DURABILITY ISSUES - LYCOMING O-320, O-360 AND O-540 ENGINES FITTED TO ROBINSON HELICOPTER CO R22 AND R44 MODELS

An independent industry-supported investigation

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21 October 2019
1. Executive summary

Issue

Across the period 2016-2019, operators of piston-engine powered light utility helicopters (predominantly Robinson Helicopter Company model R22 and R44 types operated in the northern parts of Australia) began reporting an increase in the rate of premature engine cylinder failures. This loss of durability typically manifested as a low cylinder compression test result during routine maintenance – necessitating the removal and replacement of the affected cylinder. In some instances, cylinder failure had occurred within the first 100 hours of service.

Data from the Civil Aviation Safety Authority’s Defect Reporting Service (DRS) database showed compression loss was attributable to inlet or exhaust valve degradation and sealing loss. Follow-up investigation by the engine manufacturer showed related mechanisms of failure – both attributable to extended periods of high-temperature exposure and accelerated valve guide wear.

Reducing cylinder compression and valve failure, if not identified and addressed, will inevitably cause operational power loss in affected engines, with a credible potential for safety-of-flight issues should the power loss be abrupt. In recognition of these issues, in 2018 CASA issued Airworthiness Bulletins AWB-85-024 and AWB-85-025.

Investigation

Arising from the inherent thermodynamic complexity of the internal combustion engine, efforts to identify the factors contributing to the cylinder durability issues proved difficult, with an industry consultative group chaired by CASA not able to reach effective conclusions. Subsequently, the Australian Helicopter Industry Association (AHIA), the national peak body representing many of the affected operators, convened a specialist panel to undertake a focused, evidence-based investigation into the issues. This report represents a summary of that work.

Outcomes

The combustion of hydrocarbon-based aviation gasoline (avgas) is the principal source of thermal energy that powers the subject engines. Effective control and management of the rejected heat (i.e. the heat energy not utilised in the conversion to mechanical energy) is critical for the durability of engine components – most critically those exposed directly to the combustion process such as the cylinder valves, cylinder head and pistons. It follows then, that any change to the nature of the combustion system that can increase rejected heat levels may negatively affect the operational performance of these components and thus the engine as a whole. This becomes more critical when considering the operation of heavily-loaded engines in warm climactic conditions.

Examining the history of avgas supply to aviation operators in the northern parts of Australia, it was evident that over recent years, manufacturers had reduced the absolute levels of tetraethyl lead (TEL) in the avgas product, from historical levels of around 0.75 gPb/l in 2012, to around 0.38 gPb/l in 2018. To maintain the fuel’s Motor Octane Number for defence against damaging detonative combustion, other fuel chemistry variations would be expected – typically an increase in the level of aromatic hydrocarbon components. Data to support explicit conclusions in this area was not available to this investigation, with the manufacturer citing commercial sensitivity concerns.
When examining data from an instrumented R22 helicopter operating on contemporary domestic 100LL avgas, and subsequently on an imported higher lead, low aromatic content avgas, notable differences in sustained exhaust gas temperatures were observed across multiple flights. This observation was consistent with the published literature on aromatic hydrocarbon levels in automotive and aviation fuels, which show a proportionate increase in flame temperatures and exhaust gas temperatures for the higher aromatic fuels. The literature also shows that elevated aromatic hydrocarbon fuels have a greater carbonaceous deposit-forming tendency.

Given the engine durability issues at the centre of this work have stemmed from accelerated component degradation brought about through extended high-temperature exposure and abrasive deposit formation, this investigation concluded that the increase in aromatic hydrocarbon constituents within the aviation gasoline supplied to northern-Australian consumers had the potential to contribute directly to the engine durability issues in question.

This conclusion is further supported by:

- the evident concurrence between the emergence of the durability issue and changes to the fuel supply to northern-Australian consumers,
- the absence of other identified systemic issues with the potential to contribute to the durability issues in the manner observed,
- the nature of operation of the affected engines – in that they are inherently exposed to elevated temperature conditions due to:
  - operation in the northern climactic regions of Australia,
  - operation as an exclusively duct-cooled powerplant,
  - operation through extended periods of high power demand (i.e. mustering)
  - operation through extended period of low altitude operation (warmer air temperatures)

Recommendations stemming from this work include further detailed investigation of the operational combustion characteristics of aviation gasoline with reduced lead and elevated levels of aromatic hydrocarbon components. A timely examination of the continuing airworthiness implications for conventional piston-engine powered aircraft operated in conditions of higher ambient temperatures and using fuels with elevated aromatic hydrocarbon content is also warranted.
2. Introduction

This report outlines the conduct and outcomes of an investigation into a broad engine durability issue that has affected some operators of Robinson Helicopter Company R22 and R44 models operated in Australia.

In light of the emerging issue, a number of collaborative, stakeholder-supported investigations were commenced to identify the factors contributing to the problems being reported.

This report details the findings and outcomes of an investigation coordinated by the Australian Helicopter Industry Association (AHIA) - a body representing the interests of commercial rotary-wing aircraft operators in Australia - including many of the operators affected by the subject issue. This report should be read in conjunction with any publications and reports from other involved parties, including the Civil Aviation Safety Authority (CASA), Lycoming Engines (Avco Corporation) and the Robinson Helicopter Company Limited.

3. The issue

Across the period 2013 - 2018, several sources of information have independently and collectively shown an increase in the number of engines fitted to Robinson Helicopter Company (RHC) model R22 and R44 light utility helicopters requiring premature cylinder replacement as a result of below-limit compression measurements. In some instances, single or multiple cylinder removal was indicated during the first 100-hourly inspection from new [CASA, 2018-1].

In instances where the loss of cylinder compression was investigated, sealing issues were identified in either exhaust or intake valves, with damage to the valve, valve guide and valve seat faces contributing directly to the compression loss. The mechanisms associated with both exhaust and intake valve degradation were closely examined by the engine manufacturer and are detailed in the Failure Analysis section of this report.

3.1. Safety implications

At its most benign, low or deteriorating cylinder compression will typically reduce the available power from the engine and increase operating vibration and 'roughness'. Depending upon its origin however, low compression can be a precursor to more significant engine operability issues.

3.1.1. Exhaust valve compression loss

Progressive exhaust valve sealing loss will predictably lead to increased valve damage and ultimately a complete loss of valve sealing ability. Initially, affected cylinders will continue to operate, albeit with reducing efficiency and power delivery. As the valve sealing further deteriorates, the engine may exhibit increasing vibration and symptoms of cylinder power imbalance. Ultimately, valve failure will render the cylinder and possibly the entire engine inoperable – necessitating an immediate forced landing in both circumstances.

3.1.2. Intake valve compression loss

Should the compression loss result from intake valve and valve seat damage, there is an increased risk of induction backfire events, which, in helicopters, can lead to uncommanded and hazardous yaw reactions from the transient engine power loss [CASA, 2018-2]. In low-speed manoeuvring or

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1 Some durability issues with engine cylinders from fixed-wing aircraft were also noted.
hovering helicopter flight, unexpected and sudden yaw and/or partial power loss may lead directly to controllability difficulties or complete control loss.

### 3.2. Reports and records

#### 3.2.1. Operating fleet

As of 29 November 2018, the Australian R22 and R44 fleet numbered 1,145 rotorcraft across the various models and variants.

The report section *Types* details the engine models and types fitted to each of these helicopter variants.

<table>
<thead>
<tr>
<th></th>
<th>R22</th>
<th>R22 Alpha</th>
<th>R22 Beta</th>
<th>R22 Mariner</th>
<th>R44 Raven</th>
<th>R44 Raven II</th>
</tr>
</thead>
<tbody>
<tr>
<td>NT</td>
<td>4</td>
<td>2</td>
<td>101</td>
<td>42</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>QLD</td>
<td>4</td>
<td>2</td>
<td>281</td>
<td>4</td>
<td>113</td>
<td>67</td>
</tr>
<tr>
<td>WA</td>
<td>3</td>
<td>2</td>
<td>112</td>
<td>3</td>
<td>44</td>
<td>33</td>
</tr>
<tr>
<td>NSW</td>
<td>1</td>
<td></td>
<td>75</td>
<td>56</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>SA</td>
<td></td>
<td></td>
<td>6</td>
<td>8</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>ACT</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VIC</td>
<td></td>
<td></td>
<td>16</td>
<td>1</td>
<td>44</td>
<td>44</td>
</tr>
<tr>
<td>TAS</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>ALL</td>
<td>12</td>
<td>6</td>
<td>591</td>
<td>8</td>
<td>310</td>
<td>218</td>
</tr>
</tbody>
</table>

*Source: CASA register of aircraft, compiled 29/11/18*

#### 3.2.2. Operator narratives

The issue of frequent premature cylinder serviceability problems among R22 and R44 helicopters is dominated by narratives from helicopter operators and maintenance providers. Many cite a recent and significant increase in the rate of cylinder removals from comparatively low-time engines.

Published by the Australian Broadcasting Corporation (ABC), an article (updated in August 2018) [ABC, 2018](#) cites operator safety concerns around the issue and theorises that reductions in the fuel lead content have contributed to the engine durability problems.
3.2.2.1. Cylinder warranty returns

A useful measure of premature component degradation or failure trends across an industry is information on warranty returns - i.e. components returned to the manufacturer or vendor for refund or replacement - having not satisfactorily met the manufacturers' performance assurances. Statistics on such warranty returns for R22 and R44 engine cylinders were provided by a large Australian engine overhaul company for the preceding six years (2013 - 2019). The information provided did not specify the nature of each warranty claim, however it was understood that most claims related to the cylinder/s failing a routine maintenance compression test.

<table>
<thead>
<tr>
<th>Year</th>
<th>R22-Beta cylinders (P/N. 05K21100)</th>
<th>R22-Beta II or R44-Raven I cylinders (P/N. 05K21745)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>2014</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>2015</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>2016</td>
<td>5</td>
<td>19</td>
</tr>
<tr>
<td>2017</td>
<td>9</td>
<td>17</td>
</tr>
<tr>
<td>2018</td>
<td>8</td>
<td>60</td>
</tr>
<tr>
<td>2019 (Jan-Apr)</td>
<td>1</td>
<td>21</td>
</tr>
</tbody>
</table>

Source: Brisbane Aero Engineers Pty Ltd

3.2.3. Defect Report Service (DRS)

Earlier known as Service Difficulty Reporting or Service Defect Reporting (SDR), the Civil Aviation Safety Authority’s Defect Report Service is a system that provides for the receipt, cataloguing and dissemination of information on aircraft or aircraft part defects. CASA defines a major defect as 'something that may affect the continuing airworthiness of an aircraft and could result in a safety hazard to persons or property'.

Within Australia, reporting of major defects to CASA is required under Regulations 51 - 53 of part 4B of the Civil Aviation Regulations 1988, and Regulation 42.D.6.2 of the Civil Aviation Safety Regulations 1998.

Due to the high degree of part and component standardisation within the aviation industry, there exists a reasonable likelihood that defects identified by one organisation may also manifest within other organisations conducting similar operations with similar equipment. The importance therefore, of timely defect identification and reporting cannot be understated in terms of addressing emerging safety issues that relate to material or equipment performance.

3.2.3.1. Cylinder and valve failure

The investigation was provided with extracts from the CASA DRS database that addressed reported issues with cylinders from Lycoming 0-320, 0-360 and 0-540 engines fitted to Robinson Helicopter Company models R22-Beta, R22-Beta II and R44-Raven I helicopters, Australia-wide. The extracts contained detail on cylinder defect reports received by the authority between 2011 and 2019. Also provided was the total number of defect reports received for all R22 and R44 helicopters during each year.

Feedback from this organisation indicated that prior to 2013, warranty issues relating to valve and valve guide problems were very uncommon.
As expected, the reports contained a variety of information and detail about the subject issue, however a commonality between those reports mentioning 'cylinder', 'inlet valve' or 'exhaust valve' was that they referred to a 'leaking' or 'low compression' state.

**Reporter location**

Cylinder (valve) failure DRS reports from 2017 - 2018 were examined with reference to the state from which the reports originated. Of these 111 reports, the significant majority (97) related to exhaust valve issues.

<table>
<thead>
<tr>
<th>State</th>
<th>R22 issue</th>
<th>R44 issue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern Territory</td>
<td>54</td>
<td>27</td>
</tr>
<tr>
<td>Queensland</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>Western Australia</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>Victoria</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Unknown</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

Sources: CASA DRS summaries dated 15/5/19 - Year Dist, 9/1/19 - 2011-2018 Dist.
Cylinder location
From the 2011 - 2018 DRS data, CASA conducted a distribution analysis examining the position of the affected cylinder/valve assembly within the engine layout.

When installed within the Robinson helicopter, the engines are oriented such that the No. 1 cylinder is located at the rearmost left position when looking towards the front of the helicopter.

**R22** (O-320, O-360) – plan view, looking rearward

<table>
<thead>
<tr>
<th>Cylinder position</th>
<th>No. 1</th>
<th>No. 2</th>
<th>No. 3</th>
<th>No. 4</th>
<th>Unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet valve issue</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Exhaust valve issue</td>
<td>8</td>
<td>11</td>
<td>24</td>
<td>9</td>
<td>7</td>
</tr>
</tbody>
</table>

*Source: CASA DRS summary dated 9/1/19 - Cylinder Dist.*

**R44** (O-540) – plan view, looking rearward

<table>
<thead>
<tr>
<th>Cylinder position</th>
<th>No. 1</th>
<th>No. 2</th>
<th>No. 3</th>
<th>No. 4</th>
<th>No. 5</th>
<th>No. 6</th>
<th>Unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet valve issue</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Exhaust valve issue</td>
<td>1</td>
<td>6</td>
<td>8</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>15</td>
</tr>
</tbody>
</table>

*Source: CASA DRS summary dated 9/1/19 - Cylinder Dist.*
3.2.3.2. Reporting limitations

Commentary from general aviation industry correspondents suggests that despite the mandatory requirements underpinning the DRS system, reporting rates may vary across organisations and operators. Comparison of data from defective component return rates (for warranty claims) against DRS submissions for the same issue has reportedly shown significant differences between the two metrics. This is evident to some extent in a comparison of data presented in sections 3.2.2.1 and 3.2.3.1, although notably, the data compares more favourably in recent times. It is possible that growing industry concern around the issue has precipitated increased defect reporting.

Numerous issues have been cited and proposed in explanation of the DRS reporting problem, however for the purposes of this investigation, the reader should be mindful that the statistics cited in the previous sections likely represent a subset of the total number of defect issues encountered.

The Civil Aviation Safety Authority continues to work closely with the GA sector in an endeavour to improve DRS reporting rates and assist the industry to understand its obligations and the benefits that can flow from a strong defect reporting and feedback system.

3.2.4. Research

On 14 November 2018, the Australian Transport Safety Bureau (ATSB) published a safety information bulletin entitled Exploration of change in aviation gasoline lead content in northern Australia on reported engine-related occurrences (AR-2018-058). The research contained therein had been initiated in response to information received by the ATSB that suggested an increase in helicopter engine issues in northern Australia was potentially linked to a change in the lead content of aviation gasoline (Avgas) sold in those areas.

The ATSB’s analysis drew upon its database of safety occurrences (incidents and accidents) reported under the mandatory provisions of the Transport Safety Investigation Regulations 2003. The analysis did not include reports of defects and problems found during maintenance activity and reportable to CASA under the Defect Report Service (DRS).

Based on its review of safety occurrence data, the ATSB safety information bulletin concluded that:

- There has been no discernible increase in reported engine failures or malfunctions in northern Australia after the introduction of Avgas 100LL in December 2015.
- There was an increase in reported occurrences of engine failures or malfunctions in helicopters with Lycoming piston engines since 2014, largely dominated by northern Australia. However, occurrence numbers are low so some year-to-year variation from chance alone is expected. Additionally, the increase did not align with the introduction of Avgas 100LL in December 2015.
- A disproportionate number of helicopter engine failures or malfunctions where the failure mechanism could not be identified occurred after the introduction of Avgas 100LL in December 2015. Although it could not be identified what these failures were at the time of publication, the possibility that new factors may exist contributing to engine failures in northern Australia cannot be eliminated.
- Overall, the review did not identify a link between the introduction of Avgas 100LL in December 2015 and reported engine-related occurrences in northern Australia. However, taking into account the data limitations, the small number of occurrences, and the proportion of unknown failure mechanisms, it was not possible to draw any absolute conclusions.
3.3. Failure mechanisms

The engine manufacturer (Lycoming) conducted a series of laboratory analyses on cylinders removed from service due to failing compression tests. These analyses focussed on characterisation of the exhaust and/or intake valve and valve seat damage and were aimed at identifying factors contributing to the damage sustained. Ancillary inspections of the associated cylinder components were also undertaken for benchmarking against expected engine condition for the engine time elapsed (time since overhaul or new).

Due to commercial confidentiality considerations, copies of the Lycoming laboratory reports were not available to this investigation. The information presented following is a summary of that presented by Lycoming technical representatives and expands on that contained within CASA airworthiness bulletins AWB 85-024 and AWB 85-025.

3.3.1. Exhaust valves

As received, affected cylinder exhaust valves typically presented with erosion and high-temperature oxidation of the seating face and corners. Notably in many cases, such damage extended for only a proportion of the full valve circumference, accompanied by a discolouration/deposit patterning that reflected the operating temperature distribution across the valve head.

Figure 1. Exhaust valve degradation and discolouration
3.3.1.1. Poor valve sealing

Effective valve sealing depends on the close concentric alignment between valve head and seat, the width of the contact area between valve face and seat face and the condition of the seating surfaces. There are a number of scenarios that can contribute to poor valve sealing:

- Improper valve and seat machining or refacing during manufacture or maintenance.
- Excessive valve guide - stem clearances from improper manufacture/maintenance or abrasive wear of the valve guide during service.
- Accumulations of deposits on the valve face or seat that are not effectively displaced or cut-through by the valve seating action.

3.3.1.2. Valve cooling

Engine exhaust and intake valve temperatures are controlled and regulated through conduction between the valve head and seat when the valve is closed, and through conduction along the valve stem and through the valve guide into the cylinder head. Many Lycoming engines employ a sodium (metal) filled chamber within the valve stem and head - this greatly assists the transfer of heat away from the critical head and seat areas.

Figure 2. Thermal flow through a closed (Lycoming) exhaust valve

Effective seating (contact) between the valve head and seat is critical to the dissipation of heat from the valve and control of the valve material temperatures. Poor seating between the valve and valve seat will prevent the normal conductive cooling of the valve periphery during the intervals that the valve is normally closed. Unable to effectively cool, the valve material temperature will rise in those areas; leading to increased oxidation and the asymmetric discolouration that often is indicative of valve thermal issues. Ultimately, affected valves may develop radial thermal-fatigue cracks around the periphery - leading eventually to material loss (chipping) and complete valve failure.

3.3.1.3. Valve seating area

It can be seen from this mechanism that the area over which the valve contacts the seat can play a significant role in the effectiveness of valve cooling. Determined principally by the width of the valve seat, the valve contact area will govern the heat dissipation, valve seat pressure and the ability of the valve to ‘cut through’ deposits formed on the seating surfaces. Optimum exhaust valve seat width is determined largely by engine design, but also any aspect of operation that dictates the engine’s thermal load. Engines running hotter, through fuel mixture practices, power demands or environmental conditions may benefit from valve seat widths toward the upper limits [Schwaner, 1991].

Valve seat widths

Direct feedback from a large Australian engine overhaul organisation indicated that, upon receipt from the manufacturer, replacement Lycoming engine cylinder and valve assemblies for both the parallel and angle valve models would typically present exhaust valve seat widths below the minimum values specified within the engine overhaul documentation.

The October 2010 revision of the Overhaul Manual - Lycoming Aircraft Engines - Direct Drive specifies the following valve seat dimensions for reconditioning purposes:

<table>
<thead>
<tr>
<th>Model</th>
<th>Seat face width - INTAKE</th>
<th>Seat face width - EXHAUST</th>
</tr>
</thead>
<tbody>
<tr>
<td>All parallel valve cylinder assemblies (except O-235-C, O-290-D, O-435-A)</td>
<td>0.076&quot; to 0.117&quot;</td>
<td>0.058&quot; to 0.077&quot;</td>
</tr>
<tr>
<td>All angle valve head cylinder assemblies</td>
<td>0.074&quot; to 0.093&quot;</td>
<td>0.091&quot; to 0.106&quot;</td>
</tr>
</tbody>
</table>

Source: Figure 6-26, Lycoming manual 60294-7-13 October 2010.

By comparison, exhaust valve seats measured by the overhaul organisation were typically within the range 0.030" to 0.040" (parallel valve cylinders) and around 0.080" (angle valve cylinders). Intake valve seats for parallel valve cylinders were around an average of 0.080" and 0.075" for angle valve cylinders³.

Operational trials - reworked valve seats

In light of these observations, in May 2018 the overhaul organisation commenced re-working the exhaust valve seats on all affected cylinders - widening the effective seat widths to the upper limit specified in the overhaul manual (0.077"). Feedback from the organisation indicated that as of May 2019, around 400 cylinders had been processed as such, with a return rate for valve sealing issues being around 1%. This was indicated as a significant improvement over previous return rates, which were cited as high as 20% in some years⁴.

Manufacturer’s comments

Feedback on the seat width issue from the engine manufacturer noted that while the specification for valve seat widths for new production cylinders is less than that for overhauled cylinders, the values measured on new items were still considered to be below expected limits⁵. The manufacturer’s specifications for new production valve seat widths were considered proprietary and not available to this investigation. The manufacturer undertook to examine this issue at depth with the quality control section of the organisation.

³ Email: Brisbane Aero Engineers to Lycoming, 8 May 2019
⁴ Email - Brisbane Aero Engineers, 6 May 2019
⁵ Email: Lycoming to Brisbane Aero Engineers, 30 May 2019
3.3.1.4. Guide wear

Commentary from the engine manufacturer and local engine overhaul workshops indicated that uneven exhaust valve guide wear, or 'bell mouthing' towards the lower end of the guides has been identified in numerous cases of premature low compression cylinder removal. The increased clearance between valve stem and guide allows the valve to move laterally and out of concentricity with the seat - leading increasingly to poor seating, poor sealing and accelerated thermal damage.

Premature or excessive valve guide wear has been an issue for Lycoming engines historically; in 1996 the company began introducing its 'Hi Chrome' exhaust valve guide to combat valve guide bell mouthing wear [Lycoming-SI-1485A]. All Lycoming engines and cylinder kits have employed this material since March 1998 and Lycoming Mandatory Service Bulletin No. 388 requires all engines to undergo a periodic inspection of valve guide condition on an ongoing basis (helicopter engines) or until the guides have been replaced with the 'Hi Chrome' variants (all other engines).

In-service valve guide wear has typically developed from combustion deposits accumulating along that part of the valve stem that extends into the exhaust port when the valve is open, and is subsequently withdrawn into the valve guide as the valve closes. The deposits act abrasively between the valve stem and guide bore as the valve moves axially during engine operation. This deposition process has also been attributed to exhaust valve 'sticking', where the free movement of the valve is inhibited by the stem accumulations; preventing the valve from fully closing. Valve rotation - necessary for face and seat wear distribution and cleaning - can also be inhibited by stem deposits. Valves that are prevented from normal rotation in this way may sustain localised and premature sealing surface damage.

The origin and compositions of these valve stem deposits can vary appreciably - published literature typically cites these as by-products of combustion, however commentary from Lycoming on the subject issue identifies the deposits as hard carbonaceous compounds generated from the thermal oxidation and pyrolysis of engine lubricating oil. Such 'coking' occurs as engine oil migrates along the valve stem and guide; becoming exposed to progressively higher surface temperatures until it breaks down - thickening and solidifying against the valve stem and guide bore. In such circumstances, it is recognised that the oxidation resistance and thermal behaviour of the oil will to some extent dictate the extent and nature of deposit formation, as will the deposit forming tendencies of the fuel itself.

3.3.2. Intake valves

Service Defect Reports received by CASA have shown low compression cylinders with visual evidence of engine oil coking and deposition around the intake valve guide exit and the corresponding valve stem. These cylinders typically present localised valve and valve seat 'guttering' - damage caused by combustion extending across the valve sealing faces in a transient 'flash-off' event precipitated by the coke/carbon accumulation - progressively damaging the surfaces and further degrading the sealing efficacy in that area. Once valve sealing degrades, combustion gases may increasingly bypass the valve - leading to rapid failure.
Figure 3. Intake valve with localised heating damage

Ref. CASA AWB 85-025

Figure 4. Intake valve guttering damage and stem coke accumulation

Ref. CASA AWB 85-025
3.3.2.1. Coking

Analysis of the valve guide deposits by the engine manufacturer confirmed their composition as consistent with decomposed and oxidised engine lubricating oil - thus a mechanism similar to the proposed oil migration behaviour affecting the exhaust valves.

A key difference here however, is the accumulation of coke (i.e. fully oxidised engine oil) beyond the limits of the intake valve guide bore. In considering the surface sweeping behaviour of the intake air/fuel mixture passing this area on each intake stroke, the engine manufacturer hypothesised that such coke accumulation could only occur when the engine was inoperative (with the surfaces at high temperatures). Occurring immediately following engine shut down, the sweeping gas flow ceases - allowing oil migrating along the valve guide to emerge and accumulate before surface temperatures caused oxidation, solidification and eventual coke formation.

3.3.2.2. Pre-shutdown engine cooling

As can be seen from the proposed intake valve coking mechanism, exposure of engine oil to surfaces at high temperatures predisposes those surfaces to the formation and accumulation of coke, with the incumbent increased risk of combustion anomalies and valve damage.

To lessen the risk of engine damage resulting from inadequate engine cool down procedures, the Robinson Helicopter Company on 29 February 2019 published a specific Hot Climate Cool Down Procedure as an addendum to the Pilot's Operating Handbook (POH) for their rotorcraft. This procedure provided for an extended cool down procedure if ambient temperatures exceeded 38 C and reinforced the need for compliance with the existing cool down procedures at all other times.
4. Contextual information

4.1. Engine design

4.1.1. Types

As noted previously, this investigation specifically considers the Lycoming O-320, O-360 and O-540 engine types powering the Robinson Helicopter Company light utility helicopters, models R22 and R44 respectively.

These engines are four or six cylinder horizontally-opposed, air cooled reciprocating piston engines with displacements between 320 cubic inches (5.24 litres) and 540 cubic inches (8.85 litres) and developing between 150 hp (112 kW) and 235 hp (173 kW) output power.

All engines installed in R22 and R44 helicopters are de-rated in terms of the maximum continuous power - through limitations in allowable manifold absolute pressure (MAP) and maximum RPM.

Engine variants fitted to the R22 include:

- O-320-A2B (R22)
- O-320-A2C (R22)
- O-320-B2C (R22 HP, R22 Alpha, R22 Beta)
- O-360-J2A (R22 Beta II)

Engine variants fitted to the R44 include:

- O-540-F1B5 (R44 Astro, R44 Raven I)
- IO-540-AE1A5 (R44 Raven II - see note).

Note: Although listed above, the IO-540 fuel injected engine powering the R44 Raven II helicopter has not been identified in reports as sustaining the extent or nature of the durability issues affecting the O-360 and O-540 naturally-aspirated engines.

4.1.2. Characteristics

4.1.2.1. Cylinder heads and valves

The O-320, O-360 and O-540 engine variant fitted to the R22 and R44 helicopter series share a similar parallel overhead-valve design, where the inlet and exhaust valves sit parallel to each other within the cylinder head and are actuated by camshaft-driven pushrods acting via rocker arms. The exhaust valves are of a hollow shaft, sodium-filled design while the intake valves have solid shafts. Intake and exhaust valves bear on hardened steel seats and operate through guides set into the cylinder head.

4.1.2.2. Parallel valve vs. angle valve cylinder heads

Other Lycoming aircraft engines feature cylinder head designs with intake and exhaust valves inclined with respect to the cylinder axis (i.e. angled valves). Parallel valve cylinders typically have a combustion chamber with a comparatively-flat top and the valve hardware (guides, springs, rockers) oriented much closer together when compared with the angle valve cylinders. While making for more compact valve train arrangements, parallel valve cylinders typically have less area for head material and cooling fins, and as such, have been implicated in issues relating to elevated cylinder head temperatures - such as accelerated or premature valve and valve guide wear [AOPA].
4.1.2.3. Helicopter engine cooling

Unlike fixed-wing aircraft that utilise open cowling arrangements, with the propeller thrust and forward motion of the aircraft providing airflow across the engine cylinders, the Robinson R22 and R44 helicopters employ a direct-drive squirrel-cage fan mounted to the engine output shaft. This draws air from the rear of the helicopter and forces it across the cylinders and oil cooler via two fibreglass and aluminium shrouds. A cockpit-controlled sliding valve allows for a variable mixture of heated or cool air to be fed to the carburettor as required (carburettor heat). The shroud ducting is configured so as to direct the fan-forced air across the cylinders from above; exhausting beneath the engine assembly.

4.1.2.4. Instrumentation

Engine instrumentation varies between models and variants, however typical fitted engine instruments on most rotorcraft include:

- RPM - engine and main rotor
- Manifold pressure (MAP)
- Oil pressure
- Oil temperature
- Cylinder head temperature (CHT)
- Carburettor air temperature

These instruments are contained within a console that sits centrally between the two front seats.

4.1.3. Fuel and lubrication

4.1.3.1. Fuels

All Lycoming reciprocating piston engines fitted to Robinson helicopters are certified to operate on a range of petroleum-based gasoline products, including both leaded, unleaded and some automotive variants. The Robinson Helicopter Company operating handbooks and Lycoming Service Instruction 1070AA (current at the time of writing) specifies the following permitted fuel standards for the O-320, O-360 and O-540 carburetted engines used in R22 and R44 rotorcraft.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Grade</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>DEF-STAN 91-090 - Standard Specification for Aviation Gasolines</td>
<td>100LL</td>
<td>Leaded</td>
</tr>
<tr>
<td>ASTM D910 - Standard Specification for Aviation Gasolines</td>
<td>100</td>
<td>Leaded</td>
</tr>
<tr>
<td></td>
<td>100LL</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100VLL</td>
<td></td>
</tr>
<tr>
<td>TU 38.5901481-96 - High-Octane Gasoline for Gasoline Engines</td>
<td>91</td>
<td>Leaded</td>
</tr>
<tr>
<td>GOST 1912-72 - Aviation petrol</td>
<td>B91/115</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B95/130</td>
<td>Leaded</td>
</tr>
<tr>
<td>DEF-STAN 91-090 - Standard Specification for Unleaded Aviation Gasolines</td>
<td>UL 91</td>
<td>Unleaded</td>
</tr>
<tr>
<td>ASTM D7547 - Standard Specification for Unleaded Aviation Gasolines</td>
<td>UL 91</td>
<td>Unleaded</td>
</tr>
<tr>
<td></td>
<td>UL 94</td>
<td></td>
</tr>
<tr>
<td>EN 228:2014 - Automotive fuels - Unleaded petrol - Requirements and test methods</td>
<td>Super Plus</td>
<td>Unleaded</td>
</tr>
</tbody>
</table>
Grades

Within Australia, there have been only two principal grades of aviation gasoline (Avgas) used in recent times - 100/130 and 100LL. The key characteristic for these fuels is the Motor Octane Number (MON) - a metric that reflects the fuels' resistance to detonation (explosive combustion) when compressed as an air-fuel mixture within the cylinder of a piston engine. The higher the MON, the greater the volumetric compression ratio that may be used within the engine to achieve higher performance and efficiency.

The detonation resistance of a gasoline fuel (and thus its MON) is predicated on the following compositional elements:

- **Alkylate (isooctane)** - a high-octane component produced through an alkylation process from isobutane and olefins. Alkylate is used as a blend-stock to raise the MON of straight-run gasoline (naphtha) distilled from crude oil.
- **Aromatics (reformate)** - high-octane aromatic hydrocarbons (e.g. benzene, toluene, xylene) produced by catalytic reforming of refinery naphthas.
- **Tetra-ethyl lead (TEL)** - the addition of small quantities of TEL to gasoline significantly increases the MON and has had ancillary historical beneficial effects such as reducing valve seat wear by acting as a high-temperature lubricant. TEL has been attributed as a major contributor to air and soil-borne environmental lead pollution (a potent and cumulative neurotoxin) and has been phased out within automotive gasoline in most industrialised countries.

100/130

This traditional avgas is coloured green and has an *Aviation Lean* MON of 100 and an *Aviation Rich* PN of 130. The fuel contains TEL additions of up to 0.83 grams of lead per litre (gPb/l).

100LL

Representing a 'Low Lead' composition, 100LL avgas is coloured blue and has mostly replaced 100/130 in most markets. It has a maximum permissible TEL content of 0.56 gPb/l and retains a *Aviation Lean* MON rating of 100.

Specification basis

Because of the complexity and variability of the chemical make-up of typical gasoline products, specifications will typically standardise on a combination of physical and chemical properties that define the performance and behaviour of the product. Section 4.1.1 of DEF-STAN 91-091 states:

*Aviation gasoline is a complex mixture of hydrocarbons that varies depending on crude source and manufacturing process. Consequently, it is impossible to define the exact composition of aviation gasoline. This specification has therefore evolved primarily as a performance specification rather than a compositional specification. It is acknowledged that this largely relies on accumulated experience.*

A key example of this approach is the specification of MON requirements for aviation gasoline, *rather* than requirements for the individual chemical components that contribute to the MON. ASTM D910 thus requires, for grade 100LL aviation gasoline, a minimum MON of 99.6, rather than specifying individual requirements for the alkylate, aromatics and TEL\(^6\). In this way, manufacturers will blend the components to achieve the required MON and may use a range of alkylate, aromatic and TEL proportions to achieve this.

\(^6\) Maximum limits only specified for TEL additions.
The reliability and durability of an engine operating on a product thus defined will be a function of the interaction between the characteristics of the fuel and the way the engine is operated on that fuel. The fitness-for-purpose of an aviation gasoline then, is dependent on the fuel not behaving in a way that could have a direct or cumulative damaging effect on the engine components.

**Tetraethyl lead**

Section X1.2.7 of ASTM D910 provides the following narrative on the use of Tetraethyl lead (TEL) in aviation gasolines:

Tetraethyl lead offers the most economical means of providing high antiknock value for aviation gasoline. It is added to aviation gasoline in the form of a fluid which, in addition to tetraethyl lead, contains an organic halide scavenging agent and an identifying blue dye. The scavenging agent is needed to keep the tetraethyl lead combustion products volatile so that they will theoretically be completely discharged from the cylinder. Actually, lead compounds are deposited in the combustion chamber and some find their way into the lubricating oil. The products of combustion of tetraethyl lead fluid are also known to be corrosive. Since deposition and corrosive tendencies are undesirable, the quantity of tetraethyl lead in aviation gasoline is limited by specification commensurate with economic considerations.

**Aromatics**

Section X1.8.1 of ASTM D910 provides the following narrative on the use of aromatic hydrocarbon compounds in aviation gasolines:

Low boiling aromatics, which are common constituents of aviation gasolines, are known to affect elastomers to a greater extent than other components in aviation gasoline. Although Specification D910 does not include an explicit maximum aromatic limit, other specification limits effectively restrict the aromatic content of aviation gasolines. Benzene is virtually excluded by the maximum freezing point of −58°C, while other aromatics are limited by the minimum heating value and the maximum distillation end point. Thus, the heating value limits toluene to about 24%. Xylenes have a slightly higher heating value and, therefore, would permit somewhat higher aromatic concentrations; however, their boiling points (above 138°C) limit their inclusion at levels not higher than 10%. Total aromatic levels above 25% in aviation gasoline are, therefore, extremely unlikely.

**Health issues**

Both aromatic hydrocarbons and tetraethyl lead have associated health issues when used as components of aviation (and automotive) gasolines.

**Aromatics**

By virtue of their volatility and chemical make-up, aromatic hydrocarbons of the types commonly identified in gasoline products can be used to induce a 'high' or hallucinogenic effects in persons deliberately concentrating and inhaling vapour from the gasoline product. Used repeatedly in this fashion can result in long-term harm or death. The Australian Parliament introduced the Low Aromatic Fuel Act 2013 to combat such abuses and manufacturers such as BP have introduced low aromatic fuels such as Opal in affected areas.

**Tetraethyl lead**

A potent neurotoxin, lead (TEL) additions in automotive gasoline fuels began to be phased out in the early 1970s to reduce environmental exposure and permit the use of catalytic converter technology to further reduce automotive exhaust emissions. Due to higher detonation resistance requirements however, TEL remains an active component within aviation gasoline fuels used by higher performance aircraft engines.
4.1.3.2. Engine oils

All four-stroke reciprocating piston engines require a reserve of lubricant to control wear, aid in heat transfer, control corrosion and assist with sealing and mechanical cushioning. Lycoming Service Instruction 1014 (version 1014M current at the time of writing) makes recommendations as to a range of lubricating oils suitable for all Textron Lycoming horizontally-opposed aircraft engines. These lubricants typically fall into one of two key types:

- Straight mineral oils conforming to MIL-L-6082 or SAEJ1966 specifications, or
- Ashless dispersant oils conforming to MIL-L-22851 or SAEJ1899 specifications.

Any brand name lubricating oil to these specifications is accepted for use.

Recommendations as to the respective grade of lubricating oil to be used are made according to the average ambient air temperature in which the engine is to be operated. Part I of the service instruction contains the following:

<table>
<thead>
<tr>
<th>Average Ambient Air Temperature</th>
<th>Mineral Grades (SAE)</th>
<th>Ashless Dispersant Grades (SAE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Above 80° F (27° C)</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Above 60° F (16° C)</td>
<td>50</td>
<td>40 or 50</td>
</tr>
<tr>
<td>30° F to 90° F (-1° C to 32° C)</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>0° F to 70° F (-18° C to 21° C)</td>
<td>30</td>
<td>30, 40 or 20W40</td>
</tr>
<tr>
<td>0° F to 90° F (-18° C to 32° C)</td>
<td>20W50</td>
<td>20W50 or 15W50</td>
</tr>
<tr>
<td>Below 10° F (-12° C)</td>
<td>20</td>
<td>30 or 20W30</td>
</tr>
<tr>
<td>All temperatures</td>
<td>Not applicable</td>
<td>15W50 or 20W50</td>
</tr>
</tbody>
</table>

The table is also accompanied by the following note:

AVERAGE TEMPERATURES - The ambient ground air temperatures listed in the chart are meant only as a guide. Actually a great deal of personal judgement must be used when selecting the seasonal grade of oil to put into the engines. For example, if an aircraft is to be flown into an area which is much warmer or colder, only personal judgement on the part of the operator can determine what grade oil to use. When oil inlet temperatures approach the maximum allowable during operation, it is a good indication that a higher viscosity oil should be considered.

Mineral grades

The straight mineral grades of aviation lubricating oils are blended directly from petroleum base stocks and contain minimal additives. These products are mostly single viscosity grade (i.e. the 'thickness' or viscosity changes proportionally with the temperature. These 'traditional' products are used primarily during run-in of new or newly-overhauled engines, or where environmental temperatures do not vary significantly.

Ashless dispersant grades

These products contain non-metallic additives to improve oxidation resistance, thermal stability and to minimise the accumulation of sludge, contaminants and other solid deposits. The 'ashless' descriptor relates to the control of combustion products when these oils enter the combustion chamber and are burnt. These oils may be single (Wxx) or multi-grade products (xxWyy), with the latter containing polymeric viscosity modifiers to reduce the viscosity change over the range of temperatures the oils may operate.
Semi-synthetic grades

The base stock of conventional lubricating oils is derived from refined crude oil - hence the mineral base. To further enhance the high temperature performance and stability, 'synthetic' oil components are blended (around 20-50%) with mineral base stocks to produce a lubricant that generally demonstrates greater elevated temperature oxidation resistance when compared to most 100% mineral oil grades.

Additives

All ashless dispersant lubricating oils contain a range of chemical additives to enhance the product performance. Of note, Lycoming Service Instruction 1070AA (see Fuels) mandates the use of lubricants containing part number LW-16702 additive for all engines operating on unleaded fuels. LW-16702 additive contains the high-pressure lubricating compound tricresyl phosphate (TCP) which helps in reducing wear and mitigating spalling (contact fatigue cracking) issues that affected some Lycoming engines. FAA airworthiness directive 80-04-03 requires the use of additive LW-16702 in O-320-H, O, LO, TO and LTO-360-E engines. The LW-16702 product is available as a supplement for adding to engine oils, and a number of commercial aviation engine oils are manufactured with additives that are equivalent to, or identical with the Lycoming LW-16702 product.

Lycoming Service Instruction SI-1409C (2009) advocates the use of the LW-16702 additive in all Lycoming piston aircraft engines except for installations that utilise a friction type clutch and a common engine oil system for the transmission and clutch assembly.

Field use

Information provided to this investigation indicated that the majority of Robinson R22 and R44 helicopter operators experiencing cylinder durability issues have employed SAE60 grade ashless dispersant oils, such as AeroShell® W120. Some operators reported using multigrade, semi-synthetic oils such as AeroShell® 15W50 or Total Aero DM 20W60.
4.2. Manufacture

4.2.1. Materials

The Lycoming O-320 and O-540 series engine cylinders are comprised of two major parts - the head and barrel, which are screwed and shrunk together. The cylinder heads are made as an aluminium alloy casting with a fully machined combustion chamber and the barrels are machined from chromium-nickel-molybdenum steel forgings with integral cooling fins.

The cylinders are equipped with a single intake and exhaust (poppet type) valve which sit against hardened steel seats within recesses in the cylinder head. The valves operate through guides shrunk and pressed into the cylinder heads. Intake valve guides are typically produced from aluminium bronze, whereas exhaust valve guides from a high-nickel cast-iron alloy ('Ni-resist') [Busch, 2018].

The cylinder exhaust valves on from the O-320 and O-540 engines are a hollow, sodium-metal filled design. The intake valves are of solid construction.

4.2.2. Component change review

4.2.2.1. Valve guides

Prior to 1998, some Lycoming aircraft engines were fitted with exhaust valve guides that exhibited premature 'bell-mouthing' type wear; contributing to a greater risk of valve sticking and/or sealing surface degradation. Mandatory Service Bulletin SB388 (2004) was introduced to require assessment of valve guide and valve condition at minimum 300 hour intervals, with Service Instruction SI1485 following to introduce a new 'Hi-chrome' wear resistant valve guide material. SI1485A noted that all Lycoming cylinder assemblies produced after 1998 contained guides produced from the new material.

4.2.2.2. Carburettors

Lycoming O-320, O-360 and O-540 engines fitted to R22 and R44 helicopters employ single barrel, float type carburettors, with an idle cut-off mixture control.

Lycoming Service Instruction 1523G provides the following cross-reference to carburettors approved for operation on R22 and R44 engines.

<table>
<thead>
<tr>
<th>Helicopter</th>
<th>Engine</th>
<th>AVStar</th>
<th>Marvel-Schebler</th>
</tr>
</thead>
<tbody>
<tr>
<td>R22</td>
<td>O-320-A</td>
<td>LVC-5-4PA</td>
<td>MA-4SPA</td>
</tr>
<tr>
<td>R22 HP, Alpha Beta</td>
<td>O-320-B</td>
<td>LVC-5-4PA</td>
<td>MA-4SPA</td>
</tr>
<tr>
<td>R22 Beta II</td>
<td>O-360-J</td>
<td>LVC-5-4PA</td>
<td>MA-4SPA, MA-4-5</td>
</tr>
<tr>
<td>R44 Astro, Raven I</td>
<td>O-540-F</td>
<td>LVC-5-5PA</td>
<td>MA-4-5</td>
</tr>
</tbody>
</table>

Historically\(^7\), all naturally-aspirated, non-fuel-injected Lycoming aircraft engines employed Marvel Schebler carburettors, however around 2010, the Avstar line of products was certified and introduced as a replacement for the Marvel Schebler units. Fundamentally, both designs operate in the same way - employing a fixed main jet to control fuel flow at operational engine speeds.

As such, this main jet size determines the engine's fuel-air mixture ratio - being selected at the factory or overhaul workshop when the assembled engine is test run. No provision for manual (in-flight) mixture control is provided, with the engines configured for 'full rich' operation at all times. There was no evidence available to this investigation that correlated the carburettor type with the cylinder durability issues.

\(^7\) Email - BAE, 14 Aug 2019
4.3. Maintenance

4.3.1. Overhaul requirements

The Robinson Helicopter Company refers to Lycoming Service Instruction 1009 (latest revision) for defined time-before-overhaul limits across the engines fitted to R22 and R44 helicopters. Service instruction SI1009 prescribes a 2,000-hour standard operating time before overhaul (TBO), with provision for an additional 200 hours for new engines or engines overhauled by Lycoming factory facilities or using Lycoming approved parts and procedures.

4.3.2. Prescribed maintenance

Scheduled maintenance for the R22 and R44 helicopter engines is specified within the applicable Robinson Helicopter Company maintenance manual. The following defined maintenance activities are directly relevant to the engine cylinders and valves:

<table>
<thead>
<tr>
<th>Maintenance activity</th>
<th>Lycoming instruction</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder compression test</td>
<td>SI 1191</td>
<td>Every 100 hours</td>
</tr>
<tr>
<td>Maintenance procedures and service limitations for valves</td>
<td>SB 301</td>
<td>Every 300 hours</td>
</tr>
<tr>
<td>Procedure to determine exhaust valve and guide condition</td>
<td>SB 388</td>
<td>First 100 hours, then every 300 hours</td>
</tr>
<tr>
<td>Engine oil &amp; filter change</td>
<td>SB 480</td>
<td>First 25 hours, then every 50 hours / 4 months</td>
</tr>
</tbody>
</table>

4.3.3. Compression

Cylinder compression measurement is a condition-monitoring activity undertaken during periodic (100-hourly) engine maintenance. It is a test that measures the amount of gas leakage past the piston rings and valves of an engine cylinder and provides an objective indication as to the condition of the engine cylinders and thus the suitability (or otherwise) of the engine for continued service.

The compression test typically applied to aircraft piston engines is the differential compression test [AviationPros]. This test uses apparatus that provides pressurised air to the engine cylinder which has both valves closed (typically the piston is positioned at top-dead-centre on the compression stroke). Any pressure loss due to air leaking past the piston rings or cylinder valves will be indicated by a pressure lower than the pressure of the air behind a standard orifice that is built into the testing device. Differential pressure readings are typically recorded as XX/YY where XX is the recorded cylinder pressure reading and YY is the set pressure of the air applied to the standard orifice (typically 80 psi).
4.3.3.1. Compression limits

Aircraft engine manufacturers typically specify limits for individual cylinder compression values and also for maximum variability between cylinders on an engine.

Lycoming Service Instruction No. 1191A [Lycoming-SI-1191A] states that:

- Pressure readings for all cylinders should be nearly equal; a difference of 5 psi is satisfactory; a difference of 10 to 15 psi indicates an investigation should be made. NOTE Unless the pressure difference exceeds 15 psi the investigation should not necessarily mean removal of the cylinder; often a valve will reseat itself and result in acceptable compression during a later check which should be made within the next 10 hours of operation.

- If the pressure reading for all cylinders is equal and above 70 psi; the engine is satisfactory; less than 65 psi indicates wear has occurred and subsequent compression checks should be made at 100 hour intervals to determine rate and amount of wear. If the pressure reading is below 60 psi or if the wear rate increases rapidly, as indicated by appreciable decrease in cylinder pressure, removal and overhaul of the cylinders should be considered.
US Federal Aviation Administration (FAA) Advisory Circular No. AC 43.13-1B [FAA-AC-43.13-1B] states:

- A loss in excess of 25 percent of the input air pressure is cause to suspect the cylinder of being defective; however, recheck the readings after operating the engine for at least 3 minutes to allow for sealing of the rings with oil.

A twenty-five percent loss of the input air pressure corresponds to a compression reading of 60/80 psi.

4.3.3.2. **Low compression - factors**

Low compression measurements within a reciprocating engine can be attributed directly to ineffective sealing between the inlet and/or exhaust valve faces and seats, and/or between the piston, piston rings and cylinder walls. Techniques can be used to isolate the source of the leakage and assist with remedial activities, however it is routine practice to remove and replace the affected cylinder if the measured values fall outside defined limits.
4.4.  Operation

4.4.1.  Engine operating limits - temperature

The respective Robinson Helicopter Company Pilots' Operating Handbooks for the R22 & R44 helicopters provide the following relevant temperature limits for the O-320, O-360 and O-540 engines:

- Cylinder head: 500°F (260°C) maximum (red line on cockpit gauge)
- Oil: 245°F (118°C) maximum (red line on cockpit gauge)

The engine manufacturer's operating handbooks mirror these limits, however they also publish guidance for 'desirable' or maximum service life operating temperatures:

- Cylinder head: maintain between 150°F and 435°F (66°C and 224°C)
  Green Arc on cockpit gauge: 200 to 500°F (93 to 260°C)
- Oil: Above 30°F (-1°C) ambient air temperature, maintain at 180°F (82°C)
  Green Arc on cockpit gauge: 75 to 245°F (24 to 118°C)

Guidance or instruction on exhaust gas temperature (EGT) control and management is not provided, as the helicopters are not equipped with the ability to vary the fuel mixture during normal engine operation.

4.4.2.  Operating regimes

Both R22 and R44 helicopter types enjoy a wide popularity in Australian operations, with the R22 helicopter extensively employed for mustering and rotary-wing flight training; the R44 more broadly for many forms of aerial work, sport/pleasure flying (including joy flights/sightseeing charters) and instructional flying.

The 2017 Bureau of Infrastructure, Transport and Regional Economics (BITRE) report on Australian Aircraft Activity\(^8\) noted 1,081 Robinson Helicopter Company rotorcraft on the Australian register, accruing around 256,000 flying hours across the year. Of the general aviation fleet as a whole, approximately 137,600 hours was undertaken performing agricultural mustering - the majority utilising Robinson R22 models and performed in the northern parts of the country (WA, NT and Qld).

4.4.3.  Speeds and power settings

Engines installed and operating in rotorcraft operate in a regime that is notably different to fixed-wing aircraft installations.

Rotorcraft rely fundamentally on maintaining a near-constant main rotor speed \(N_R\) throughout all phases of flight. With simple direct drive arrangements, this equates to a near constant and continuous engine operating speed - which for 100% \(N_R\) on the R22 is 2,550 rpm and 2,665 rpm on the R44. Power demands during flight are met by a collective-linked throttle control system to maintain a constant main rotor speed.

4.4.4.  Environments

Climatologically, the northern parts of Australia are characterised by tropical and sub-tropical conditions, with the highest temperatures, humidities and rainfalls occurring during the traditional 'wet season' months of November to April.

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\(^8\) The most current report at the time this report was compiled
Figure 7.  Temperatures - Katherine, NT

![Temperature chart]

Source: Bureau of Meteorology

Figure 8.  Relative humidity - Katherine, NT

![Humidity chart]

Source: Bureau of Meteorology
Figure 9. Temperatures - Kununurra, WA

Source: Bureau of Meteorology

Figure 10. Relative humidity - Kununurra, WA

Source: Bureau of Meteorology
Mustering operations (and thus the majority of R22 helicopter flying) in these regions is typically undertaken during the dry season months of May to October.

It is also notable that, in comparison to fixed-wing aircraft, helicopters employed in mustering operations would spend a significantly higher proportion of their total operating time at low altitudes, where the ambient air temperatures are typically highest.

4.4.5. Fuels

4.4.5.1. Supply in Australia

Using the early 2000s as a benchmark, aviation gasoline was at that time produced domestically at three refineries [ATSB, 2001]:

- BP, Kwinana, Western Australia
- Shell, Geelong, Victoria
- Mobil, Altona, Victoria

Aviation gasoline was also imported (and exported) by the individual oil companies.

Since that time, aviation gasoline supply to Australian markets has changed significantly, with the cessation of avgas production at Altona around 2000 and a corresponding increase in the importation of avgas from overseas sources such as South Korea, Singapore and China.

In 2005, Koninklijke Vopak N.V. (Vopak), an independent international tank storage company, opened a direct importation fuel terminal at Berrimah, near Darwin in the Northern Territory. From this terminal, aviation gasoline is imported and distributed to vendors in the northern parts of Australia. The Vopak terminal also provides for the local distribution of avgas refined at Geelong.

Commercial avgas production at the BP Kwinana refinery is understood to have ceased in 2015, with supply subsequently being imported from sources in south-east Asia.

In 2015, Viva Energy Ltd (Viva) purchased the Geelong refinery infrastructure and distribution rights for its products from Shell and is the exclusive licensee for Shell products in Australia. Avgas manufactured at the Viva refinery in Geelong (Corio) is presently shipped to the Vopak terminal in Darwin, from where it is distributed to general aviation industry operators.

4.4.5.2. Chemistry & grades

In the early 2000s, aviation gasoline was manufactured to the DefStan 91-091 / ASTM D910 100/130 grade. This product carried a maximum permissible TEL content of 0.83 gPb/l and a minimum 99.6 Motor Octane Number (MON). In December 2015, Viva adopted a formal grade change from 100/130 to 100LL (with a corresponding dye colour change from green to blue); although records indicate that the product had been trending below the prescribed maximum lead level for 100LL avgas (0.56 gPb/l) for about a year prior.

In support of the investigations into the issues at hand, Viva Energy Australia provided summary analytical records for fuel supplied into the Vopak terminal, Darwin (and henceforth to retailers and consumers) across the period 2012 – 2018. Similar information from BP Australia, while provided to governmental regulatory and investigation authorities, was not available to this investigation due to cited commercial sensitivity concerns.
Lead

Compositional records provided by Viva for avgas available at the Darwin Vopak terminal from 2012 through to 2018 showed that TEL levels have progressively reduced - trending from typical levels between 0.73 - 0.78 gPb/l in 2012-13, to 0.35 - 0.40 gPb/l in 2017-18.

The first Viva (Shell) product (from the Geelong refinery) was delivered into the Vopak Darwin terminal in March 2015; prior to that time avgas at Vopak Darwin originated from the BP refinery in Kwinana.9

Figure 11. Avgas lead trend, Vopak terminal, Darwin

![Avgas Lead Trend Chart](image)

Source: Viva Energy Australia presentation, Dec 2018.

Octane (MON)

Viva avgas produced in Geelong from 2013-2018 showed a slight declining trend, from around 103 MON in mid-2013, to just below 102 MON at the end of 2017.

Figure 12. Motor Octane Number trend - Geelong refinery

![Motor Octane Number Chart](image)

Source: Viva Energy Australia presentation, Dec 2018

9 Viva Energy Australia presentation - Dec 2018
Density

Although not a prescribed characteristic, the density of gasoline is a function of the compositional make-up of the blend and as such, can be used to flag changes in the proportions of the hydrocarbon constituents.

The Geelong refinery product density remained relatively constant across the 2013 - 2017 period, suggesting minimal bulk changes in the product composition.

**Figure 13.** Bulk density - Geelong refinery

![Density @ 15°C kg/m³](image)

*Source: Viva Energy Australia presentation, Dec 2018*

Aromatic hydrocarbons

The volume proportion of aromatic hydrocarbon components is also not prescribed by the manufacturing specifications, however the value must be reported on analytical certificates (i.e. it is a prescribed refinery test for each batch of avgas produced).

The Geelong refinery product by analysis showed a consistent proportion of aromatic hydrocarbons of around 17% by volume across the period 2013 - 2018.

**Figure 14.** Aromatic hydrocarbons % by volume - Geelong refinery

![Aromatics (%vol)](image)

*Source: Viva Energy Australia presentation, Dec 2018*
4.4.5.3. Sampling & testing

A program of independent sampling and testing of avgas fuel available from distributors around Australia was undertaken across January and February 2019.

The samples were as follows and characterised for density, colour, aromatics and tetra-ethyl lead.

1. Alice Springs Helicopters, NT
2. Outback Helicopters, NT
3. JRS Logistics Jandakot, WA
4. Helispirit Kununurra, WA
5. Airwork, Caboolture, QLD

<table>
<thead>
<tr>
<th>Test</th>
<th>Method</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density @ 15°C</td>
<td>ASTM D4502, kg/m³</td>
<td>719.3</td>
<td>718.9</td>
<td>710.2</td>
<td>719.2</td>
<td>719.4</td>
</tr>
<tr>
<td>Colour</td>
<td>Visual</td>
<td>Blue</td>
<td>Blue</td>
<td>Blue</td>
<td>Blue</td>
<td>Blue</td>
</tr>
<tr>
<td>Aromatics</td>
<td>ASTM D1319, % Vol</td>
<td>15.0</td>
<td>14.0</td>
<td>9.2</td>
<td>15.1</td>
<td>16.6</td>
</tr>
<tr>
<td>TEL</td>
<td>ASTM D3341, gPb/l @ 15°C</td>
<td>0.370</td>
<td>0.374</td>
<td>0.424</td>
<td>0.364</td>
<td>0.368</td>
</tr>
</tbody>
</table>

Source: Intertek Caleb Brett, test certificate No. AU190-0021814/4311000

From this work, it was evident that the fuel sample from JRS Logistics (Jandakot, WA) presented about 5% Vol. lower in total aromatic hydrocarbon content, and around 0.05 g/Pb correspondingly higher in TEL, when compared to the samples from northern WA, QLD and NT. Those samples were consistent for all examined aspects and typical of the product produced at the Viva Energy Geelong refinery.

While analytical information was not available to confirm, the differing analysis results for the fuel obtained from JRS Logistics suggested that BP Australia provided this product from its imported stocks.

4.4.5.4. Combustion

The operation of a conventional spark-ignition reciprocating piston engine is based on the combustion of a compressed gaseous mixture of hydrocarbon fuel and air. Within naturally-aspirated, carburettor-equipped engines such as those powering the Robinson R22 and R44 Astro and Raven I helicopters, liquid gasoline is metered and vapourised as it mixes with air and is drawn through the intake valves into the cylinder during the engine’s intake stroke. Compressed by the rising piston, the fuel-air vapour is ignited as the piston approaches the top of its stroke, whereupon the combustion proceeds and rapidly increases the gas pressure within the cylinder, driving the piston back down the cylinder and generating the power and torque used to drive the rotor systems.

It can be seen that the combustion characteristics of the fuel-air mixture are thus central to the effective and reliable operation of the engine. Normal combustion occurs when a flame front propagates smoothly and evenly through the mixture from the points of ignition. The rate and stability of this flame front propagation and the temperatures achieved during combustion can be significantly influenced by changes to:

- the mixture ratio (proportions of fuel and air)
- the intake air temperature
- the manifold pressure (engine power setting)
- the compression ratio (amount the original volume is compressed within the cylinder)
- the fuel combustion characteristics
- the timing of the ignition spark.

Detonation

Detonation is a condition describing the explosive or sudden combustion of the fuel-air mixture in advance of the propagating flame front. Under certain conditions in the combustion chamber, the fuel-air mixture may auto-ignite, generating shockwaves that can affect the durability of components in the powertrain through increased pressure rise rates, increased maximum pressures and increased heat transfer to pistons and cylinder heads [ATSB, 2007].

Engines employing higher compression ratios require fuels that have an established resistance to auto-ignition that allows engine power to be developed without detonation. The fuel's octane rating or grade quantifies that resistance and thus requires manufacturing controls to ensure a margin of safety against detonation for all normal (certified) engine operating conditions.

Temperatures and cooling

When considering the temperature rise in engine componentry associated with fuel/air combustion, effective engine design measures are necessitated to ensure that the operating temperatures of those components do not exceed safe operating limits for reliability and durability. Indeed, many engine components and systems are designed to operate most effectively and efficiently within a range of temperatures and optimum engine durability is achieved by maintaining those temperatures throughout the various engine operating regimes.

For stable control of engine temperatures, a balance must be achieved between heat input from fuel combustion and heat output from engine cooling. With numerous factors affecting both input and output, most aircraft powerplants are fitted with temperature indicating equipment, such that the pilot may monitor the engine and control its operation to manage temperatures directly.

**Figure 15.** Heat flows during operation (with engine gauges)
Chemistry effects

As discussed in the Specification basis subsection, gasoline fuels may vary considerably in their chemical composition, provided they meet or exceed the performance requirements outlined within the appropriate specification. The range of requirements placed on gasoline fuels are those arrived at by way of decision as to the performance parameters most critical to the safe and reliable performance of engines using those fuels. It is self-evident that other characteristics and parameters may vary within the confines of the prescribed parameters.

Aromatic hydrocarbon content

A notable variation in the total volume-fraction of aromatic hydrocarbon components making up aviation gasoline was evident when making comparisons between avgas 100LL product from different refinery sources. Avgas independently sampled from vendors in early 2019 showed compositions presenting between 9 - 16% by volume of aromatic components, whereas higher historical records for lead content (as TEL) in avgas supplied from the Vopak terminal suggest that the level of aromatic hydrocarbon components in earlier fuel production may have been considerably lower.

Limited information exists in the literature around the characterisation of aviation gasoline with respect to aromatic content. An experimental study in 2003 [Azetsu, 2003] showed that aromatic content of hydrocarbon fuels with otherwise similar calorific values has an elevating effect on flame temperatures and soot production. A similar 1972 study found that in the combustion of aromatic hydrocarbons, the engine combustion chamber temperature was substantially higher than that with isoparaffins (i.e. iso-octane or alkylate).

Research [Kalghatgi, 1995] has also shown that the combustion chamber deposit formation tendency of a gasoline fuel increases as the aromatic content of the fuel increases, and that polynuclear aromatics (poly-aromatics) were strong deposit formers. This finding is consistent with those that show the greater soot-forming tendencies of aromatic-containing fuels.

In February 2015, the US Federal Aviation Administration (FAA) published DOT/FAA/TC-14/51; a technical report on the Anti-Knock and Power Performance Evaluation of Swift Fuels 100SF Blended with Commercial 100 Low-Lead Aviation Gasoline in a Full-Scale Engine [FAA, 2015]. 100SF (UL102) is an unleaded high-octane aviation gasoline produced by Swift Fuels LLC. UL102 is manufactured to ASTM D7719 Standard Specification for High Aromatic Content Unleaded Hydrocarbon Aviation Gasoline. The UL102 product tested contained 73.3% aromatic hydrocarbon content and less than 0.01 gPb/l of TEL, against the 10.1% aromatic and 0.327 gPb/l TEL content of the 100LL commercial avgas. The report examined the performance of proportionate blends of UL102 with commercial 100LL avgas (ASTM D910) in ranges from 0 to 100% and tested in Lycoming IO-540-K and Continental IO-360-DB aircraft engines under high ambient temperature conditions. In both cases it was observed that the high aromatic UL102 fuel produced an average exhaust gas temperature (EGT) of 40°F - 70°F higher than the comparable 100LL fuel at equivalent power settings. The blends of UL102 and 100LL showed the same trend, with the greater proportions of the high aromatic fuel in the blend, the higher the average EGT.

Tetra-ethyl lead additions

Historical refinery data shows a notable reduction in the tetra-ethyl lead (TEL) content of avgas fuels between 2012-13 and the present day. Records for the Vopak terminal near Darwin reflect a lowering of TEL content in excess of 50% across this period.

While TEL is added to aviation gasoline as a fluid containing an organic halide lead scavenging agent (typically ethylene dibromide), that agent is not completely effective and lead compounds are deposited on the combustion chamber, piston and valve surfaces and subsequently accumulate within the engine lubricating oil.
The remnant lead compounds formed from the combustion of leaded gasolines have traditionally provided a degree of high-temperature lubricating behaviour. While the problem of valve seat recession (encountered upon the introduction of unleaded fuels for automotive use) was mitigated through the introduction of wear-resistant valve seats, there is anecdotal evidence and commentary that the lead compounds migrating into the lubricating oil of aviation engines may also have beneficial effects in terms of high-pressure contact lubrication more broadly throughout the engine.

Lycoming oil additive LW-16702 (either as an additive or contained within a finished lubricant) is prescribed\textsuperscript{10} for all engines operating on approved unleaded aviation gasolines. The LW-16702 additive contains tricresyl phosphate (TCP), an anti-wear and high-pressure lubricating compound.

### 4.4.6. Piston Aviation Fuels Initiative (PAFI)

With increasing pressures to remove lead compound additions from aviation gasoline fuels, work has increased on the study and exploration of alternative formulations that do not contain tetraethyl lead, yet retain the appropriate octane and other performance characteristics necessary for high combustion ratio aircraft engines. The Piston Aviation Fuels Initiative (PAFI) was established following the US FAA’s adoption of the Unleaded Aviation Gasoline Transition Aviation Rulemaking Committee Charter in 2011. The PAFI mission is:

*To evaluate candidate unleaded replacement fuels and identify those fuels best able to technically satisfy the needs of the existing aircraft fleet while also considering the production, distribution, cost, availability, environmental and health impacts of those fuels.*

In 2012, the PAFI steering group was established and in 2014, nine candidate fuels from five suppliers were proposed for the program. Of those formulations, four products were selected for Phase-1 of the program (laboratory testing), which commenced in 2015.

From that work, two fuels were selected to participate in the Phase-2 trials (engine and aircraft flight testing), which commenced in mid-2016. These were:

- Swift Fuel LLC's UL102 - this is a high-aromatic avgas to ASTM D7719, containing approximately 73% aromatic hydrocarbons and having a typical density around 800 kg/m\textsuperscript{3}.
- Shell Aviation's 100UL - less information was available about this product at the time of reporting, however it is also understood to be a high aromatic gasoline, with typical density in the range of 750 - 780 kg/m\textsuperscript{3} [Ells, 2014].

In September 2018, the FAA announced that Phase-2 testing had been suspended following the identification of 'unique issues with each fuel that needed to be addressed.' Further information as to the nature and extent of these issues was not provided by the FAA, however the Aircraft Owners' and Pilots Association (AOPA) reported that 'testing to date has revealed important knowledge about the effects of different fuel formulations on engine durability and hot-weather operations.'

### 4.4.7. Engine data monitoring

Aircraft (and rotorcraft) engines typically operate through a range of conditions and states during the flight cycle. From engine start, through take-off, cruise and manoeuvring flight, landing and shutdown, the operating parameters can vary appreciably. While engine manufacturers design and certify their powerplants to operate safely and robustly through defined parameter ranges, sustained operation at the margins of some of those parameter ranges can adversely impact the durability of components and ultimately, the engine itself.

As the internal combustion engine is, in its most fundamental form, a mechanism for deriving mechanical energy from the combustion of a chemical fuel, the interactions between parts and

\textsuperscript{10} Lycoming Service Instruction 1070AA Table 1 - Caution.
components of that mechanism during operation can sometimes be complex and dynamic. While basic systems for monitoring of key engine parameters vital to engine reliability are required by the engine and/or airframe manufacturer, these systems often only provide a broad oversight of engine condition and performance. Significantly greater insights into the performance of a powerplant can be achieved with the installation and use of a contemporary Engine Data Management (EDM) system.

4.4.7.1. Instrumentation

Data acquisition and display systems for aircraft reciprocating piston engines are manufactured by a number of companies, however all typically employ a range of sensor technologies to continuously measure the following operational parameters\(^{11}\) and log the values to non-volatile memory for later analysis.

- Lubricating oil temperature
- Lubricating oil pressure
- Induction air temperature
- Manifold absolute pressure (MAP)
- Outside (ambient) air temperature (OAT)
- Cylinder head temperature (CHT, all cylinders)
- Exhaust gas temperature (EGT, all cylinders)
- Fuel flow rate
- Electrical system voltage

These parameters are also displayed in real-time to the pilot/crew, enabling an enhanced real-time awareness (and control) of the engine's operating state.

Figure 16. JP Instruments EDM 830

Ref: https://www.jpintimstruments.com/shop/edm-8301/

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\(^{11}\) https://www.jpintimstruments.com/shop/edm-8301/
### 4.4.7.2. Trials

To gain a more detailed understanding of engine conditions during helicopter operations, a trial program was developed for an R22 rotorcraft equipped with a JP Instruments EDM 830 data acquisition unit. These trials allowed for the close monitoring of key engine parameters and the controlled variation of variables such as fuel grade and power delivery to ascertain their effects on the engine's operating conditions.

<table>
<thead>
<tr>
<th>Rotorcraft</th>
<th>Robinson Helicopter Company R22-Beta, S/N 4531, Registration VH-OVZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>Textron Lycoming O-360-J2A</td>
</tr>
<tr>
<td>Engine TBO</td>
<td>0 h at commencement of monitored flights (i.e. newly-overhauled)</td>
</tr>
<tr>
<td>Operator</td>
<td>Outback Helicopters Pty Ltd</td>
</tr>
<tr>
<td>Fuel suppliers</td>
<td>Top End Flying Fuels (Stark Aviation Pty Ltd) - Viva Energy Avgas 100LL</td>
</tr>
<tr>
<td></td>
<td>BellaPetro - Warter Fuels S.A. Avgas 100/130</td>
</tr>
</tbody>
</table>

### 4.4.7.3. Trial fuels

For comparison, the two fuels employed in the data monitoring trials were characterised as follows:

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Domestic 100LL Avgas</th>
<th>Imported 100/130 Avgas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brand</td>
<td>Viva Energy Avgas 100LL</td>
<td>Warter Fuels S.A. Avgas 100/130</td>
</tr>
<tr>
<td>Data source</td>
<td>Viva Energy Australia, Certificate of Quality, Avgas 100LL, batch VEV019A9, 14 Jan 2019</td>
<td>Warter Fuels Spolka Akcyjna, Quality Certificate, AVGAS 100/130, Lot No. 19/IN/142, 15 May 2019</td>
</tr>
<tr>
<td>Density at 15°C, kg/m³</td>
<td>718.3</td>
<td>692.7</td>
</tr>
<tr>
<td>Specific energy, MJ/kg</td>
<td>43.7</td>
<td>44.4</td>
</tr>
<tr>
<td>Colour</td>
<td>Blue</td>
<td>Green</td>
</tr>
<tr>
<td>Lead content, gPb/l</td>
<td>0.38</td>
<td>0.72</td>
</tr>
<tr>
<td>Aromatic hydrocarbons %V/V</td>
<td>16.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Motor Octane Number (MON)</td>
<td>101.6</td>
<td>103.4</td>
</tr>
<tr>
<td>Reid Vapour Pressure, kPa</td>
<td>43.8</td>
<td>45.7</td>
</tr>
</tbody>
</table>

### 4.4.7.4. Observations and data

Data acquisition occurred during normal operational tasking of the helicopter - predominantly during ferry flight or stock mustering operations. Data was obtained over 31.4 operating hours across 20 flights between 7 August and 3 September 2019 using the domestic Avgas 100LL, and a subsequent 12 hours across 7 flights using the imported Avgas 100/130. A final flight back on the domestic avgas concluded the principal data-collection exercise.

The operational data was provided as-downloaded from the EDMS unit and decompressed using the EDMS manufacturer’s EzTrends software. Analysis of the data was undertaken using Microsoft Excel, with key attention to the following measured parameters:
- Exhaust Gas Temperature (EGT) - all cylinders, °F
- Cylinder Head Temperature (CHT) - all cylinders, °F
- Outside air temperature (OAT) - °C
- Manifold Absolute Pressure (MAP) - in/Hg
- Engine speed - revolutions per minute (RPM)
- Fuel flow (FF) - G/h
- Oil temperature (OILT) - °F

Peak temperatures

Comparisons were made graphically across peak temperature values measured for all flights greater than 0.5h duration, for exhaust gas, cylinder head and oil temperature.

**Figure 17.** Peak exhaust gas temperatures, by flight
Figure 18. Peak cylinder head temperatures (with average outside air temp), by flight

Figure 19. Peak oil temperatures and average outside air temperature, by flight
Time-at-temperature

Fundamentally, thermal damage and degradation of engine materials and components manifests as a function of the temperatures that material sustains across its service, as well as the time the material spends at such temperatures. Accordingly, the exhaust gas temperature data was integrated against the sample time interval to examine the duration-at-temperature exposure that the engine combustion chamber components sustain when operating on each of the two fuels in question. An arbitrary exhaust gas temperature of 1,475 °F was chosen for the comparison.

**Figure 20.** Percentage of total flight time above 1,475 F exhaust gas temperature

None of the flights operated using the imported 100/130 avgas product showed more than 13% of total flight time exceeding 1,475 °F, whereas the significant majority of the flights operated using the domestic 100LL avgas exceeded 1,475 °F for over 50% of the total flight time.
5. Analysis

With the nature of the damage sustained by the Lycoming engine cylinders outlined previously in this report, this section examines the possible origins of each key factor and presents associated evidence for the existence or otherwise of each.

5.1. Cylinder durability factors

Through work undertaken by the engine manufacturer (Lycoming) and supplemented by observations from the CASA defect reporting service and local maintenance organisations, it was established that both the exhaust and intake valve and valve seat damage that has characterised the cylinder durability problem has arisen in a similar manner. As was discussed, this damage was directly linked to the effects of sustained elevated temperature operation and the accumulation of oxidised/coked lubricant and combustion deposits on the rear faces and exposed stems of both intake and exhaust valves.

**Intake valves**

- the accumulation and hardening of oil oxidation (coking) products on the valve stems and rear faces - principally during immediate post-shutdown periods.
- pre-ignition and fuel mixture flashover across the intake valve seats, leading to localised valve face and seat thermal damage and subsequent degraded sealing (compression loss).
- potential induction system backfiring and power loss events, should the intake port combustion extend further back along the induction stack.

**Exhaust valves**

- the accumulation of oil oxidation (coking) and combustion products on the exposed valve stems and rear faces.
- hardening of those deposits into dense abrasive products under the effects of sustained high temperatures.
- accelerated wear of the valve guide lower bores (bell-mouthing) as the valve stem repeatedly introduces these abrasive products into the guide.
- increasing loss of concentricity between valve head and seat as the guide wear progresses - leading to misaligned seating and a consequent reduction of conduction cooling pathways between valve face and cylinder head.
- localised and accelerated high-temperature oxidation of the valve seating face material.
- if not identified through compression testing or boroscopic inspection, valve damage can progress to thermal fatigue cracking, valve chipping and eventual valve destruction.

The accumulation of deposits on the valve stem and rear face can be simplistically attributed to the fuel mixture combustion characteristics and the high-temperature oxidation of lubricating oil that migrates along the valve stem after engine shut-down (the engines are not equipped with valve stem oil seals).

5.2. Problem emergence

When considered in terms of reported operator experience, the broader issue of cylinder durability problems emerged around 2016-17, where defect reporting and cylinder warranty return levels increased above historic levels. In this context, logic suggests that some change/s to the operating system must also have occurred around this time, such that the identified failure mechanisms became more dominant and impactful on cylinder durability.
As such, the focus of this investigation (and that of concurrent related investigations by other parties) was directed to potential factors that:

- had the potential to cause or contribute to the observed mechanisms of cylinder durability issues, and
- had (or may have) changed at a time coincident with the cylinder durability problem emerging, and
- were of a nature that could present as a common broader issue affecting a wide distribution of operators, as opposed to discrete possibilities that would not be expected to concurrently manifest across multiple operators and thus would be inconsistent with the reported experience.

5.3. Temperature management

As discussed broadly, temperature control and regulation within the internal combustion engine is fundamental to its reliable operation and the durability of its parts and components. Numerous factors control how much heat is generated during the combustion process, how heat is transferred to, and between, components, and how heat is removed from the engine through transfer to the environment.

5.3.1. Heat sources

The reciprocating piston engine is a mechanism for deriving mechanical energy (motive force) from the principle that when heated, a contained gas will expand and exert pressure upon the walls of the chamber that contains it. When that heating is achieved directly through the repeated combustion of a fuel-air mixture in a chamber containing a movable piston, we have the internal combustion engine. It follows that engine efficiency is directly linked to the amount of heating energy that can be extracted from the fuel through the combustion process, with greater amounts of heat energy released producing higher gas temperatures and thus greater cylinder pressures and power output.

All fuel materials have defined heats of combustion - that is, the amount of energy that will be released through complete combustion of a fixed quantity of the fuel. For example, 100LL aviation gasoline produced to ASTM D910 must have a minimum heat of combustion of 43.5 megajoules per kilogram (MJ/kg).

During the combustion process, various inefficiencies will result in some of the combustion heat energy transferring from the gas into the surrounding components as the engine operates. This heat energy raises the temperature of these components and must be subsequently removed if their temperature is to be controlled and prevented from rising to damaging levels.

The proportion of this rejected heat (i.e. the energy not utilised the production of work) is governed by numerous factors - typically sitting between 50% and 75% of the total thermal energy released from the fuel consumed [Baglione, 2007]. That energy will either be lost to the atmosphere through the exhaust gases (approximately 50%) or conducted into the engine materials to be later removed by cooling systems.

Any change to an engine system that increases the amount of rejected heat has the potential to raise the temperature of engine materials and accelerate their degradation. In this way, such a change can lead directly to reduced component durability and the typical experience that is at the centre of this investigation.
5.3.2. Potential systemic issues

Potential broader contributors to elevated engine temperatures include:

- fuel compositional or characteristic changes
- component design or condition changes
- ambient operating environment changes
- industry-level operating procedure changes

5.3.2.1. Fuel composition

The information presented in this investigation identifies a notable change in the compositional make-up of the avgas fuel manufactured for domestic consumption.

Detailed in the Operation - Fuels section, records for the Vopak terminal (Darwin) avgas supply across 2013 to 2018 showed a relative reduction in the total lead content (as tetra-ethyl lead, TEL) of around 50%. At all times, the lead content and other reported characteristics remained entirely compliant with the ASTM D910 / DEF-STAN 91-090 requirements for 100/130 and subsequently 100LL avgas.

As outlined in the Chemistry & Grades section, TEL is principally added to aviation gasoline to support the fuel's detonation resistance (Octane Number). As such, reducing the TEL content (for environmental, health and economic considerations) must be offset by maintaining the Octane Number through other mechanisms. This is most economically achieved by increasing the proportion of aromatic hydrocarbon compounds within the blend.

While data from the Australian refiners/suppliers was constrained in its content and availability, the marked reduction in lead content of the Vopak terminal fuel across this period suggests that the aromatic hydrocarbon content in this fuel may have increased proportionately to maintain specification MON levels.

Further to this - data from Viva Energy Australia indicated the lead content of the Geelong-refined product had only marginally reduced (by 0.05% gPb/l) across the period 2013 – 2018, with the aromatic hydrocarbon levels remaining essentially constant (at around 16-17%). With the change in Vopak terminal supplier from BP Australia to Viva Energy (Shell) in 2015 it is thus evident that the historical product supplied by BP Australia was significantly higher in lead and potentially lower in net aromatic hydrocarbon content.

5.3.2.2. Fuel combustion

As noted under Chemistry effects, the examined literature suggests that fuels containing higher levels of aromatic hydrocarbon components will burn with higher flame temperatures and with a greater potential for the formation of carbonaceous combustion products (soot).

A comparison of peak exhaust gas temperatures (EGT) measured during the Engine data monitoring program showed a small lowering of peak EGT across the flights using the imported, low-aromatic fuel, but a profound lowering of the proportion of each flight that the EGTs spent above 1,475°F when operating on this fuel.

Peak cylinder head temperatures (CHT) and oil temperatures (OILT) did not differentiate between the fuel types as distinctly as the EGT values. CHT and OILT values did, however, show a clear alignment with variations in average outside air temperatures during each flight, with warmer operating conditions producing the expected higher CHT and OILT values.
5.3.2.3. Ambient operating environments

There is an evident correlation between reports of cylinder durability issues and the geographic location of those operations, with operators in the northern climes of Australia typically experiencing a disproportionately higher number of problems than their southern counterparts.

When examined from a weather and climate dynamics point of view however, there is no evidence to suggest that the ambient operating conditions for the northern helicopter fleet have *changed* in any way that could be considered as contributory to, or influential of the durability problem in question.

5.3.2.4. Component changes

Across the period examined (2013-2018), the investigation was unable to identify any broad changes in the design or manufacture of any component that could influence the durability of cylinders fitted to the Lycoming engines in question. Engine design is understood to be stable and fundamentally sound from an operational airworthiness and certification perspective.

Valve seat widths

Heat management is particularly important for those sections of the engine directly exposed to the combustion process. Valves and valve seats must exhibit functional durability under both mechanical contact and high temperature exposure, with any mechanism that adversely affects the valve’s designed cooling characteristics having the potential to significantly impact upon valve (and thus engine) durability.

The reported experience with the post-manufacture widening of the exhaust valve seat widths on new cylinders received from the factory was entirely consistent with the subject durability issues being temperature-related. By widening the exhaust valve seats to the maximum permissible under the engine overhaul documentation, the potential for accelerated high-temperature degradation of the valve material was offset by the improved cooling pathway established by the increased contact area across the valve seat, resulting in a more durable exhaust valve assembly and notably reduced warranty returns.

5.3.2.5. Operating procedure changes

Like the design and component history, the investigation was similarly unable to identify any broad or fundamental operational changes that had occurred within the operating helicopter fleet, or prescribed by the engine or airframe manufacturers.

5.3.3. Potential discrete issues

Numerous engine system scenarios exist that can produce increased engine temperatures. Component faults, maladjustments, maintenance anomalies or operating outside published limitations all have the potential to produce engine behaviours that can accelerate temperature-related breakdowns.

- Cooling system faults - obstructions, cowling/ducting damage, fan throughput restrictions
- Ignition timing faults or maladjustment
- Carburetion/mixture control and fuel flow

As noted previously however, from a statistical viewpoint when considering a broad-based issue affecting multiple operators, there is a low probability that these factors will be at the root of the issue, as it is unlikely that any given issue will manifest with the commonality necessary to produce the combined adverse experience.
5.3.3.1. Cooling faults

Cooling system obstructions, cowling/ducting damage or any condition that can affect the effective removal of heat from the engine can result in over-temperature conditions. This investigation found no indications or evidence of a systemic cooling system fault or condition that had the potential to produce the outcomes in question.

5.3.3.2. Ignition timing

Optimal combustion of a fuel-air mixture within the combustion chamber of an internal combustion engine takes a finite period and occurs as the progressive movement of a flame front through the mixture from the point/s of ignition.

Accordingly, ignition of the mixture (firing of the spark plug/s) must be timed to ensure the optimal correlation between charge gas heating and piston position within the cylinder. In terms of heat transfer, ignition timing can influence engine and exhaust temperatures by changing the time available for combustion of the mixture.

In terms of the issue at hand, issues such as misadjusted ignition timing, while possible on an individual or local pool of rotorcraft, would not be expected to be manifest across a broader fleet - maintained and operated by a range of independent organisations and individuals.

5.3.3.3. Mixture control and fuel flow

The relationship between fuel-air mixture and the temperatures developed within the exhaust gases and cylinder heads is fundamentally well understood and of importance to operators of aircraft and rotorcraft with variable mixture engine controls.

The R22 and R44 helicopters are equipped with fixed mixture controls, with no provision for leaning or richening the mixture during operation. Fuel-air mixture is effectively set through the use of fixed-orifice jets within the carburettor assembly. While it is possible to vary the mixture by altering the jet sizes (and thus the fuel flow rates) from the established values, there was no evidence to suggest that this practice was systemic across the industry or linked to the durability experiences.

5.4. Deposit formation

As outlined in the discussions around failure mechanisms, both intake and exhaust valve issues have been shown to be related to the deposition and accumulation of solids on the upper faces and lower (exposed) stem lengths.

5.4.1. Oxidised lubricating oil

During engine operation, lubricating oil fed to the valve actuating (rocker) assemblies is able to migrate in small quantities between the valve stem and guide. This lubricant is exposed to increasing temperatures as it approaches the intake/exhaust ports and combustion chamber. Evidence from the field CASA, 2018 shows that the lubricant can decompose at these elevated temperatures - reverting to a solid form as the volatile products of the decomposition are driven off. This solid carbonaceous material (coke) may accumulate and contribute to valve guide wear, pre-ignition, flashover and induction backfire events.

Decomposition and oxidation of engine lubricants is a process inherent to their exposure to elevated temperature. The process is time-temperature dependent and is also a function of the lubricant composition, with contemporary semi-synthetic oils being blended to present improved decomposition and oxidation resistance when compared to their traditional mineral-based counterparts.
5.4.2. Combustion products

Combustion of the fuel-air mixture within an engine is never a complete process; complex chemical products of combustion are produced on every firing cycle - the majority of which are carried from the engine in the exhaust gas flow. Where exhaust gases impinge upon surfaces within the combustion chamber and exhaust ports however, cooling occurs and allows the deposition and accumulation of solid products. The extent and nature of combustion chamber deposits is a function of fuel composition, lubricating oil composition and surface temperatures, with cooler surfaces promoting deposition and higher temperatures reducing it.

Combustion products may also undergo continued chemical processes after deposition, with oxidative pyrolysis and similar reactions producing remnant materials with hard, abrasive and refractory properties.

Combustion residues and deposit formation can be strongly influenced by engine fuels and operating methodologies. Oxides and similar compounds of lead have been identified in deposits within engines operated on traditional higher-lead fuels, with 'lead fouling' of spark plugs a notable example. Engine fuel-air mixture is also a known contributor, with rich mixtures producing greater quantities of carbon-rich (soot) deposits which may later pyrolyse and harden. Fuels containing a greater proportion of aromatic hydrocarbons have also been shown to have a greater soot and deposit-forming tendency.
6. Key findings

The following findings are drawn from the information collected during this investigation and summarised herein.

6.1. Cylinder durability problems

1. The broad issue of poor operational durability of Robinson Helicopter Company model R22 and R44 engine cylinders was principally one of accelerated valve, valve guide and valve seat wear, leading to loss of cylinder compression and the potential for partial power loss events during engine operation.

2. Valve and valve seat wear was attributable to the cumulative damaging effects of valve stem deposits and sustained high temperature exposure.

3. Valve stem deposits formed from a combination of fuel combustion products and lubricating oil migration, decomposition and pyrolysis.

6.2. Fuels

1. In 2015, aviation gasoline supplied to customers in northern Australia from the Darwin Vopak distribution terminal changed from a product locally-manufactured at the BP Kwinana refinery, Western Australia, to product refined by Viva Energy Australia at its Geelong, Victoria refinery.

2. Historically (pre-2015), the avgas product supplied from the Vopak terminal contained lead (as tetra-ethyl lead) at typical levels between 0.52 gPb/l (Jan 2015) to 0.78 gPb/l (Dec 2012).

3. Following the change in supplier in 2015, avgas from the Vopak terminal contained lead at levels around 0.35 - 0.46 gPb/l and a typical aromatic hydrocarbon content of 16-17% by volume.

4. Aromatic hydrocarbons, when present in gasoline formulations, act to inhibit auto-ignition (detonation) under compression of a gasoline/air charge. As such, they find application in offsetting reducing tetraethyl-lead additions in higher performance fuels.

5. When examining fuel compositional trends, reducing lead levels with a consistent octane rating can suggest an increasing aromatic hydrocarbon content.

6. Fuels containing moderate proportions of aromatic hydrocarbon compounds have been demonstrated in the literature to produce higher exhaust gas temperatures and greater levels of carbonaceous combustion deposits, when compared against equivalent low aromatic fuels under the same operational conditions.

7. Comparative operational trials between a domestically-supplied 100LL avgas (approx. 16% aromatic hydrocarbons / 0.38 gPb/L lead), and an imported 100/130 avgas (approx. 0.2% aromatic hydrocarbons / 0.72 gPb/L lead), showed the imported fuel to produce demonstrably lower sustained exhaust gas temperatures, when compared with the domestic avgas across the total time of each trial flight.

8. Aromatic hydrocarbon content limitations are not explicitly prescribed within contemporary standards and specifications for aviation gasoline.

6.3. Operating conditions

1. The engines operated in Robinson Helicopter Co R22 and R44 models predominantly rely on the forced flow of ambient air across the cylinders for the control of engine operating temperatures. Ambient air temperature is thus a key determinant of engine operating temperatures.
2. It is self-evident that helicopter (and other) aircraft engines in northern Australia would routinely operate across higher ambient air temperature ranges than their southern counterparts. This would be particularly applicable to mustering helicopters by way of the significant proportion of their operating time spent at low altitudes.

6.4. Systems
1. The investigation did not identify any systemic aspects of the maintenance or operation of the affected engines that could be held as a contributing factor to the mechanisms affecting cylinder durability.
2. The choice of lubricating oil grade and type was an identified variable across the operating engine fleet. While some of these lubricants (typically the semi-synthetic, multigrade types) would be expected to demonstrate superior resistance to oxidation and pyrolysis at elevated temperatures, there was no substantive information available to suggest a correlation between the durability experience and lubricant choice.

6.5. Defect reporting
1. The formal Defect Reporting Service (DRS) operated by the Civil Aviation Safety Authority (CASA) has been limited in its effectiveness in the context of bringing timely attention to the associated cylinder durability issues.
7. Recommendations

The following recommendations for future action and consideration are drawn from the findings of this investigation. The recommendations are not targeted at any specific individual or organisation, however they may fall within the remit of those organisations with carriage of safety and operational reliability of light utility helicopters.

Accordingly, the Australian Helicopter Industry Association (AHIA) recommends that:

1. Authorities with access to the historical data should examine the compositional characteristics of fuel provided by BP Australia to northern-Australian customers (via the Vopak terminal), with attention to aromatic hydrocarbon content.

2. Further work be undertaken to further and more fully characterise the thermal and operational performance of aviation gasolines containing moderate levels (10-20%) of aromatic hydrocarbon compounds. Such work should include an empirical comparison of these fuels with low-aromatic aviation gasolines in the following areas and across operational mixture ratios:
   a. Combustion behaviour and resultant rejected heat levels
   b. Deposit formation & characteristics
   c. Engine combustion chamber and valve cooling characteristics

3. Consideration be given to the potential airworthiness implications for conventional piston engine powered aircraft operating in environments of high ambient air temperature and using aviation gasoline products containing reduced lead and correspondingly increased levels of aromatic hydrocarbon compounds.

4. Advisory materials be prepared and circulated to relevant helicopter operators, to supplement the information available in the CASA Airworthiness Bulletins (AWB) and facilitate the awareness and control of risks associated with prolonged engine operation at high temperatures using aviation gasoline products containing moderate levels of aromatic hydrocarbon compounds.

5. Helicopter operators and maintainers should remain vigilant as to the issues outlined within this report and ensure they continue to follow best-practice operation and maintenance protocols.
8. References


Busch, M. 2018. Mike Busch on Engines, United States, Savvy Aviator Inc.


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