.

Viscosity at 40°C was 24.75 centiStokes versus 27.6 centiStokes on Mobil Jet Oil II MSDS [1] – 10.4% below optimum. Mobil recommend that typical viscosity ranges for turbine applications should remain within +/-5% of new oil.

Total Acidity was 0.1 mg KOH/g versus 0.03 mg KOH/g on Mobil Jet Oil II MSDS [1] – more than three times greater than 'new' oil. This typically indicates build-up of acidic by-products formed during lubricant oxidation.

The size of the sample was too small (less than 120 ml) for complete analysis to be completed – accurate determination of Flash Point.

Mobil recommend daily visual inspection for critical application turbine oils as a cloudy/hazy appearance can indicate moisture ingress.

It is not clear whether any lubricant sampling or analysis program is in place for the unit.

(5) CONCLUSION

It is apparent that the bearings ran for some time with increasingly contaminated lubricant - the source of the initial contamination has not been identified.

Both cages have fractured/separated probably as a result of excessive heat. The significant amount of separation noted between rolling element and cage pocket (Figure 44) and the distortion of pocket geometry (Figure 43) suggest running with sub-optimal lubrication conditions.

The fretting corrosion around the inside of the housing (Figures 49) suggest poor fit between components. The wear and 'blueing' (Figure 47) is probably secondary damage caused by rotating contact due to increasing clearance between cage and rolling elements.

An appropriate lubricant sampling and analysis program should have picked up trends departing from nominal – particularly important parameters such as viscosity and acidity.

(6) RECOMMENDATIONS

In order to avoid fretting corrosion, or slow the process, the tolerances (fit) should be adjusted. Some manufacturers recommend the application of an anti-fretting paste or compound. SKF, however, does not recommend the use of specially formulated adhesives to avoid fretting corrosion; a 'precision' fit should always be sought.

It would be prudent to review current oil sampling and analysis procedures to ascertain if any changes might afford earlier detection of contamination issues. It is suggested that attention should be paid to OEM and lubricant manufacturer recommended cleanliness levels perhaps through regular sampling and analysis.

Advice should be sought from the Original Equipment Manufacturer (OEM) regarding optimum lubricant selection.

A review of recent operational parameters might confirm whether significant changes in load on the engine had taken place.

A review of bearing selection criteria might be beneficial to ensure that state-of-the-art quality bearings are being utilised. Hybrid bearings (with specialist coatings) are available which can help mitigate against early wear effects and lubricant contamination.

References

[1] Exxon Mobil Corporation. Mobil Jet Oil II PDS. Exxon Mobil website - http://pds.exxonmobil.com/USA-English/Aviation/PDS/GLXXENAVIEMMobil_Jet_Oil_II.aspx

APPENDIX A

SKF BEARING DAMAGE CLASSIFICATION

(ADAPTED FROM ISO 15243:2004)

SKF BEARING DAMAGE CLASSIFICATION
(ADAPTED FROM ISO 15243:2004)

5.1.1	**Fatigue**	The change in the material structure, which is caused by the repeated stresses developed in the contacts between the rolling elements and the raceways. Fatigue is manifested visibly as ***spalling*** of particles from the surface. The time between beginning and advanced spalling varies with speed and load. In any event it is typically a condition that will not cause catastrophic failure.
5.1.2	Subsurface fatigue	The initiation of ***micro-cracks*** below the raceway surface. When these micro-cracks propagate to the surface they produce ***spalls*** (flaking).
5.1.3	Surface initiated fatigue	Distress of the surface. Failure of the rolling contact metal surface asperities (roughness) due to inadequate lubrication conditions.
5.2.1	**Wear**	The progressive removal of material resulting from the interaction of two sliding or rolling/sliding contacting surfaces during service.
5.2.2	Abrasive wear	The result of inadequate lubrication of the ingress of contaminants.
5.2.3	Adhesive wear (smearing, skidding, galling)	A material transfer from one surface to another with friction heat, sometimes with tempering or re-hardening of the surface.
5.3.1	**Corrosion**	The deterioration of a metal surface as a result of oxidation or a chemical reaction on metal surfaces.
5.3.2	Moisture corrosion	Oxidation of the surfaces in the presence of moisture.
5.3.3.1	Frictional corrosion	The chemical reaction activated by relative micro-movement between mating surfaces under certain friction conditions.
5.3.3.2	Fretting corrosion	The oxidation and wear of surface asperities under oscillating micro-movements.
5.3.3.3	False brinelling	The formation of shallow depressions resulting from micro-movements caused by cyclic vibrations when a machine is at standstill. Equally spaces depressions matching the rolling element pitch appear in the raceways.
5.4.1	**Electrical erosion**	The damage to contact surfaces (removal of material) caused by the passage of electrical currents.
5.4.2	Excessive current	Sparking and localised heating from current passage in the contact area because of ineffective insulation.
5.4.3	Current leakage	The generation of shallow craters from 9low) current passage. The crates are closely positioned

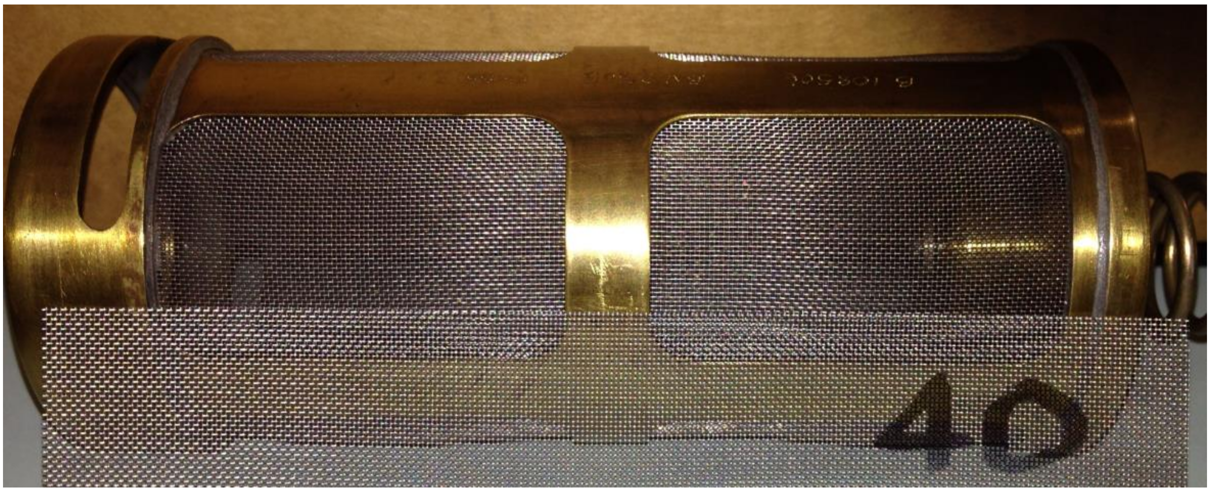
		to one another. They develop over time into flutes parallel to the rolling axis and are equally spaced.
5.5.1	**Plastic deformation**	Permanent deformation occurs whenever the yield strength of the material is exceeded.
5.5.2	Overload	Overloading by static or shock loads, leading to plastic deformation. Bearing surfaces that are dented or gouged by hard, sharp objects.
5.5.3	Indents from debris	Over-rolled particles in the contact areas from dents in the raceways and rolling elements. The size and shape of the dents depends on the nature of the particles.
5.6.1	**Fracture**	The ultimate tensile strength of a material is exceeded and complete separation of a part of a component occurs.
5.6.2	Forced fracture	A fracture resulting from a stress concentration in excess of material's tensile strength.
5.6.3	Fatigue Fracture	A fracture resulting from frequently exceeding the fatigue strength limit of the material.
5.6.4	Thermal cracking	Cracks that are generated by high frictional heating and usually occur perpendicular to the direction of the sliding motion.

Table A1 *– bearing damage classification adapted by SKF from ISO 15243:2004.*

APPENDIX 5 – Lube Oil Supply Filters Micron Ratings

Photo of Pressure Filter Mesh Comparison

Photo of LP Filter Mesh Comparison



ASTM E11 / ISO 565/3310-1 Comparison Chart		
ASTM E11		ISO 565/3310-1
Standard	Alternate	Size
850µm	No.20	850µm
-	-	800µm
710µm	No.25	710µm
-	-	630µm
600µm	No.30	600µm
-	-	560µm
500µm	No.35	500µm
-	-	450µm
425µm	No.40	425µm
-	-	400µm
355µm	No.45	355µm
-	-	315µm
300µm	No.50	300µm
-	-	280µm
250µm	No.60	250µm
-	-	224µm
212µm	No.70	212µm
-	-	200µm
180µm	No.80	180µm
-	-	160µm
150µm	No.100	150µm
-	-	140µm

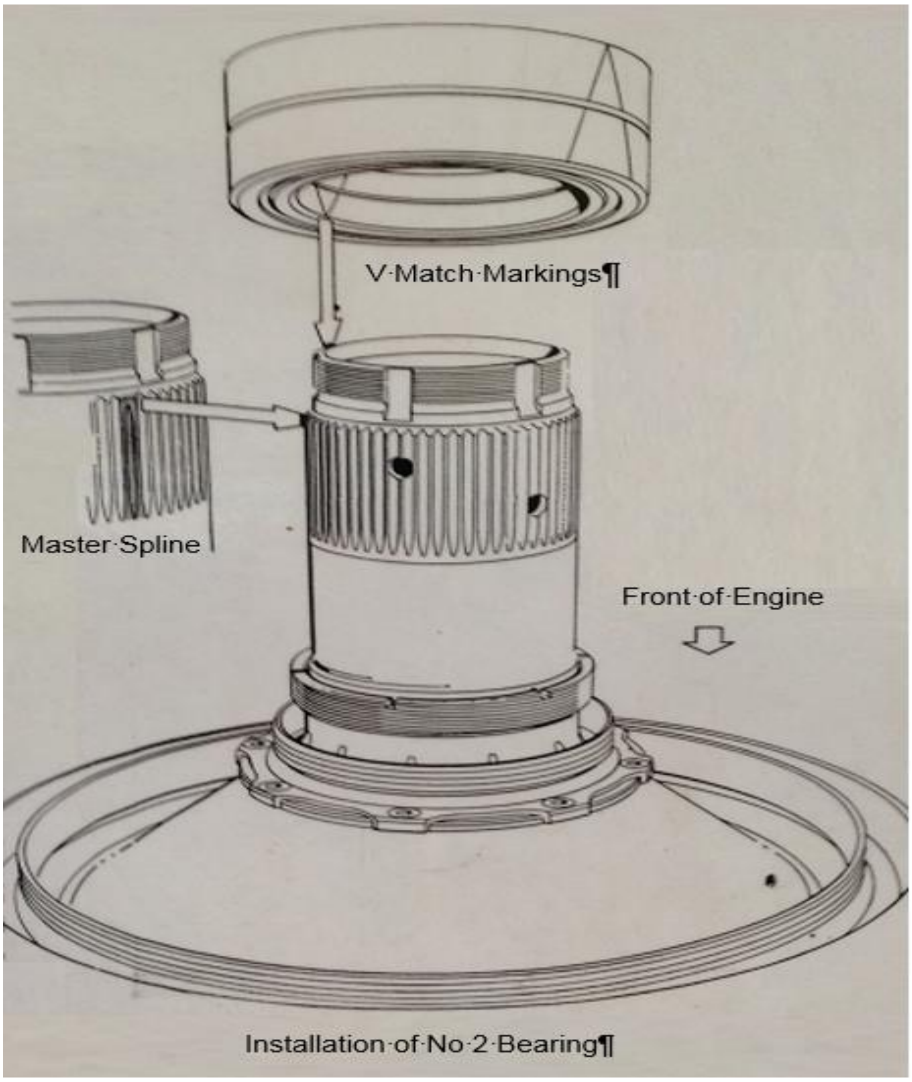
APPENDIX 6 – No 2 Bearing Assembly and Installation Verification Report

No 2 Bearing Assembly & Installation Verification Report

PI examined the No 2 double bearing (matched pair) and confirmed that the bearing had been correctly assembled and installed into the GG at engine build Aug/Sept ’14. (We were unable to inspect the full bearing at the Bulk Strip stage as the outer races were stuck in the bearing housing due to distortion resulting from the bearing failure. The bearing was sent to SKF for metallurgical and failure analysis, where SKF had to cut the housing open.)

The following gives an overview of the process verifying the bearing correct match-marked assembly, order/orientation and installation. (Note that SKF in their Report mistake the bearing assembly model/design and orientation, and also confuse the front and rear bearings.)

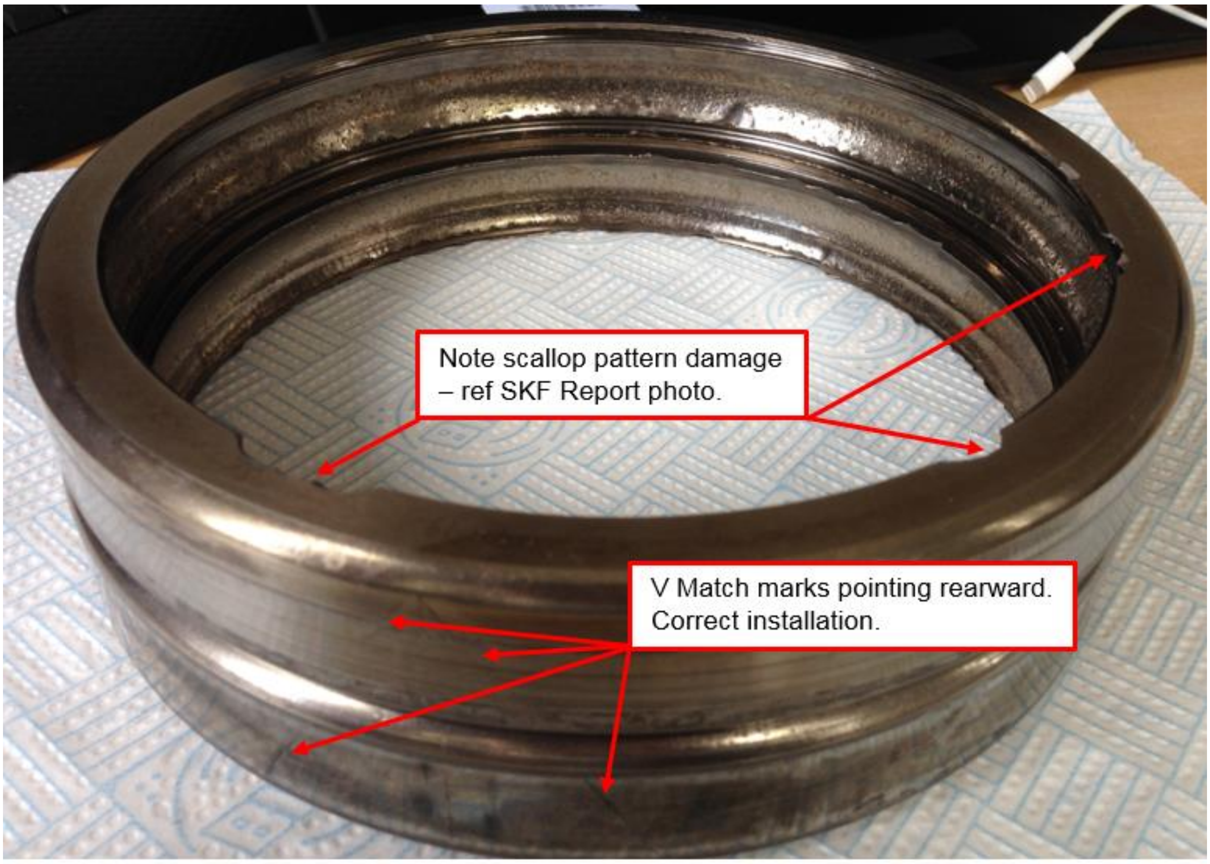
The photo below from OEM/Alba Build Instruction shows an illustration of the bearing pair assembly match marking and installation orientation that was used for reference in PI’s examination, which verified the assembly, orientation and installation of the bearing as correct to specification.



The photo below from SKF Report shows the bearing assembly from the rear side, as received at SKF with the outer races stuck in the housing. SKF denote the uppermost race as the front bearing whereas it's actually the rear bearing. Note the damage scallops on the race face for reference further below.

***Figure 3** – Housing 'as received' with both outer rings in place. The Front bearing is uppermost in the photo.*

The photo below shows the outer races removed from the housing. The V match mark is visible spanning across the two races, pointing in a rearward direction per the installation drawing further above, albeit the rear race V is somewhat faded due to rotation scoring of the race in the housing during the bearing failure. (Again note the damage scallops on the rearward face of the rear bearing, as in above photo, demonstrating that the races were installed correctly. Also note the ball grooves worst abrasion damage being at the front side of the races due to the LP Compressor forward thrust.)

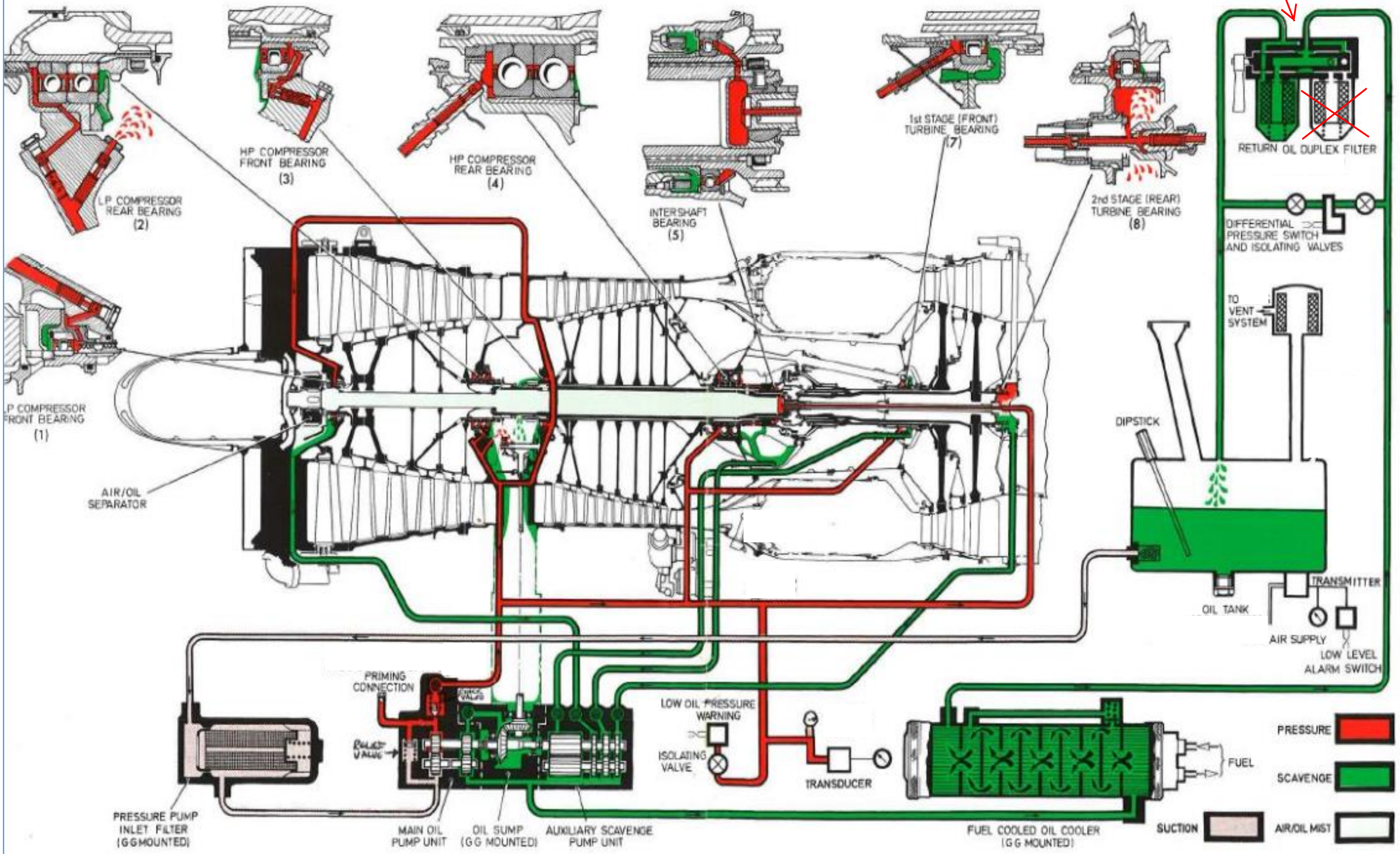


The photo below shows the V match marks on the outer races more clearly. Circumferential scoring is also visible particularly on the diameter of the rear race (top) caused by rotation of the race in the housing during the bearing failure process.

Photo below shows the two inner races (split pair). The V match mark is clearly visible spanning across the four half-races. PI witnessed the removal of the races from the GG as being in this correct order and orientation with the V pointing in a forward direction per the installation drawing further above, thus confirming the bearing assembly and installation were correct to specification.

APPENDIX 7 – Olympus Lube Oil System Diagram

Note that Hyrdro's Lube Oil System has a single Return Filter, not duplex.

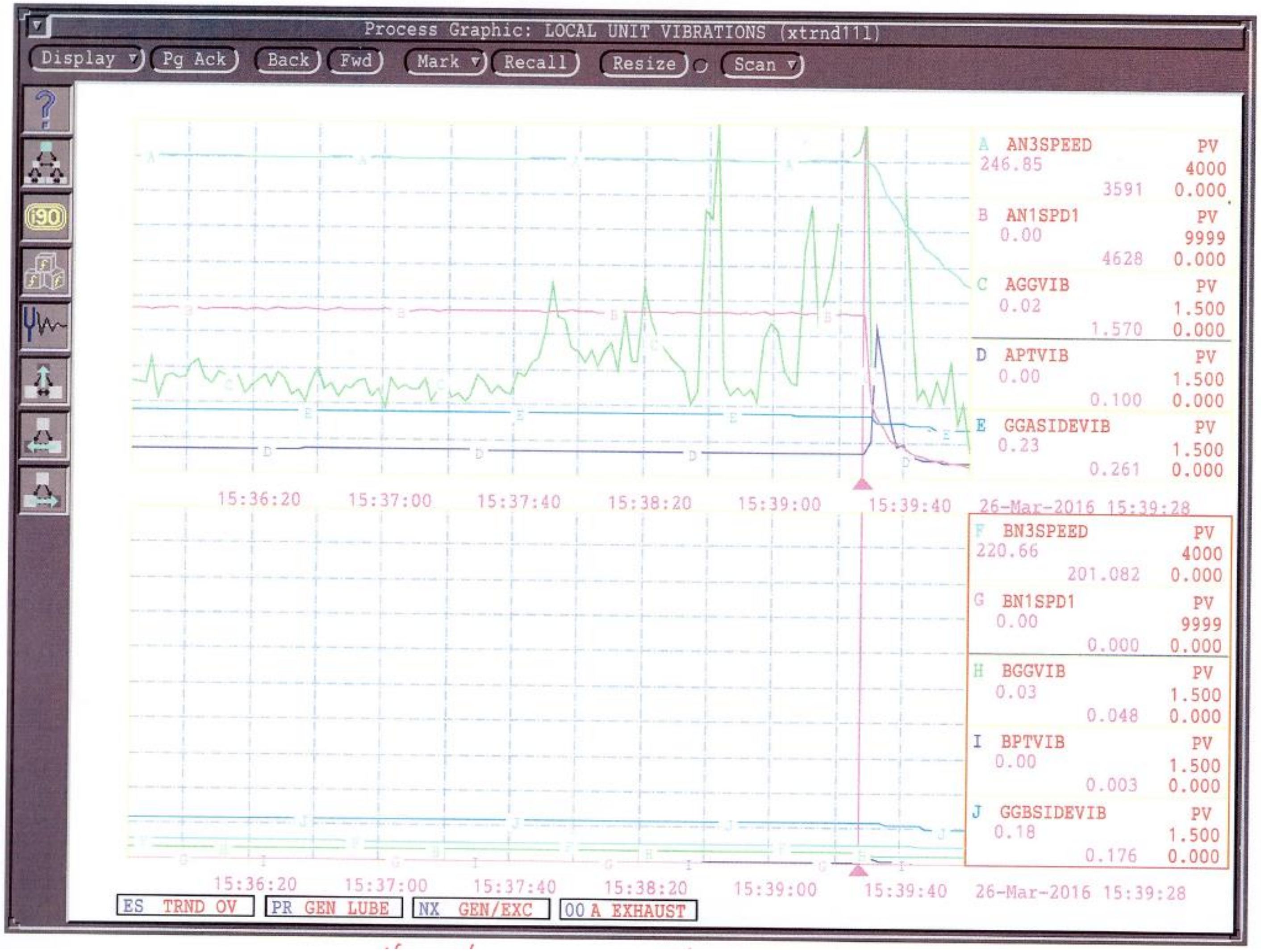


Typical Olympus Gas Generator Lube Oil System Diagram

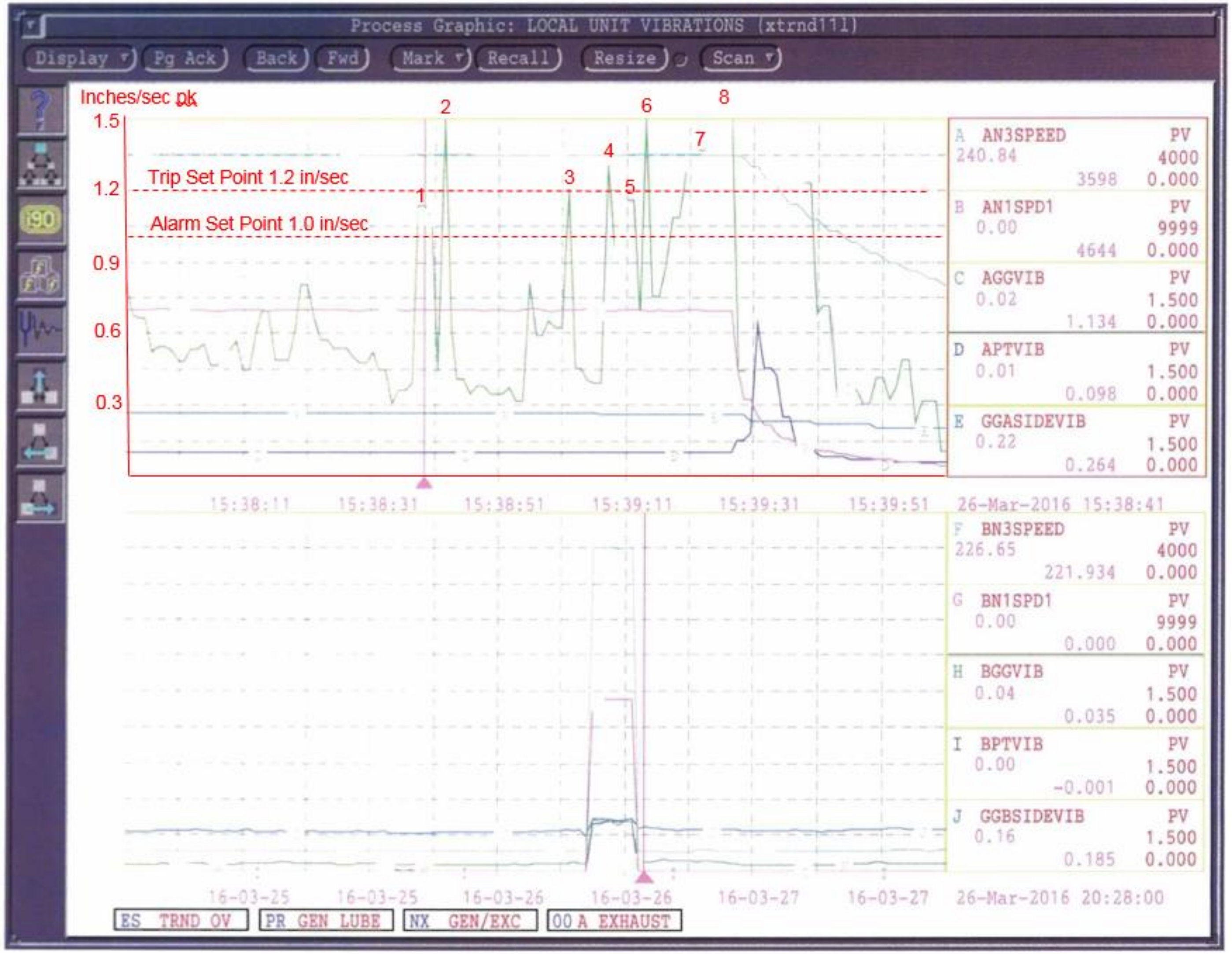
APPENDIX 8 – GG Vibration Trend and Operation Events Log

Analysis of GG Vibration Trend 26 March 2016

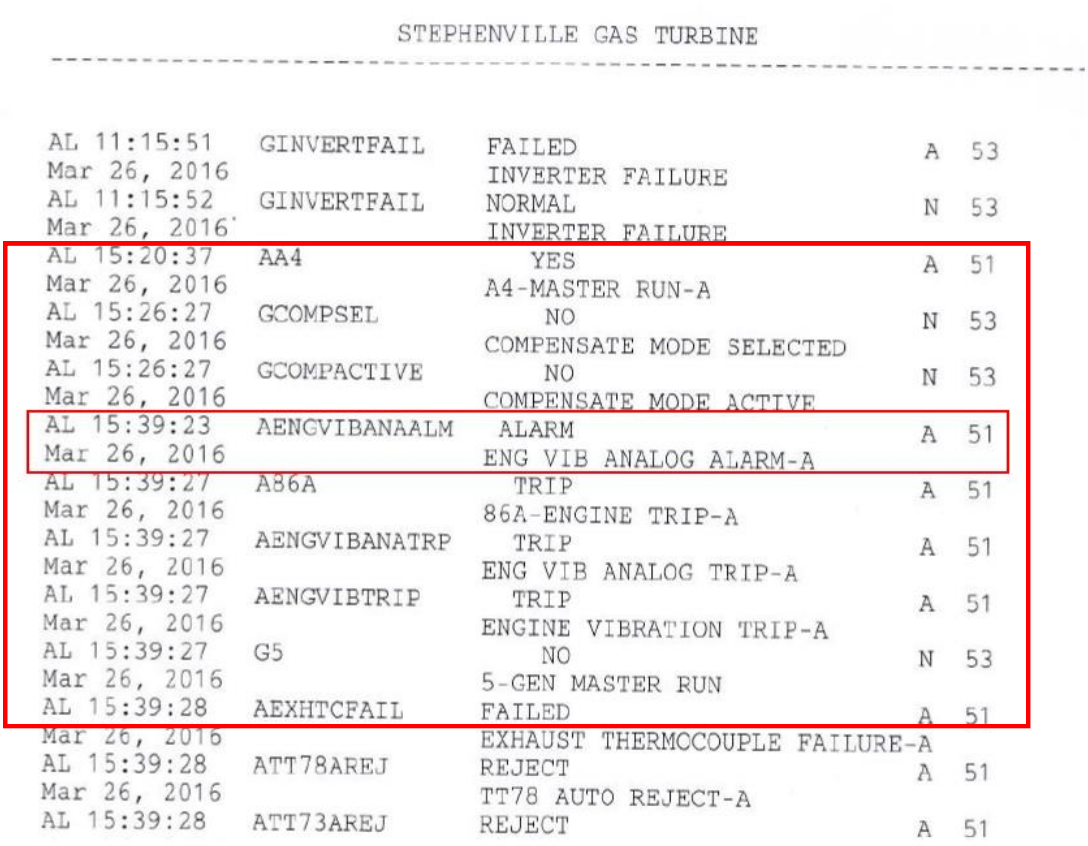
The Trend Graph below shows the GG vibration running steady at approx. 0.37 inches/sec peak, then suddenly increasing (start of No 2 bearing mechanical failure) and becoming erratic from approx. 15:37:40 onwards, with several high amplitude spikes before finally tripping at 15:39:27 (ref Turbine Events Log) at 1.570 inches/sec peak.



The Trend Graph below shows the high vibration and spikes in better resolution than does the above Graph. All the numbered spikes have amplitudes above the high vibration alarm set point 1.0 in/sec peak. Spikes 2, 4, 6, 7 and 8 are above the high vibration trip set point 1.2 inches/sec peak. Yet, there is only one alarm recorded in the Turbine Events Log at 15:39:23 which is only four seconds before the turbine finally tripped and appears to have been part of the same/final spike event. The turbine should have tripped at Spike 2 at approx. 15:38:45 (assuming there is no time delay in the trip function).



Extract from Hydro Turbine A Events Log Printout 26 March 2016



```
                         STEPHENVILLE GAS TURBINE
-------------------------------------------------------------------------

AL 11:15:51    GINVERTFAIL     FAILED                             A  53
Mar 26, 2016                   INVERTER FAILURE
AL 11:15:52    GINVERTFAIL     NORMAL                             N  53
Mar 26, 2016                   INVERTER FAILURE
AL 15:20:37    AA4               YES                              A  51
Mar 26, 2016                   A4-MASTER RUN-A
AL 15:26:27    GCOMPSEL           NO                              N  53
Mar 26, 2016                   COMPENSATE MODE SELECTED
AL 15:26:27    GCOMPACTIVE        NO                              N  53
Mar 26, 2016                   COMPENSATE MODE ACTIVE
AL 15:39:23    AENGVIBANAALM    ALARM                             A  51
Mar 26, 2016                   ENG VIB ANALOG ALARM-A
AL 15:39:27    A86A              TRIP                             A  51
Mar 26, 2016                   86A-ENGINE TRIP-A
AL 15:39:27    AENGVIBANATRP     TRIP                             A  51
Mar 26, 2016                   ENG VIB ANALOG TRIP-A
AL 15:39:27    AENGVIBTRIP       TRIP                             A  51
Mar 26, 2016                   ENGINE VIBRATION TRIP-A
AL 15:39:27    G5                 NO                              N  53
Mar 26, 2016                   5-GEN MASTER RUN
AL 15:39:28    AEXHTCFAIL      FAILED                             A  51
Mar 26, 2016                   EXHAUST THERMOCOUPLE FAILURE-A
AL 15:39:28    ATT78AREJ       REJECT                             A  51
Mar 26, 2016                   TT78 AUTO REJECT-A
AL 15:39:28    ATT73AREJ       REJECT                             A  51
```

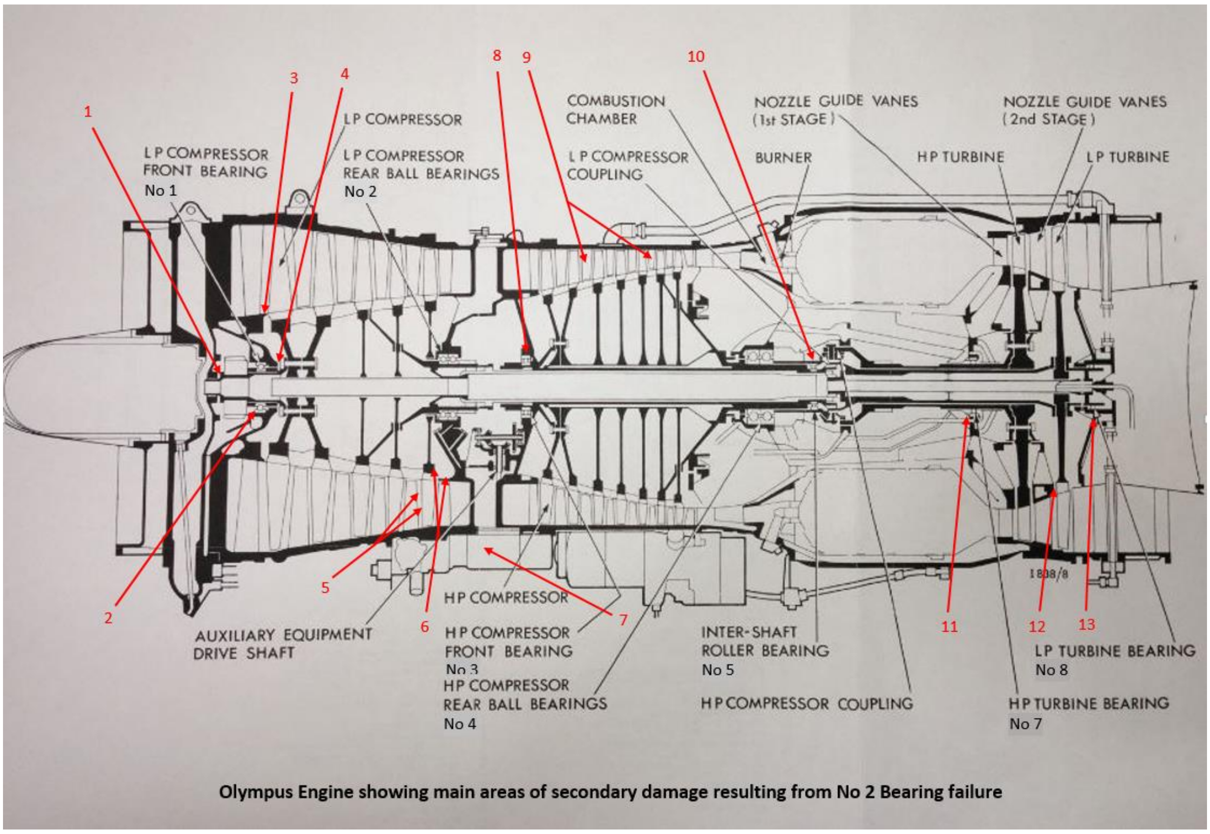
APPENDIX 9 – Secondary Damage Report

Olympus GG 202204 Secondary Damage Report

This photo report describes the main areas of secondary damage found throughout the GG resulting from the No 2 bearing failure. In accordance with turbine reporting convention the areas are described in sequence from front to rear of the GG.

Photos of Secondary Damage Areas

Photo numbers refer to damage area numbers shown in the Olympus sectional illustration below. Illustrations of the damage areas, numbered as per respective photos, showing the location and sectional details of the areas are contained in the Illustrations Section, starting on page 13.



Olympus Engine showing main areas of secondary damage resulting from No 2 Bearing failure

Photo 1 below: shows LP Compressor shaft front end labyrinth seal bush damage from running contact with the shaft lock nut.

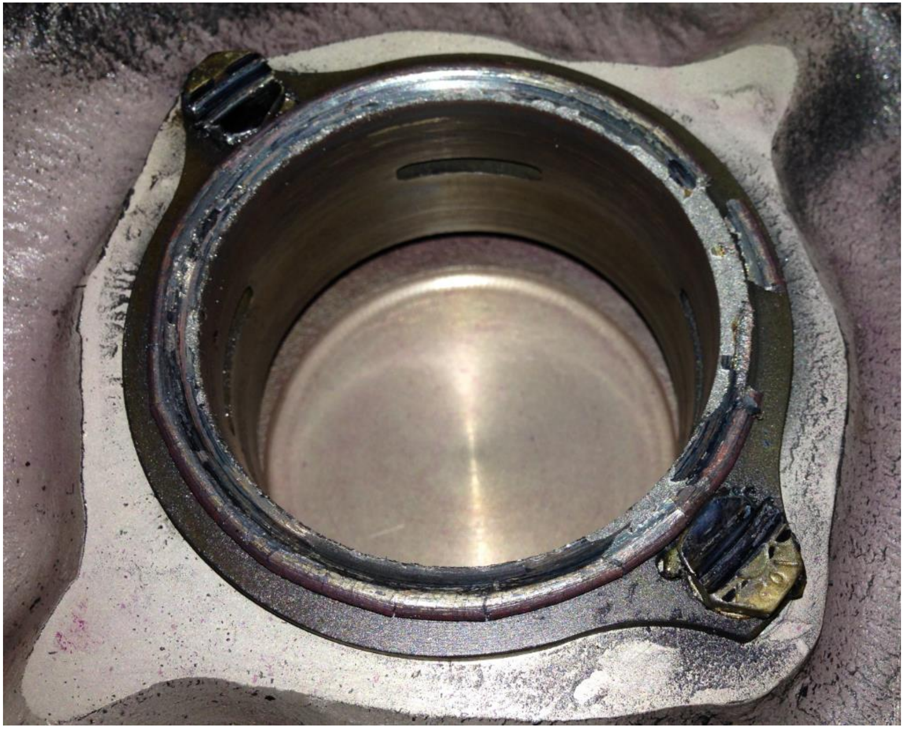


Photo 2 below: shows matt micro pitted surfaces of No 1 bearing rollers caused by lube oil system contamination. Also shows larger corrosion pitting.

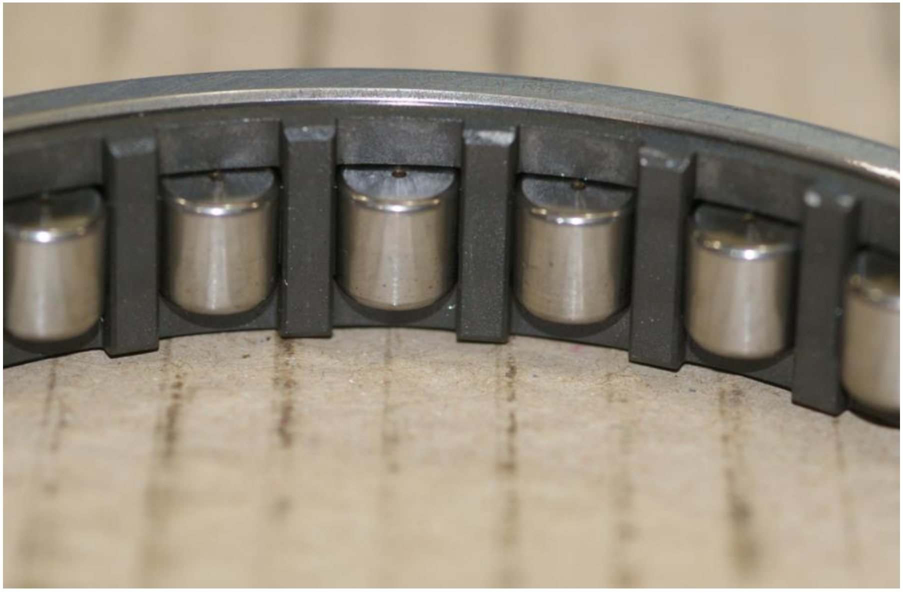


Photo 3 below: shows LP Compressor 1st stage blades platforms front edge deep abrasion metal loss (to flush with disc) from running contact with Inlet Guide Vanes platform segments.

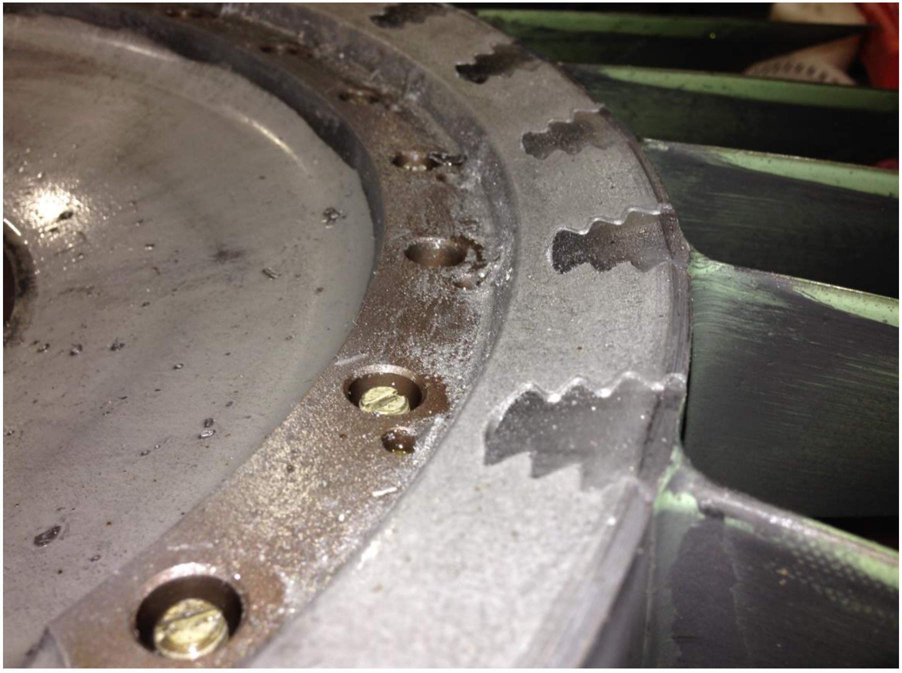


Photo 4a below: shows No 1 bearing housing rear face deep abrasion metal loss from running contact with the LP Compressor Rotor 1st/2nd stage discs retaining bolts.

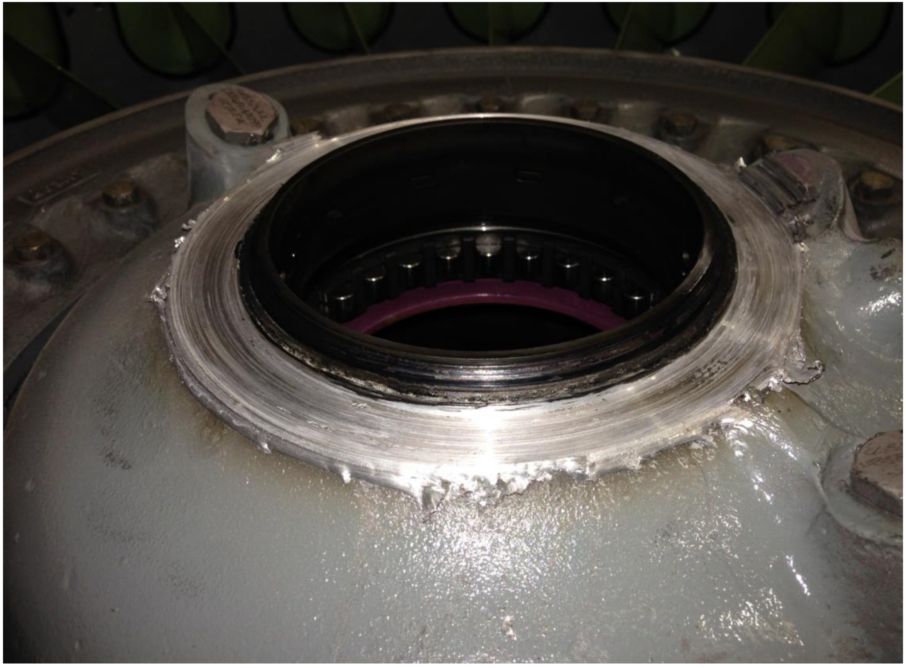


Photo 4b below: shows the LP Rotor 1st/2nd stage discs retaining bolts that caused the bearing housing damage in the photo above. Aluminium pick-up shows on two prominent bolts.

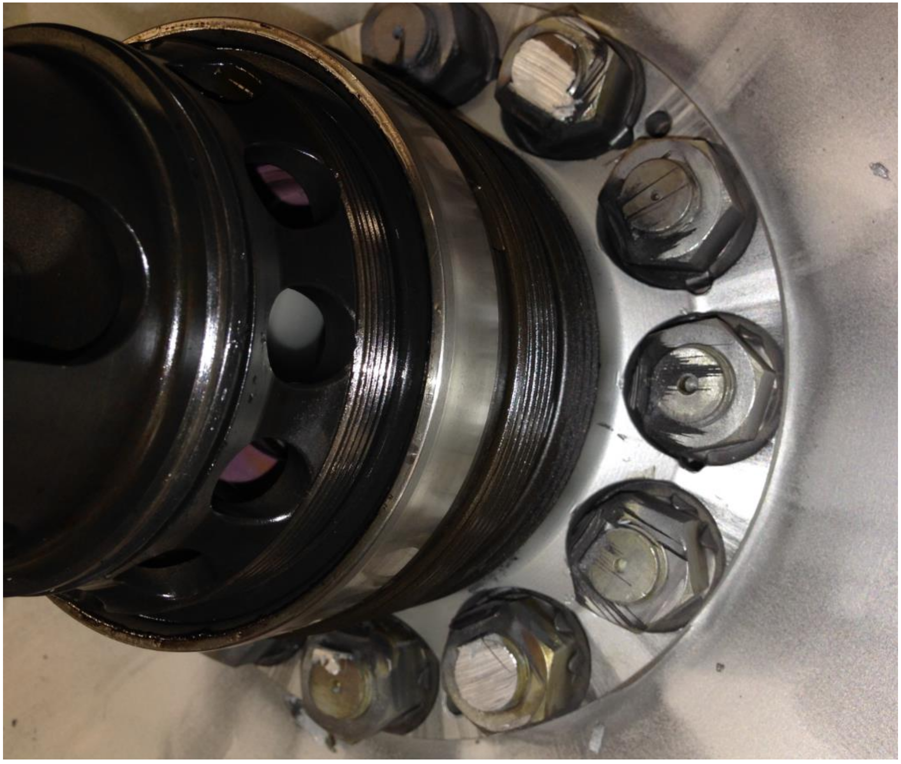


Photo 5a below: shows LP Compressor Rotor 5th stage blades heavy damage from running contact with stator guide vanes. Deep rotational scoring is also seen on the inter-stage disc from running contact with the IGV's tips due to the rotor having dropped as a result of the No 2 bearing damage.

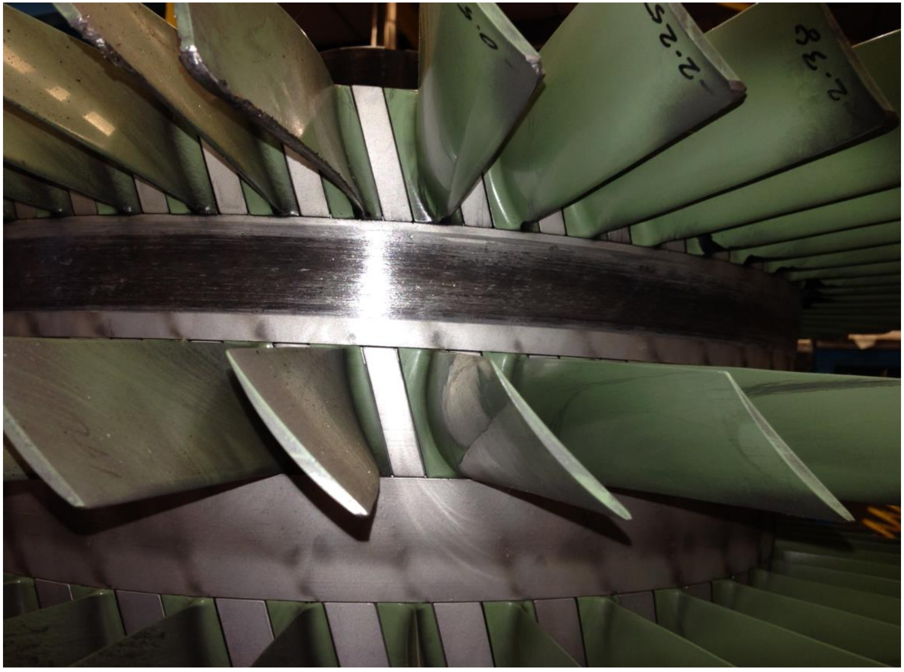


Photo 5b below: shows LP Compressor 5th stage stator vanes damage corresponding with the blades damage shown in the photo above. The open gap at the top of the vanes slot shows that the LP Compressor casing has distorted at that area due to running contact force.

Photo 6a below: shows LP Compressor 5th stage disc rear side & bolting damage caused by two released stud/nut heads that had snapped off due to stress at the No 2 bearing housing resulting from the bearing failure.

Photo 6b below: shows Intermediate Casing damage also caused by two the two released stud heads. The two broken studs can be seen just above the removed cover at bottom.

Photo 6c below: shows a close-up of the two broken studs.

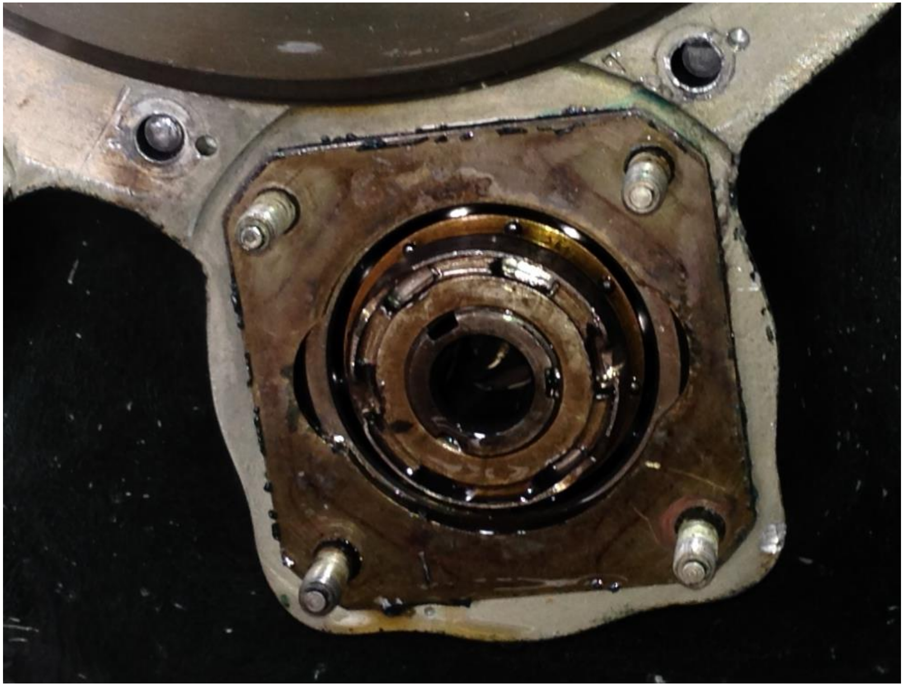


Photo 7 below: shows scavenge lube oil pump gears housing diameter deep abrasion metal loss caused by debris from No 2 bearing damage. (The pump was still operational.)

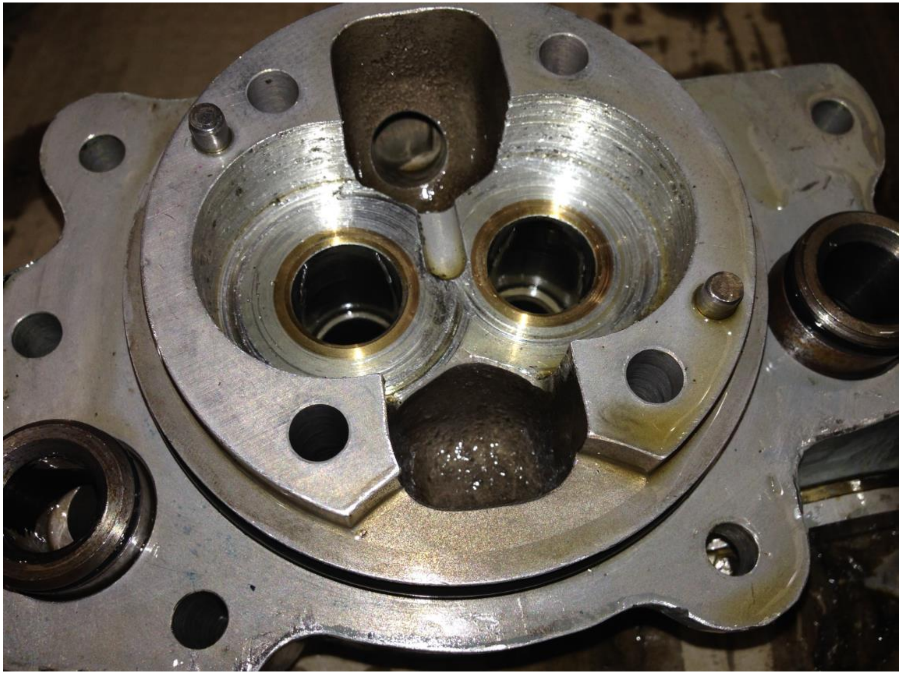


Photo 8 below: shows matt micro pitted surfaces of No 3 bearing rollers caused by lube oil system contamination, also visible.

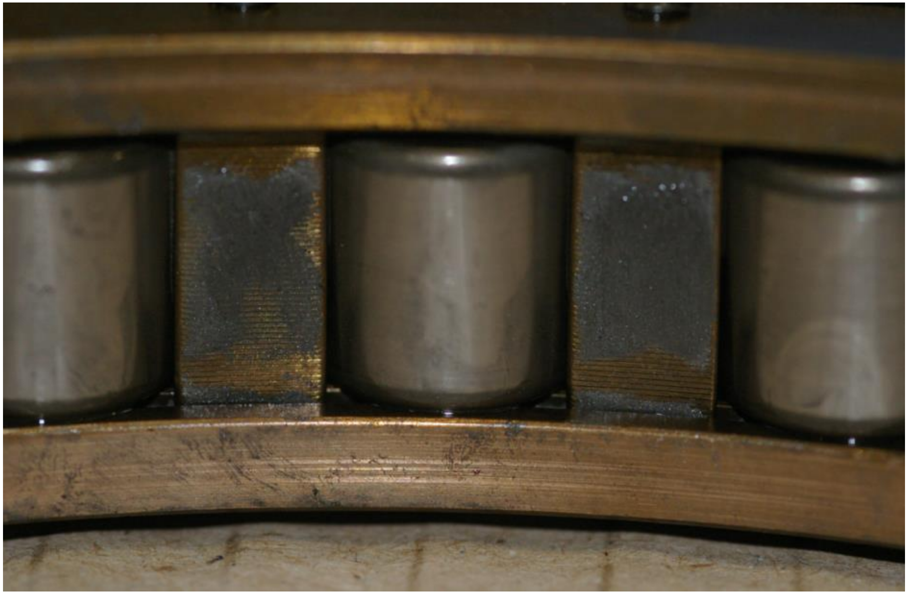


Photo 9 below: shows HP Compressor Rotor blades impact damage caused by debris from LP Compressor front end damage released into the compressor air stream. The damage is typical of that seen throughout the HP Compressor stages.

Photo 10a below: shows matt micro pitted surfaces of No 5 bearing rollers caused by lube oil system contamination. Also shows larger corrosion pitting, along with metal flake fragments from oil thrower damage.

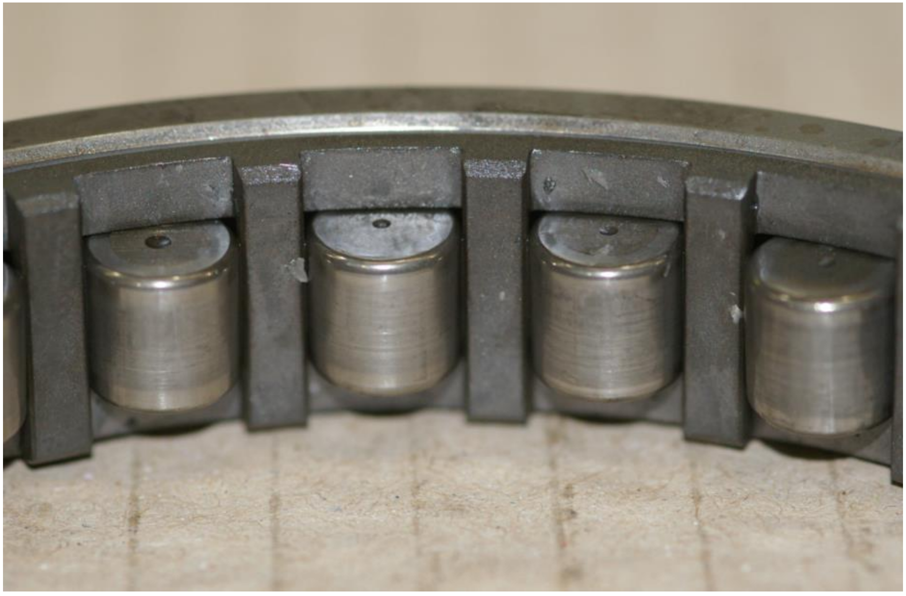


Photo 10b below: shows No 5 bearing oil thrower high friction/heat and crack initiation damage from running contact with the LP Compressor Rotor drive coupling hub.

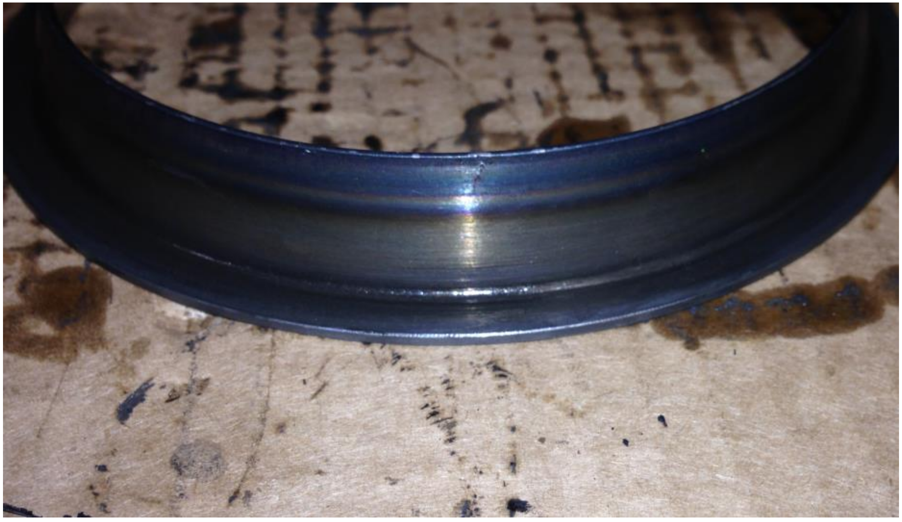


Photo 10c below: shows LP Compressor Rotor drive coupling hub damage corresponding with the damage shown in the photo above.

Photo 11 below: shows matt micro pitted surfaces of No 7 bearing rollers caused by lube oil system contamination. Also shows larger corrosion pitting.

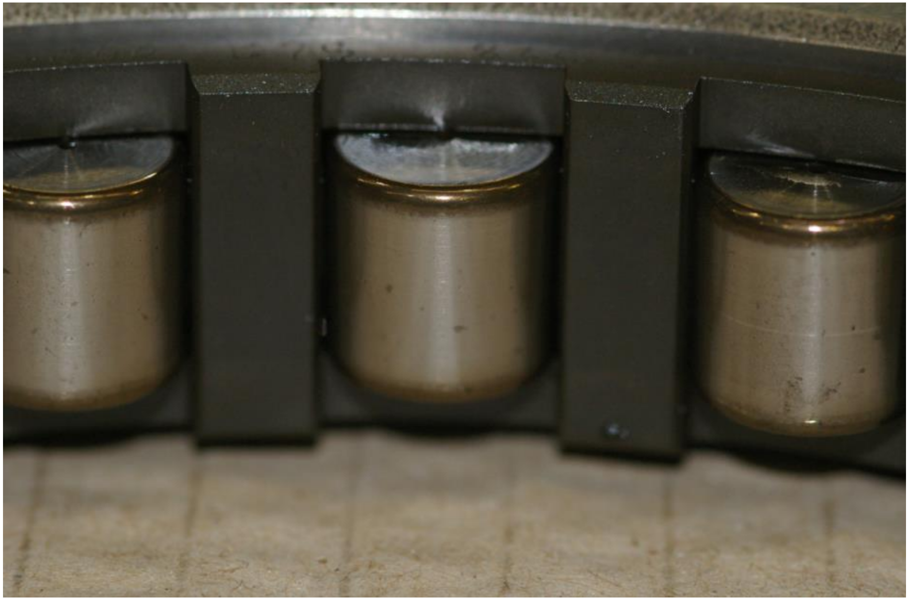


Photo 12a below: shows LP Turbine Nozzle Guide Vanes segments retaining bolts heads damage from running contact with Turbine Rotor blades fir tree roots lock tabs. Also shows examples of minor aluminium melt spatter impingement on the vanes.

Photo 12b below: shows LP Turbine Rotor blades fir tree roots lock tabs damage corresponding with the damage shown in the photo above.

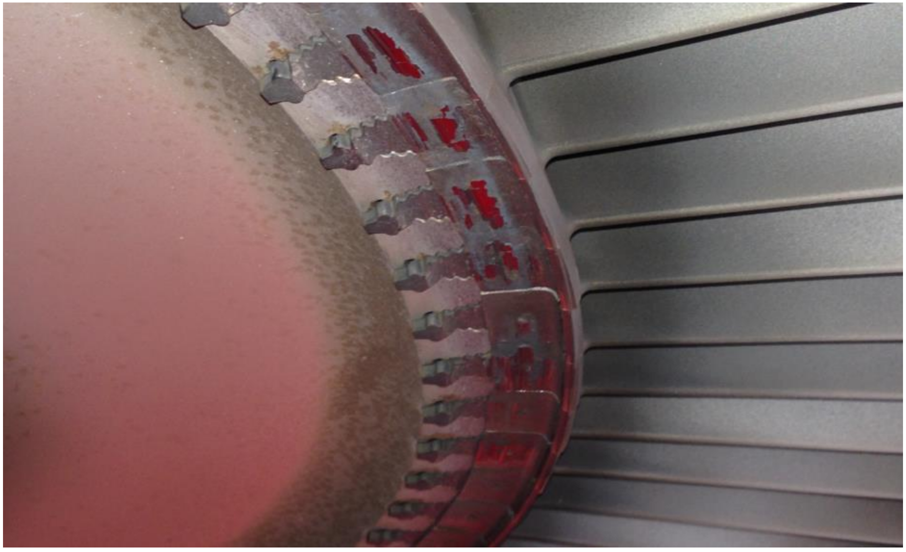
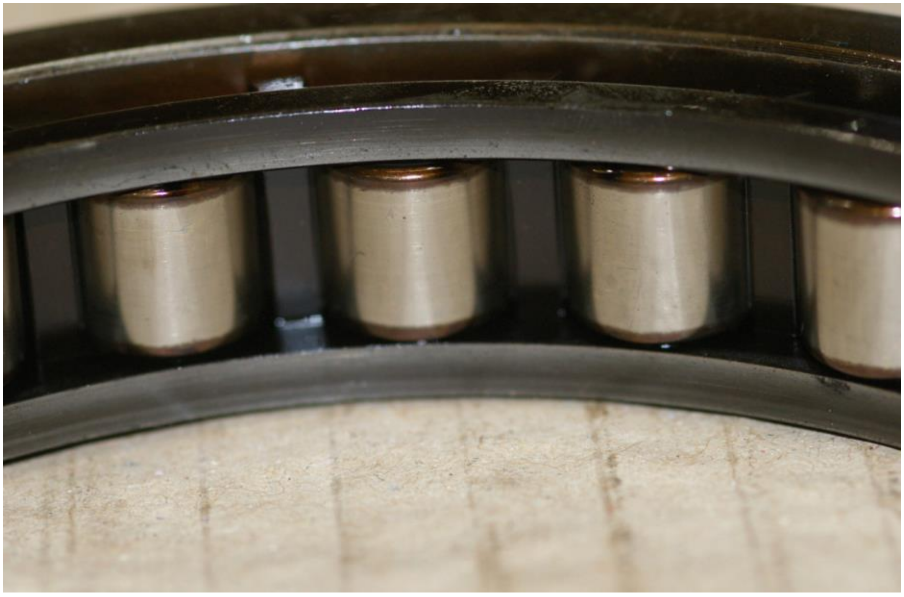


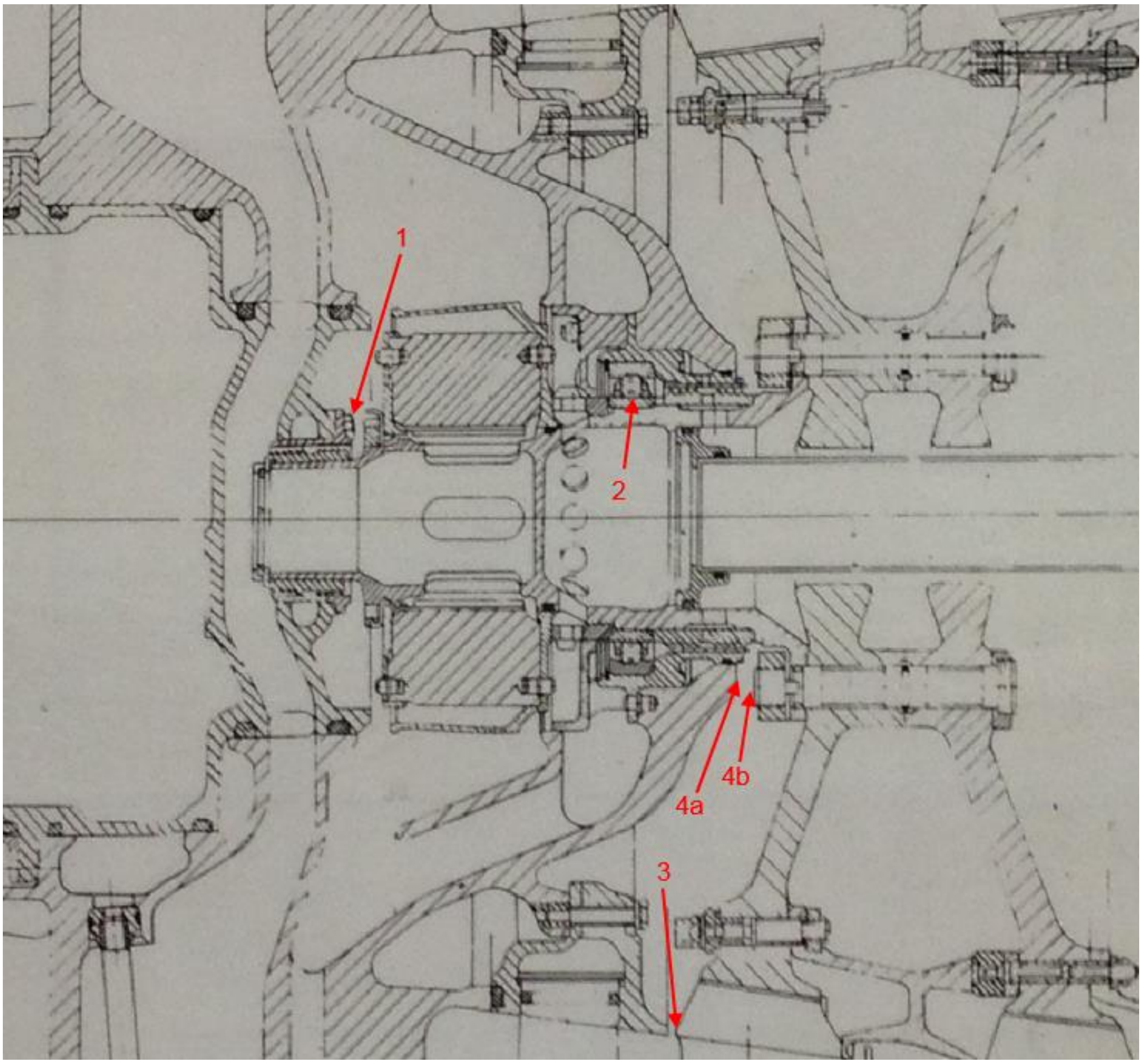
Photo 13 below: shows matt micro pitted surfaces of No 8 bearing rollers caused by lube oil system contamination. Also shows larger corrosion pitting.



It was also observed during strip inspections that re-solidified aluminium melt spatter had impinged on the turbine section nozzle guide vanes and rotor blades. This had resulted from LP Compressor front end damage debris released into the compressor air stream and carried through the combustion system.

Photo 14 below shows a typical example of the aluminium melt spatter found on the turbine blades.

GG Illustrations Showing Secondary Damage Areas in Detail



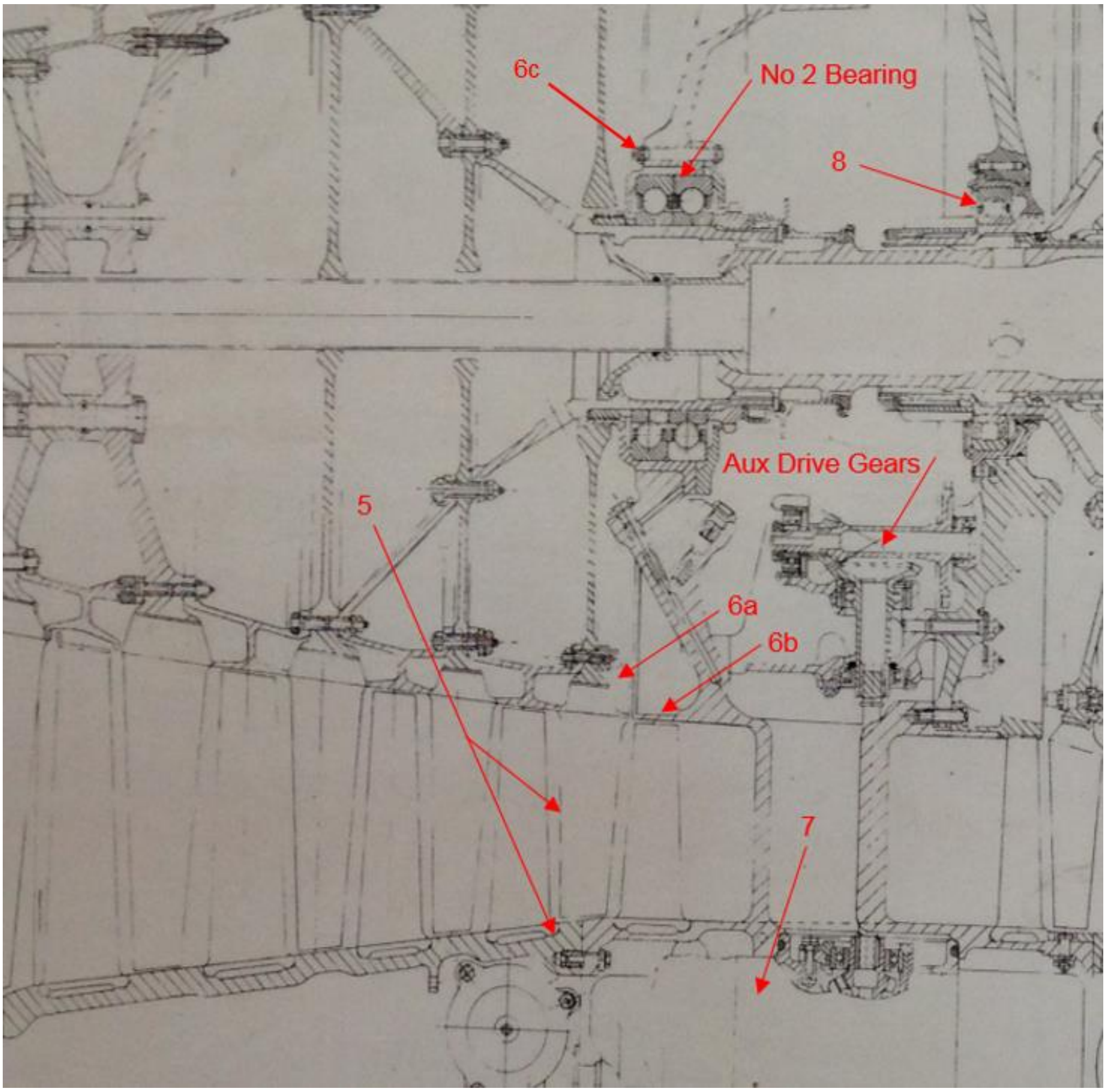
1 LP Compressor Rotor shaft front labyrinth seal bush retaining bolts.

2 No 1 Bearing (roller type).

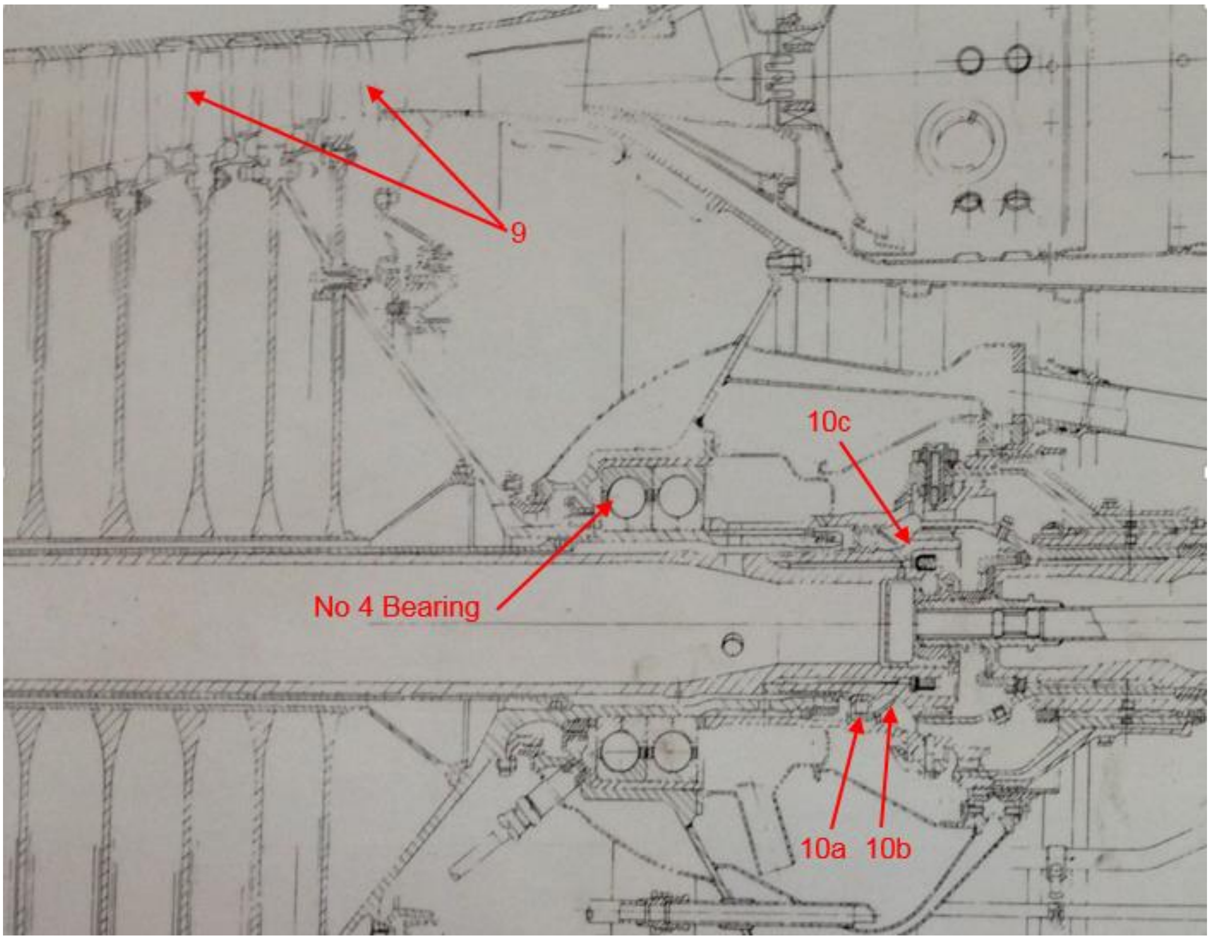
3 LP Compressor Rotor 1st stage blades platforms.

4a No 1 Bearing Housing (part of Intake Casing) rear face

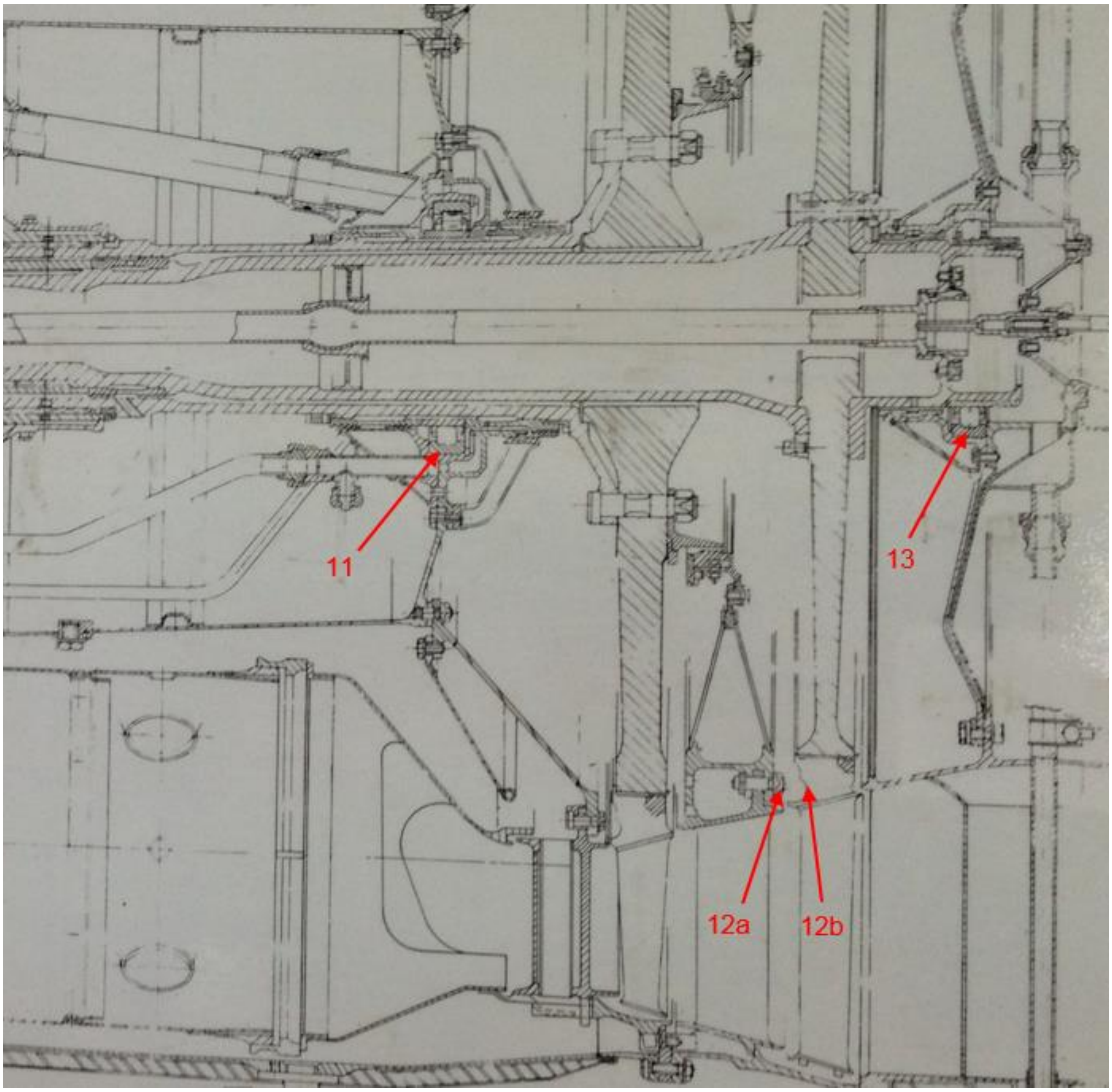
4b LP Compressor Rotor 1st/2nd stages discs retaining bolts.



5a	LP Compressor Rotor 5th stage blades (and 4th/5th inter-stage disc)
5b	LP Compressor Stator 5th stage vanes and dovetail slot/compressor casing)
6a	LP Compressor Rotor 5th stage disc and retaining bolts.
6b	Intermediate Casing.
6c	No 2 Bearing Housing studs (two broken).
7	Scavenge lube oil pump gears housing.
8	No 8 Bearing (roller type)



9	HP Compressor Rotor blades.
10a	No 5 Bearing (roller type)
10b	No 5 Bearing oil thrower.
10c	LP Compressor Rotor drive coupling hub.



11 No 7 Bearing (roller type).

12a LP Turbine nozzle guide vanes disc/retaining bolts.

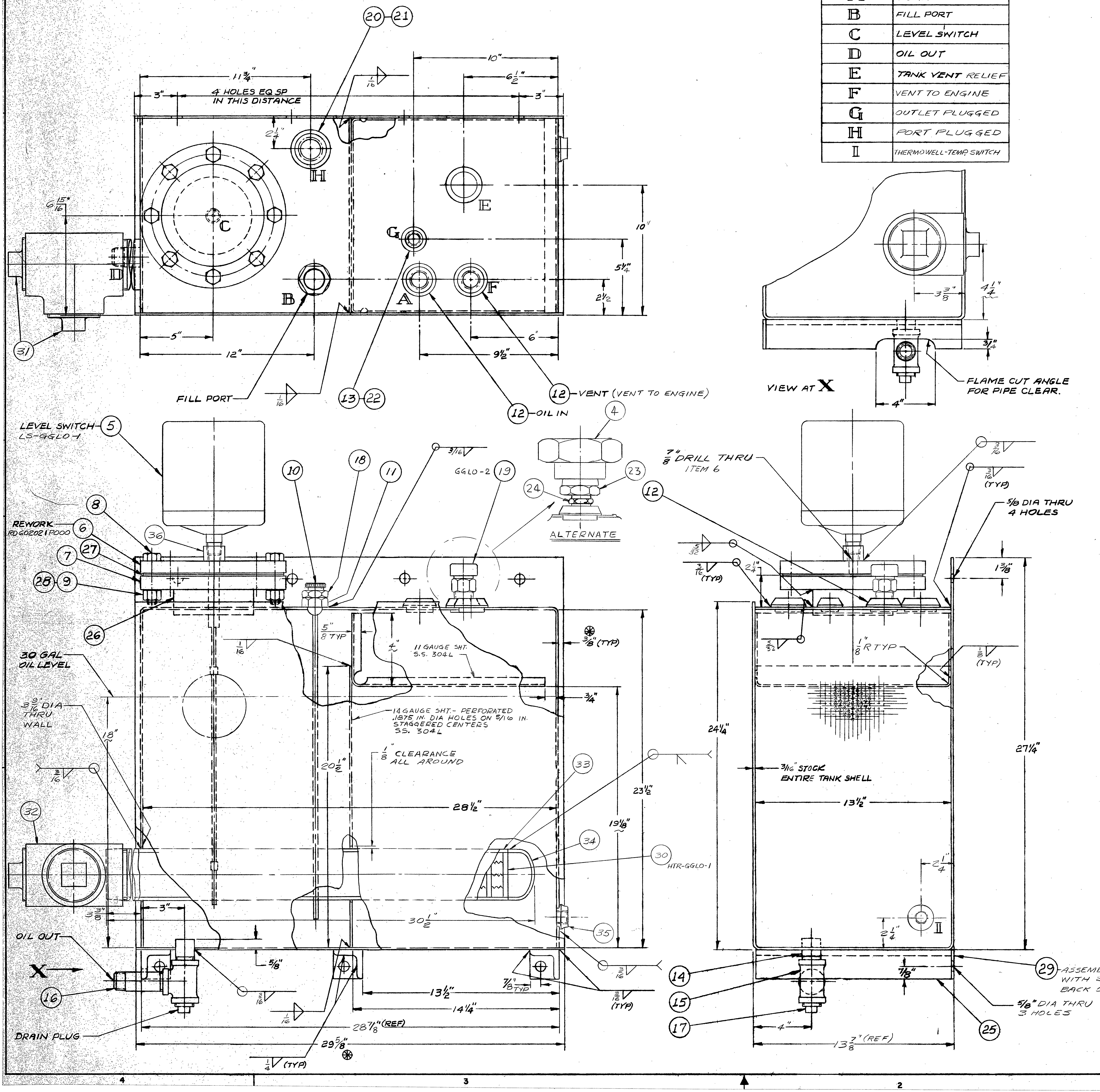
12b LP Turbine Rotor disc fir tree roots lock tabs.

13 No 8 Bearing (roller type)

APPENDIX 10 – Lube Oil Tank Design Drawing

ENGRG ORDER NUMBER	CHG. LTR. DATE	REVISIONS DESCRIPTION	APPR.

CONNECTION	
A	OIL IN
B	FILL PORT
C	LEVEL SWITCH
D	OIL OUT
E	TANK VENT RELIEF
F	VENT TO ENGINE
G	OUTLET PLUGGED
H	PORT PLUGGED
I	THERMOWELL-TEMP. SWITCH



⊛ LIP AT ENDS OF TANK MAY BE OMITTED AT VENDORS OPTION 28 1/2" INSIDE TANK LENGTH NOT TO CHANGE

ALL WELDS TO BE STRUCTURALLY SOUND

TOLERANCE ± 1/16" UNLESS OTHERWISE SPECIFIED

TANK TO BE FREE OF LEAKS

TANK SHELL MATERIAL:
304L STAINLESS STEEL

SHELL CORNERS SHOWN AS BENT (BY BRAKE OR OTHER MEANS) MAY BE MADE AS FILLET WELDED SEAMS AT SUPPLIERS OPTION

495033
SHEET

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DTR.	JLL	10-14-74
CKR.	HRS	11-18-74
SUPV.		
MET.		
MFG.		
ENGR.	HRS	11-18-74
ENGR.	HW	11/27/74
ENGR.		11/27/74

POWER SYSTEMS
CURTISS-WRIGHT CORP., WOOD-RIDGE, NEW JERSEY, U.S.A.

TANK ASSEMBLY,
GAS GENERATOR LUBE OIL
OLYMPUS

CODE IDENT. NO. 66640
SIZE F
495033
SCALE 3/8":1"
UNIT WT.
SHEET

APPENDIX 2 –

ALBA POWER LIMITED REPORT RELATED TO THE ROOT CAUSE FAILURE ANALYSIS OF HARDWOODS

Root Cause Analysis
Olympus S/N 202205
Issue 3

Customer: Newfoundland Hydro

Date: 09 January 2016

Project Number: Alba 5402

Alba Power Ltd
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sales@albapower.com
www.albapower.com

Quality Certification
ISO 9001:2008
ISO 14001:2004
OHSAS 18001:2007
Scotland

Table of Contents

Note:

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1 Introduction

During operation, Olympus S/N 202205 was shut down and investigations identified significant damage to the combustion cans.

Following notification of the shutdown, Alba Power mobilised a field service engineer and the necessary replacement parts to allow a combustion can replacement to be carried out on site. However during the initial scope it became apparent that the extent of damage to the gas turbine was out with a field repair capability (damage noted to the turbine section). Full details of this works can be found in Alba Power 5166 Field Service Report.

The extent of damage identified resulted in the gas turbine being returned to Alba Power for full overhaul and investigation.

2 Previous Borescope inspection December 2015

During a routine inspection (December 2015) the gas turbine underwent borescope inspection of the hot end component, this confirmed the gas turbine to be in a reasonable condition with no significant defects noted.

During the inspection a potential crack was noted around the interconnector. In addition significant carbon build up was noted on the burner/combustion chambers.

The level of deterioration noted over the next 2 months of operation would not occur under normal operating circumstances and was unforeseen.

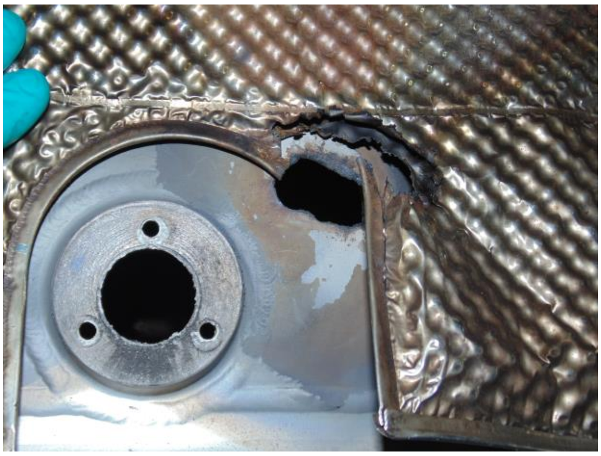
Carbon build up on Fuel Nozzle

Crack at No6 Interconnector

3 Receipt Inspection

Following removal, the gas turbine was consigned to Alba Power's overhaul facility in Aberdeen, Scotland. The gas turbine was received and inducted into the overhaul facility on 03 August 2016.

During the receipt inspection, significant damage was noted to the external combustion casings and associated heatshields.

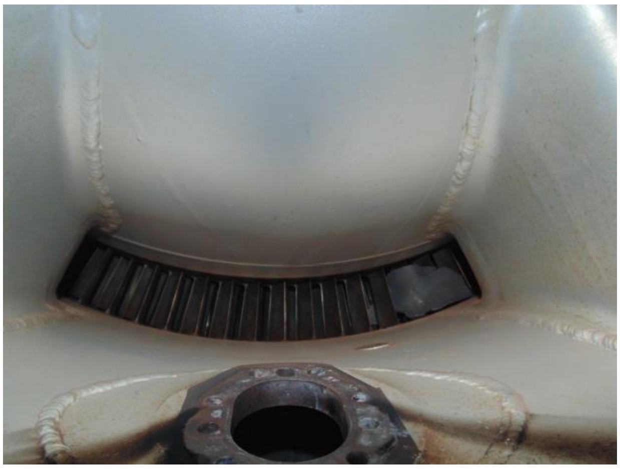
	
Holed section of heat shield and combustion chamber	Holed section of combustion chamber

Following receipt inspection the gas turbine was progressively dismantled to the main assemblies to allow further inspection.

4 Bulk Strip Review

During bulk strip, it was noted that the failed combustion chamber and associated air intake snout and burner was not fitted, however further damage to the remaining combustion chambers and surrounding components was noted, as detailed below.

Component	*Damage noted*
Combustion chambers	Material Loss/varying levels of cracking and fretting
No 7 bearing housing	Fretting and wear
Turbine entry duct	Spatter and minor impact damage
Turbine blades	Impact damage
HP nozzle guide vanes	Impact damage

	
Material loss on adjacent combustion chamber	Fretting on No 7 bearing housing support
	
Damage and detached combustion chamber parts located at HP NGV’s	Detached material located in the delivery casing

4.1 Detailed inspection

Following completion of the bulk strip, an additional Consignment was received from Newfoundland Hydro, which included the following components from Olympus S/N 202205

- No 6 Air intake snout
- No 6 Combustion chamber
- Green Magnetic chip detector

Detailed inspection of all gas turbine components identified the following parts to be rejected from further service, as detailed.

Component	Part No	Qty	Reason for Rejection
Combustion chamber	BDD2170	5	Cracking/burning/material loss
Combustion chamber	BDC8886	1	Material loss/failed
Combustion casings	BDD2995	2	Holed/burning
Heatshields	BDC7449	1	Holed/burning
HP turbine blade	BDC9998/BDE4613	40	Impact damage
HP NGV	BDC8049/BDC8047	2	Impact damage
Bearing housing	BDD5218	1	Fretting

The inspection of the combustion chambers identified these to be suffering from varying degrees of cracking, resulting in complete material detachment on 2 components.

Material loss on No 7 combustion chamber

Cracking on internal surfaces

	
Impact damage on the HP turbine blades	Fretting on LP blade outer shrouds
	
Fretting on the TED on the HP NGV location rails	Wear on the air intake snouts

In addition to the above, significant fretting was also observed on the LP turbine blade, outer shroud and the Turbine Entry Duct.

This would suggest that some level of combustion distress/excitation was present during operation.

Combustion excitation is caused by uneven or poor combustion of the fuel within the combustion section. Fuel can combust out with the desired combustion area and result in addition stress to the surrounding components. Minor excitation would be difficult to detect and only more sever excitation would be identified potentially through the spreads. The most effective method to minimise this is to ensure clean fuel is used, and the fuel system/controls is operating as expected.

5 Detailed analysis

Following detailed Inspection the failed combustion chamber was consigned for analysis to determine the cause of failure. This confirmed the following main points.

- The combustion can had been manufactured from suitable heat resistant material with no manufacturing defects noted
- Bluing and a black carbonaceous deposit possibly from ignition was present on the outer surface.
- The hardness results of the combustion can was typical for the material in the annealed condition.
- Microscopic examination and the hardness results indicated the material was in the annealed condition and showed no undesirable micro structural features that could have caused failure.
- Visual examination showed the presence of a hot spots in the central combustion zone where significant overheating and oxidation of the cooling strip had occurred
- Failure of the combustion can is thought to have been caused by hot spots due to flame impingement and/or overheating.

	
Combustion chamber No 6	Combustion chamber failed section

	
Combustion chamber No 6	Inner flare burning
	
Inner flare burning	Failed front section

6 Discussions

As the burner was unavailable for review and no detailed site survey was carried out. It is possible that defects which have not been identified have caused or contributed to the premature failure of the combustion chamber.

6.1 Burners

As shown above the burner was not available for review. Due to this the burner cannot be disregarded as a potential cause of the can deterioration. Any contamination or defect in the exit nozzle could have affected the flame pattern and caused overheating of the combustion chamber.

As noted in the previous borescope inspection (December 2015) significant carbon build up was noted. This could have a significant effect on the flame pattern, however this may also be highlighted thru the Spreads.

The 7 removed burners were found in reasonably clean condition, and it is that these were cleaned prior to being received at Alba Power. As the burners were cleaned it is impossible to know the condition when in operation. In addition during review of the site data, a step change in spread was noted therefore, it is not possible to rule out the burner as a potential cause.

Note: Operation at lower speeds will increase the possibility of carbon build up on the burners and combustion chambers. It is difficult to confirm to what extent this would occur.

6.2 Material Specification

Analysis of the combustion chamber confirmed the component to be manufactured from the correct specification material.

Due to the above it is not expected that the material spec has caused the premature failure of the combustion can.

6.3 Fuel Specification

During the workscope no fuel sample was obtained from the gas turbine therefore this remains as inconclusive.

On review of previous fuel samples provided, these appear to be within the required specification and would not be a contributing factor to the failure. However as the sample was taken 2.5 years previously, it would be recommended to increase the fuel sampling frequency.

6.4 Overheating/Spreads

During review, overheating was apparent on a number of the components within the gas turbine suggesting that these were subject to higher than normal operating temperatures. In addition, it was confirmed from the operator that an increase of spread from 20˚C to 40˚C was observed. The engine then ran for another 2-3 days prior to the shutdown.

A step change in the spreads (20˚C) is considered significant and indicates a change within the engine and could indicate the initial deterioration of the combustion casing or burner.

Potential causes

- Carbon build up clearing
- Blockage/flame pattern change from the burners
- Component movement within the turbine

6.5 Cooling

In sufficient cooling within the combustion chambers could result in overheating of the component and subsequent failure.

During review of the individual components there was no evidence of blocked cooling holes or any restrictions, therefore this is considered unlikely.

6.6 Controls/Off engine

Throughout the combustion/turbine sections of gas turbine there is evidence of overheating and excitation.

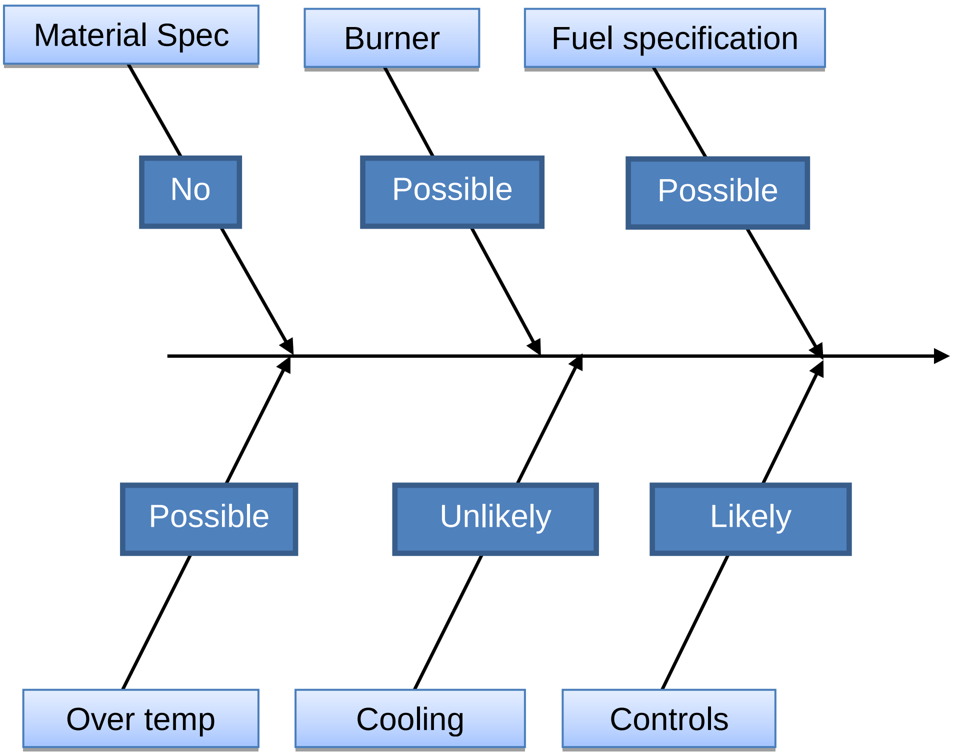
Although, fuel quality, and component condition will have an effect, the overall controls can also contribute.

The extent of damage to the combustion casings (hole burned thru) suggest that the gas turbine ran on for a period of time when the controls system should have shut down the gas turbine.

In addition to the above the fuel skid and controls can also have an effect on the fuel supply to the engine. If the fuel supply/controls is acting erratically this will affect the condition of the gas turbine.

The control system acceleration/deceleration curves can also contribute erratic fuelling of the gas turbine. If these are incorrect or not implemented, the gas turbine is vulnerable to significant fuel supply changes which can cause flame out/re-ignition. This type of running condition will increase the stress within the gas turbine and result in premature deterioration.

7 Fish bone Diagram for combustion chamber failure



Failure of combustion can

- Material Spec
- Burner
- Fuel specification
- Over temp
- Cooling
- Controls

8 Conclusion

During the above review, a number of external factors including detailed running/operational data and the No 6 burner have not been reviewed. This has limited the effect of the analysis and the likely hood that one of these factors have had an influence is high.

From the information available, the combustion chamber was found to be manufactured to the correct specification and displayed significant deterioration.

The remaining combustion chambers also displayed heavy burning and cracking indicating the complete combustion section was subjected to nonstandard operating conditions.

From the information available the most likely cause for the combustion chamber failure is the control system/Fuel supply. From Alba Power’s previous experience of the sites, it is expected that the Acceleration/Deceleration curves may be having and influence on the operation and should be reviewed.

9 Recommendations

- Review the Control system for correct setting in the acceleration/deceleration curves to ensure these are within specification.
- Due to increase in operation carry out borescope inspections on a 6 monthly basis.
- Carry out site review of fuel systems and operation.
- Review the Operating temperature/conditions of the gas turbine throughout the year.
- Initiate fuel sampling/analysis on a regular basis, if not already implemented
- Review alarm and trip setting for Spreads. Ensure these are set as per OEM.

10 Appendix I – Chemical Analysis

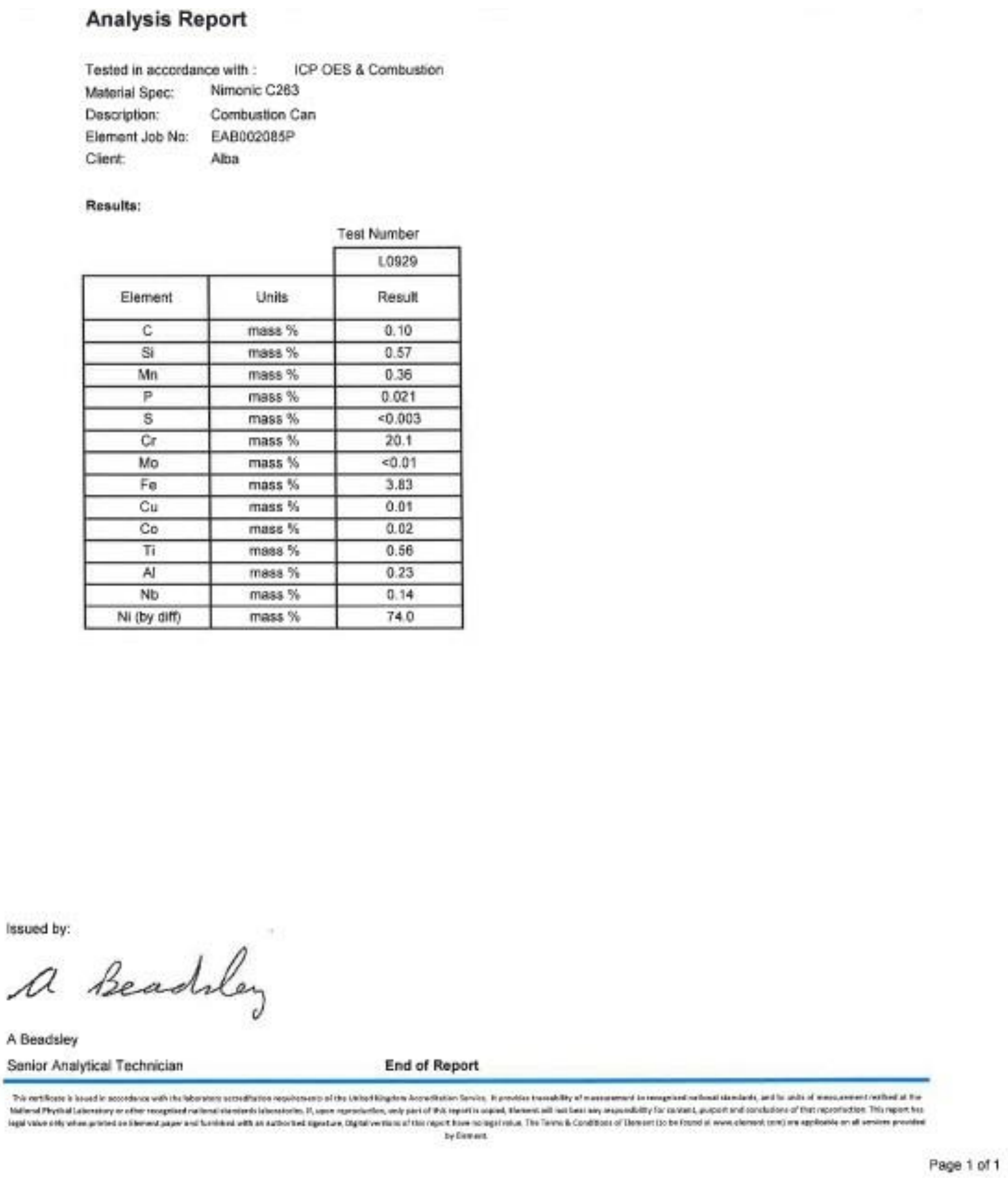
Chemical analysis was carried out on a sample taken from the sheet material at the fracture by ICP, OES and combustion.
The results obtained are recorded in Table 1.

Element	Failed Combustion Can Sample (Wt %)	Nimonic 75 Requirement*
Carbon	0.10	0.08-0.15
Silicon	0.57	1.0max.
Manganese	0.36	1.0max.
Phosphorus	0.021	0.035max.
Sulphur	<0.003	0.020max.
Chromium	20.1	18.0-21.0
Cobalt	0.02	-
Molybdenum	<0.01	-
Titanium	0.56	0.2-0.6
Aluminium	0.23	-
Iron	3.83	5.0max.
Nickel	74.0	Balance
Copper	0.01	0.5max.
Niobium	0.14	-

Table 2. Chemical Analysis Results and comparable material specification requirements.

*Requirements according to Special Metals data sheet equivalent to UNS NO6075 and ASM vol. 1 Wrought and P/M Superalloys.

The results showed the material to conform compositionally to the requirements of Nimonic 75 high nickel heat resistant alloy.
The results are recorded in the Element Certificate of Analysis C02033P/2 appended.



Analysis Report

Tested in accordance with : ICP OES & Combustion
Material Spec: Nimonic C263
Description: Combustion Can
Element Job No: EAB002085P
Client: Alba

Results:

		Test Number
		L0929
Element	Units	Result
C	mass %	0.10
Si	mass %	0.57
Mn	mass %	0.36
P	mass %	0.021
S	mass %	<0.003
Cr	mass %	20.1
Mo	mass %	<0.01
Fe	mass %	3.83
Cu	mass %	0.01
Co	mass %	0.02
Ti	mass %	0.56
Al	mass %	0.23
Nb	mass %	0.14
Ni (by diff)	mass %	74.0

Issued by:

A Beadsley

A Beadsley
Senior Analytical Technician

End of Report

11 Appendix II – Hardness testing results

Vickers hardness testing was carried out on the samples prepared for microscopic examination using a 10kgf (9.81kN) load.
The results are recorded below.

Sample	Hardness (HV)	Average(HV)
Top of can:	152; 150; 150	151
Overheated Cooling strip:	139; 148; 141	143
Melted area at rivet hole:	154; 156; 151	154

The hardness results of the combustion can was typical for the material in the annealed condition.