ACCIDENT

Aircraft Type and Registration:	Hawker Sea Fury T Mk 20, G-RNHF
No & Type of Engines:	1 Bristol Centaurus XVIII piston engine
Year of Manufacture:	1949 (Serial no: ES3615)
Date & Time (UTC):	28 April 2021 at 1315 hrs
Location:	Approximately 0.5 nm from Runway 04, RNAS Yeovilton, Somerset
Type of Flight:	Private
Persons on Board:	Crew - 1 Passengers - 1
Injuries:	Crew - 1 Passengers - 1 (Minor)
Nature of Damage:	Aircraft destroyed
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	60 years
Commander's Flying Experience:	11,550 hours (of which 36 were on type) Last 90 days - 146 hours Last 28 days - 55 hours
Information Source:	AAIB Field Investigation

Synopsis

The aircraft was being positioned for a landing on Runway 04 at RNAS Yeovilton following a low engine oil pressure indication. As the aircraft began the base turn, the engine seized suddenly and the pilot was unable to feather the propeller. Due to the extremely high rate of descent required to maintain speed it was not possible to reach the runway. The aircraft struck the ground approximately 0.5 nm from the runway threshold. The aircraft was destroyed but both occupants were able to extract themselves from the cockpit.

The engine's rear crankpin bearing had overheated, leading to extensive damage within the rear crankcase and causing the engine to seize. Due to the severe damage to the engine, the cause of the rear crankpin bearing becoming overheated was not established.

History of the flight

G-RNHF was prepared for a training flight for the front seat pilot with a pilot not rated on the Sea Fury in the rear seat for familiarisation. After completing a comprehensive brief for the sortie and reviewing the technical documents for the aircraft, the crew proceeded out to G-RNHF.

After strapping in, the pilot completed the pre-start process and the engine was started using external electrical power. The pilot reported that the engine started well and ran smoothly. The oil pressure initially indicated 110 psi with the oil cold, which the pilot considered to be normal whilst the engine warmed up. The passenger noted that his oil temperature gauge was indicating that the oil was very cold. The pilot noted that his was indicating normally, and the two occupants agreed that the rear gauge was inoperative. The Sea Fury does not have a parking brake system so relies on the pilot using the foot brakes to hold the aircraft in position. As a result of this, it is preferential to complete the engine run up checks on the ramp with the wheel chocks in place. The use of chocks and the pilot pressing on the foot brakes ensures that the aircraft is secure with the much higher power setting required for the checks.

The pilot spread the wings and completed other checks of the aircraft systems before running the engine up to 2,000 rpm. He then checked the magnetos and noted that the rpm drop seemed excessive on one. He noticed that the rpm had crept back so was lower than the 2,000 he had initially set. Having tightened the throttle friction, he again set 2,000 rpm and checked the magnetos. This time the rpm drops were within limits. The pilot noted that the oil pressure was steady at 100 psi at 2,000 rpm.

The pilot then reduced power for the slow running rpm check but was reminded by the back seat occupant who was following the checklist that he had omitted to check the supercharger gear change over which should be conducted at 2,000 rpm. The pilot re-selected 2,000 rpm and the supercharger check was carried out and found to be normal.

At 1300 hrs the pilot began taxiing G-RNHF to Runway 04 at RNAS Yeovilton. After completing the pre-takeoff checks and a final briefing, the aircraft approached the final holding position. At this point with the rpm around 600, the pilot noticed that the oil pressure was about 60 psi which was outside the normal operating limits. He confirmed with the passenger that the rear gauge was reading the same. He increased power to 1,200 rpm and the oil pressure immediately recovered. The pilot noted that repeating the engine run at 2,000 rpm for the supercharger check had probably left the oil at a higher temperature than normal and that was the cause of the momentary low oil pressure. The engine was running smoothly and there were no other signs of anything abnormal.

The aircraft took off at 1309 hrs and turned to the northwest during the departure. Seeing some weather on their track the pilot turned the aircraft to the east towards clearer skies. As the aircraft was heading out to the area of operation, the pilot noted that the oil pressure was low. He immediately informed ATC, making a PAN PAN call and turned back towards the airfield. The engine continued to run, but the pilot described it is as rather "lumpy and unsteady". He attempted to position G-RNHF for a landing on Runway 04 but having lowered the gear and flap to increase the rate of descent, the engine failed completely, generating several "violent thumps" through the airframe before it seized, leaving the propeller stationary. The pilot was unable to feather the propeller, and the increase in drag meant that it was not possible to make the airfield. The pilot made a MAYDAY call to ATC. The aircraft struck the ground around 0.6 nm from the threshold of Runway 04. The aircraft broke into several sections but both occupants were able to extract themselves from the cockpit without assistance.

Recorded information

The aircraft did not carry any devices that recorded data for the accident flight. The approximate flightpath taken by the aircraft, based on position information broadcast from it, is shown in Figure 1.

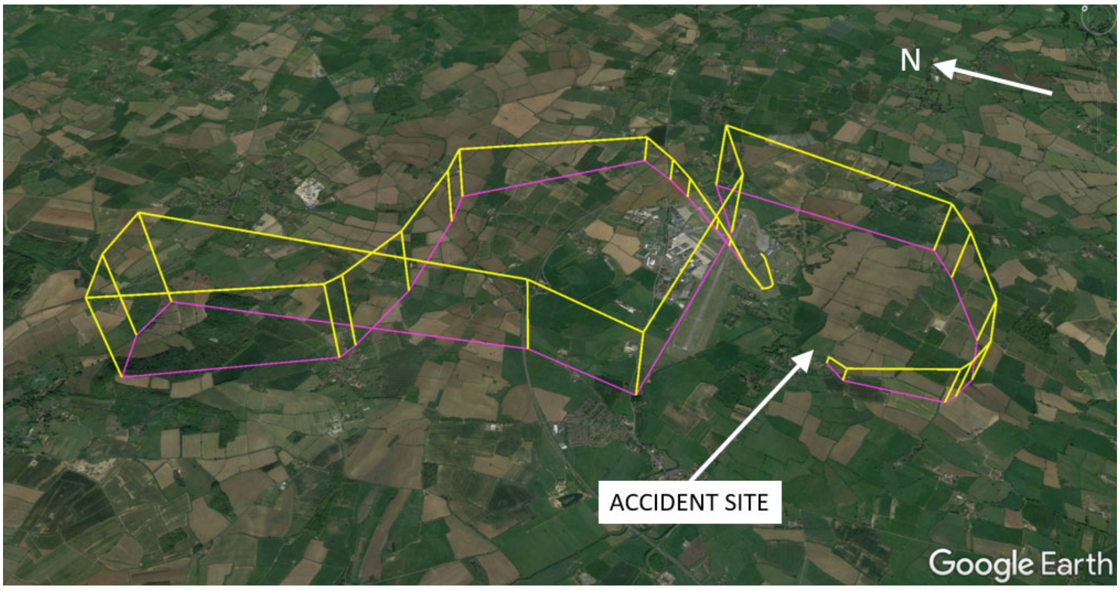


Figure 1

Accident flightpath (Image Landsat/Copernicus © 2022 Google)

The flight time between the start of the takeoff roll and the last recorded position was 5 minutes 30 seconds. It is estimated that the rate of descent, during the glide once the engine had seized, was between 7,000 and 10,000 fpm.

Accident site

The aircraft initially struck a telegraph pole, having cleared the roof of a nearby house by approximately 6 m, before it then struck the ground in a level attitude in an area of paddocks. Ground marks showed that the right main landing gear and tailwheel were extended when the aircraft touched down, however the right mainwheel then separated from the leg, which folded rearwards underneath the wing. The left main landing gear was found retracted in the wing. The aircraft slid across the surface of the paddock before striking a hedge which covered a shallow earth berm, causing the wing and engine to separate from the fuselage (Figure 2). The length of the wreckage trail from the first ground scar to the engine, which had travelled beyond the fuselage, was 95 m.

The fuselage came to rest inverted, supported by the fin and the right tailplane. It was covered in a light sheen of engine oil, which was described as normal for the type by a maintenance engineer familiar with the aircraft. No fire had occurred. The propeller was in fine pitch and all five blades were folded rearwards due to ground contact.

Figure 2
Accident site (courtesy of Defence Accident Investigation Branch)

Aircraft information

The Sea Fury T Mk 20 is two-seat, two-cockpit conversion trainer for the single-seat Sea Fury, incorporating dual controls. It is a cantilever, low wing monoplane with folding wings and retractable main undercarriage. A Bristol Centaurus XVIII radial air-cooled engine drives a five-bladed Rotol variable pitch propeller. The aircraft type entered service with the Royal Navy in 1947. Production ceased in 1955. The type had largely been retired from the Royal Navy by the late 1950s. Several Sea Furies (both single and two seat) remain airworthy around the world.

The Sea Fury T Mk 20 is a large aircraft with a maximum weight of 14,200 lb (6,441 kg), a length of 34 ft 7 in (10.5 m) and a wingspan of 38 ft 4.5 in (11.7 m). The weight of the aircraft is roughly equivalent to two Spitfires. G-RNHF was approved for passenger carrying under the CAA Safety Standards Acknowledgement and Consent regulations[1].

Centaurus XVIII engine

The Centaurus XVIII engine has 18 cylinders arranged into two radial rows of nine cylinders (Figure 3). Each cylinder has a swept volume of 2.98 litres, giving a total displacement of 53.6 litres. The engine is rated at 2,500 hp at 2,700 rpm and 9.5 psi boost pressure. The cylinders are numbered clockwise when viewed from the front, starting from the uppermost, with the front bank having even numbers and the rear bank odd numbers.

The flow of induction air-fuel mixture and exhaust gases into and from each cylinder is controlled by a sliding steel sleeve between the cylinder and piston. Each sleeve is driven by a crank, connected to gear train driven from the crankshaft, with one set of sleeve-drive gears for the forward row of sleeves and a second set of gears at the rear of the crankcase to drive the rear row of sleeves. The sleeves move in an elliptical motion and holes cut into the sleeve permit the passage of inlet and exhaust gases.

Footnote

1 CAP 1395 Safety Standards Acknowledgement and Consent (SSAC), Edition 3, January 2021.

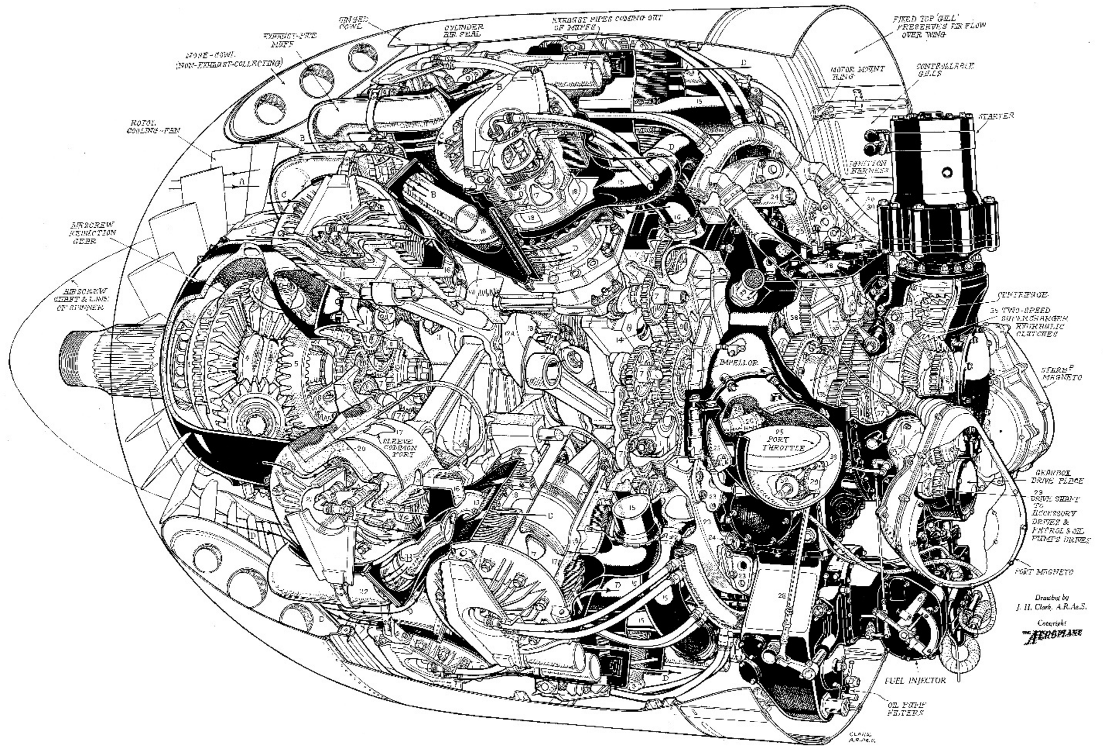


Figure 3

Bristol Centaurus engine (courtesy of Aeroplane/Key Publishing)

The crankcase is comprised of three separate aluminium alloy forgings, with circular lightening holes in the crankcase webs allowing oil to pass between the front and rear rows. The front cover, attached to the forward crankcase, encloses the front row sleeve-drive gear and supports the cover for the reduction bevel gear set that drives the propeller. A two-speed supercharger is attached to the rear of the crankcase, and a rear cover is mounted to the rear of the supercharger casing. The rear cover carries drives for two magnetos, the starter, accessory gearbox and Hobson injection carburettor.

The crankshaft is an assembly of three major components held together by four maneton[2] bolts, two each at the front and rear crankpins[3] (Figure 4). The crankpin bearings are steel sleeves coated with a tin-based soft white metal[4] bearing layer 0.015" thick. Oil is supplied to the crankpin bearings through drillings in the hollow crankshaft, and is distributed around the bearing surface through V-shaped grooves. Oil pressure is retained in the crankpin bearing by a silver-plated fixed oil retainer (Figure 5) on one side of the master rod and a floating oil retainer on the other, which also distributes oil to the articulated rod wrist pins.

Footnote

2 A maneton bolt is a fastener used to clamp the counterweight onto the crankshaft, through controlled tightening to a defined bolt stretch.

3 A crankpin is the part of the crankshaft to which the connecting rods are attached. In a radial engine, the master rod big end transfers all the loads from each cylinder to the crankpin.

4 The bearing alloy was Bristol specification B.A.C.E. 25, known commercially as Hoyt No.11 Z.3, composed approximately by weight of 86% tin, 6.0-7.5% antimony, 2.5-3.5% copper, 2.25-3.25% silver and less than 0.6% nickel.

The crankpin bearing sleeves are shrunk onto the crankpin journals to provide an interference fit, to prevent the sleeve from rotating on the journal, thereby maintaining alignment between the oil supply holes in the crankshaft and the oil entry holes in the bearing sleeve. Four dogs[5] at one end of each sleeve engage with the fixed oil retainer to further restrain the sleeve from rotating on the journal.

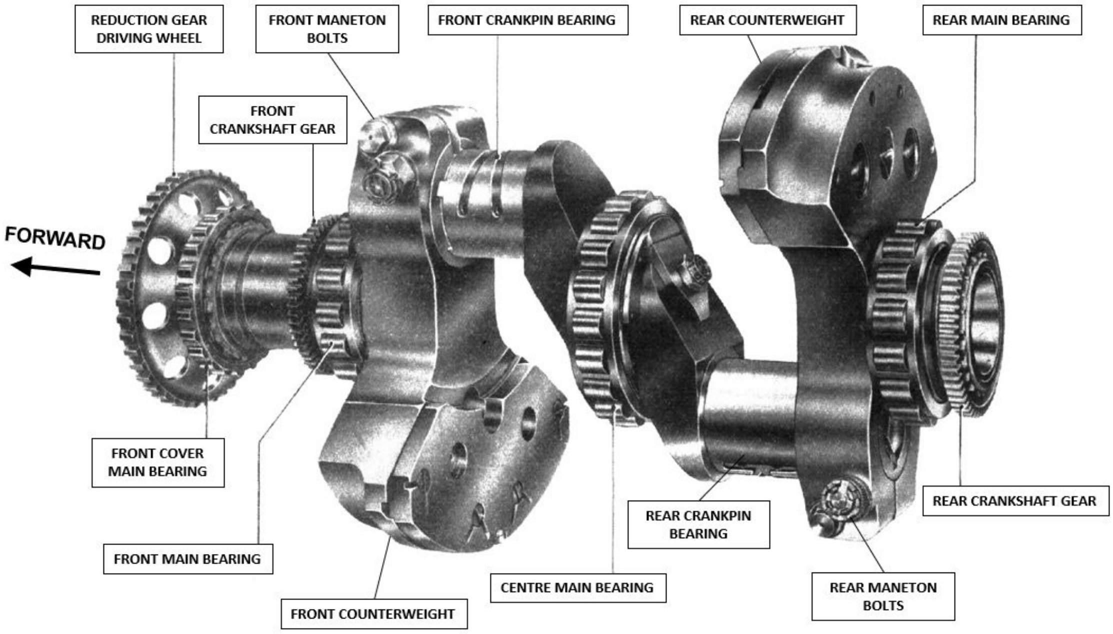


Figure 4
Crankshaft assembly

Each row of nine cylinders is connected to the crankshaft by a high-tensile steel master connecting rod, to which eight articulated connecting rods are connected via wrist pins arranged around the master rod big end. The master rod big end bore is hardened and ground to the required size at manufacture, and rides on the crankpin bearing. The crankpin bearings are reliant on the presence of a lubricating oil-film to prevent excessive bearing wear and overheating.

Footnote

5 In engineering usage the term 'dog' refers to a lug or other feature that prevents movement through physical engagement.

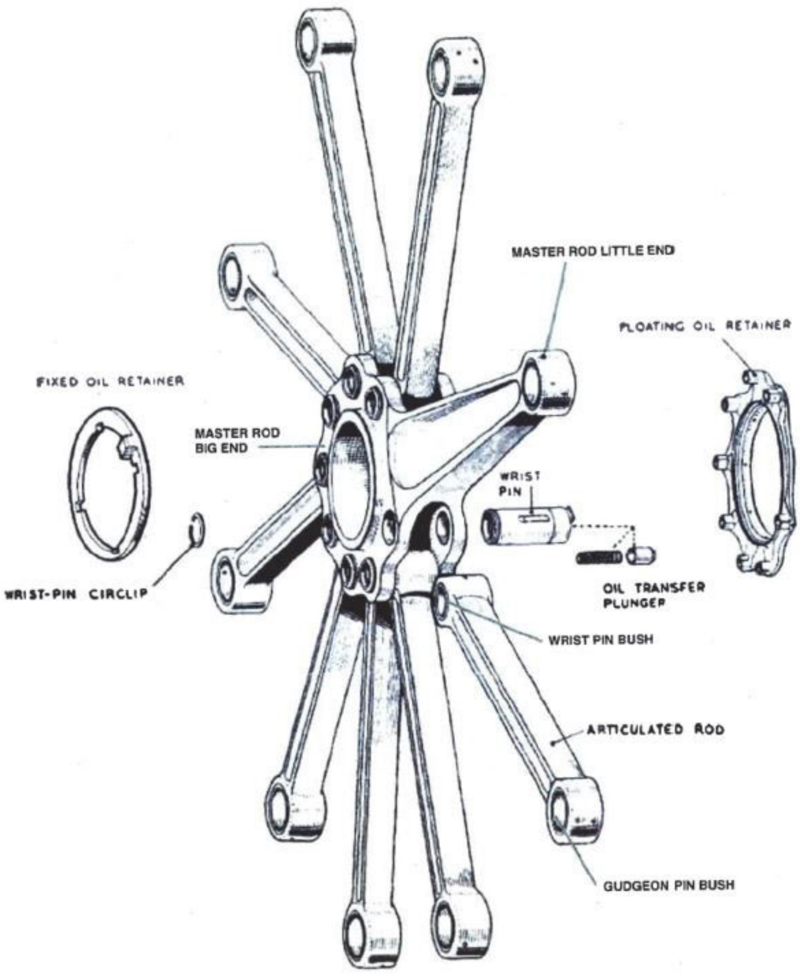


Figure 5

Master rod and articulated rod assembly

Oil grade

The *General and Technical Information publication for the Centaurus Mk 18 Aero Engine*[6], in its *Leading Particulars* section, states that the oil grade to be used in the engine is a 100-weight[7] mineral oil to Joint Service Designation (JSD) OM 270. This is a straight mineral oil with no additives. During the majority of the Sea Fury's military service life however, AeroShell Oil 100U was used, which is a dispersant[8] oil with metallic additives specifically formulated for Bristol sleeve valves engines. In 1965 the Ministry of Defence (MOD) conducted a trial of OMD 370, a 120-weight dispersant oil with non-metallic additives in Centaurus engines, however increased rates of piston ring failures, piston ring gumming and head ring failures occurred which led to the trial being halted.

Footnote

6 AP 102B-7501-1A, January 2006 (superseding AP 4146B Vol.1).
7 The weight of an oil is a measure of its viscosity; the higher the value, the thicker the oil is.
8 A dispersant additive assists in keeping combustion products suspended in the oil.

Stocks of 100U oil continued to be made available to the operator through the 1980s and 1990s until supplies were exhausted in approximately 2003. Following correspondence between the MOD and a lubricant specialist, a recommendation to use AeroShell Oil W100 was made. W100 is a 100-weight dispersant oil with non-metallic additives, widely used in poppet-valve piston engines. Correspondence between the MOD and the engine manufacturer in 2015 re-confirmed the recommendation to use W100 in Centaurus engines and stated that “it is essential to keep the oil system as clean as possible”.

Following the installation of G-RNHF’s overhauled engine, approximately six hours of engine ground-running was carried out using straight 100-weight mineral oil, before the oil was drained and replaced with AeroShell Oil W100.

Oil system

The engine is of the dry-sump type with an external oil tank mounted to the firewall and an oil cooler mounted in the left wing leading edge. The capacity of the oil system is 14 imperial gallons (112 pints) and typical engine oil consumption varies between 12 and 20 pints per hour, depending on the power setting.

Oil is gravity-fed from the tank, through a wire-mesh strainer to the engine-driven oil pump located at the base of the engine sump. The oil pump incorporates both a pressure pump and scavenge pump, which protrudes into the sump and is immersed in scavenge oil. Oil is drawn into the scavenge pump through a wire-mesh strainer. Additional scavenge return pumps, driven by the sleeve valve drive gear, are located at the front and rear row crankcases to return scavenge oil to the sump. Each scavenge return pump has a perforated inlet screen.

Oil pressure is measured at the outlet of the pressure pump and is displayed on gauges in both cockpits which also display the oil temperature and fuel pressure (Figure 6).

Figure 6

Combined oil temperature, oil pressure and fuel pressure gauge in the front cockpit

A pressure relief valve within the oil pump is set to limit the outlet pressure to 100 psi. A separate high initial oil pressure (HIOP) valve in the oil pump limits excessive oil pressure during cold starts by bleeding excessively-pressurised oil to the inlet side of the scavenge pump. High pressure oil from the pump is fed into the rear of the hollow crankshaft to lubricate the crankpin bearings, crankshaft main bearings and oil jets that splash-lubricate the bottom of the pistons and sleeves. An additional feed from the oil pump supplies two oil centrifuges which remove sludge and aeration from the oil that is fed to two clutch units used to drive a two-speed supercharger. High pressure oil is also supplied to the propeller constant-speed unit through a separate wire-mesh oil strainer. A pressure-reducing valve is used to reduce high pressure oil from the pump to 30 psi to lubricate the sleeve-drive gears and accessory gearbox.

Oil scavenged from the sump is returned to the oil tank via an anti-surge valve that returns oil directly to the tank during cold starting, when the oil is cold and viscous. Once the oil temperature has risen the anti-surge valve closes, forcing oil to flow to a thermostatic valve. When the oil temperature is below 50°C, the thermostatic valve causes the oil to bypass the oil cooler allowing the oil temperature to reach its minimum working temperature as soon as possible after the engine is started. As the oil temperature rises, the thermostatic valve progressively opens allowing more oil to flow through the cooler until the oil temperature rises to 90°C, when the valve is fully opened and all oil is passed to the cooler.

Engine history

The engine fitted to G-RNHF was an overhauled unit built around a core[9] purchased in the USA and a set of cylinders, sleeves, pistons and gudgeon pins sourced from a supplier in Australia. The previous running hours of these components was not established due to a lack of service records. Other components required for the engine were either sourced commercially or issued from the operator's parts store. A survey of the engine's modification state was performed by the maintenance organisation which concluded that the engine conformed to a 1952 build standard, with the caveat that other modifications of a later date may have been embodied but could not be proven due to a lack of technical information or part number marking.

The aircraft's maintenance organisation performed an overhaul of the engine based on the requirements contained in the Bristol Centaurus XVIII Overhaul Manual. The overhaul included disassembly of the engine into its constituent parts, stripping of protective finishes and geometric and NDT inspections of critical components as required by the overhaul manual. The engine was first run after overhaul in August 2017, fitted to G-RNHF which itself had undergone repairs following an accident in 2014[10]. The engine had accumulated 69.8 flying hours when the accident occurred. Apart from a minor oil leak from a magneto drive oil seal, there were no other engine-related deferred defects recorded.

Footnote

[9] The core engine consisted of the crankcase and crankshaft assembly, propeller reduction gearbox, sleeve-drive gears, supercharger and rear cover casings.

[10] AAIB Accident Report EW/G2014/07/32, published in the July 2015 AAIB Bulletin with an Addendum EW/C2014/07/02 published in the September 2017 AAIB Bulletin.

The Centaurus engine is not supported by the manufacturer under its Historic Engine Policy, and the maintenance facility and operator had to rely on copies of relevant technical publications they held on file. Original drawings and specifications for engine components were generally not available to them apart from a drawing of the crankshaft oil gland seal, which was issued to the maintenance facility by the manufacturer to allow a new seal to be produced, as no stocks were available.

Maintenance programme and engine lifing policy

The life between overhauls for Centaurus XVIII engines when in service use with the Royal Navy was set at 500 flying hours[11]. The maintenance organisation and operator noted that this figure was "difficult to achieve" based on their previous experience and they set the initial service life at 150 hours, with the intention of extending this figure based on satisfactory performance of the engine. They also agreed to perform an internal inspection of the engine at 50 hour intervals, with access inside the crankcase provided by removing one front and one rear cylinder at each inspection. The contents of the oil strainers and centrifuges were to be cleaned and examined at 25 hour intervals, and oil samples for a SOAP[12] programme were to be taken at 10 hour intervals.

The aircraft's maintenance programme required annual Primary inspections, Minor inspections every two years and Major inspections every six years. Routine maintenance was also specified at 25-hour intervals. A review of the maintenance records showed that the required maintenance had been carried out in accordance with the maintenance programme.

The aircraft entered an extended period of storage between November 2019 and April 2021 for which the engine was inhibited by coating the internal components with a 3:1 mix of engine oil and corrosion inhibitor[13]. Desiccant plugs were also fitted in place of the spark plugs. The engine was de-inhibited in February 2021 and run, following the required pre-oiling[14] process.

A Primary inspection was completed on 12 April 2021 and following the replacement of spark plugs to cure engine rough running, the aircraft flew from the maintenance facility to Yeovilton on 23 April 2021. The accident occurred on the next flight on 28 April 2021. As the period during which the aircraft's engine had not run was less than seven days, no pre-oiling process was carried out. The operator carried out a before-flight check on the morning of the accident flight, during which 1.5 gallons of oil was added to the oil tank, bringing the engine oil system level to 13 gallons.

Footnote

11 The AAIB understands that application of certain modifications and Bristol Technical Leaflets extended the service life of Centaurus XVIII engines beyond 500 flying hours, but has not been able to confirm this.

12 Spectrometric Oil Analysis Programme (SOAP) is a method used to monitor the health of aircraft engines and gearboxes by periodic laboratory analysis of oil samples. The laboratory tests reveal the composition and level of metallic particles suspended in the oil sample.

13 AeroShell Fluid 2XN.

14 The pre-oiling process ensures that the engine is sufficiently lubricated following inhibiting or when the engine has not been run for periods greater than seven days. It involves removing the spark plugs and pumping two gallons of heated oil through the engine oil system at a pressure of 60 psi, before rotating the propeller by hand through 12 complete revolutions. Following this a further gallon of heated oil is pumped through the engine oil system. The oil pipe between the tank and the engine is also purged of air in this procedure.

Meteorology

The weather forecast for RNAS Yeovilton was for a north-easterly wind, good visibility with broken cloud at 2,000 ft aal. Reports from the airfield at 1250 hrs indicated the wind was 040/17, visibility in excess of 10 km and cloud broken at 2,000 ft aal. There was little change between the 1250 hrs observation and the next at 1350 hrs.

Airfield information

RNAS Yeovilton is operated by the Royal Navy. It has a 2,292 m runway running 080-260° and a shorter 1,464 m runway 040-220° as well as a 600 m grass strip for light aircraft to the north of the main runway.

Personnel

The pilot of the aircraft has extensive 'warbird' experience including on the Sea Fury. Although this was only his second flight on the aircraft in the previous few years due to the aircraft storage and overhaul, he had flown a number of other similar types recently to prepare himself.

The passenger, although not rated on the Sea Fury, also has extensive experience on similar aircraft types. He was flying in the Sea Fury to familiarise himself with the aircraft and was able to offer some assistance to the pilot during the flight.

Survivability

Both the pilot and passenger were wearing full military style flying kit and helmets. Despite the extensive disruption to the aircraft during the accident, neither pilot suffered serious injuries. The cockpit area proved to be strong, maintaining its shape although it came to rest almost completely inverted. None of the harness straps failed and the helmets protected the occupants' heads during the accident sequence as well as during their escape from the aircraft. The pilot was able to leave the cockpit through the smashed front canopy and the rear canopy had slid back during the accident sequence allowing the passenger to vacate the rear cockpit. There was no post-accident fire.

Examination of the pilot's helmet after the accident showed that it had suffered a significant blow at some point during the accident sequence. Although the pilot suffered a small fracture to the skull, the helmet had protected him from a much more serious head injury.

Aircraft operation

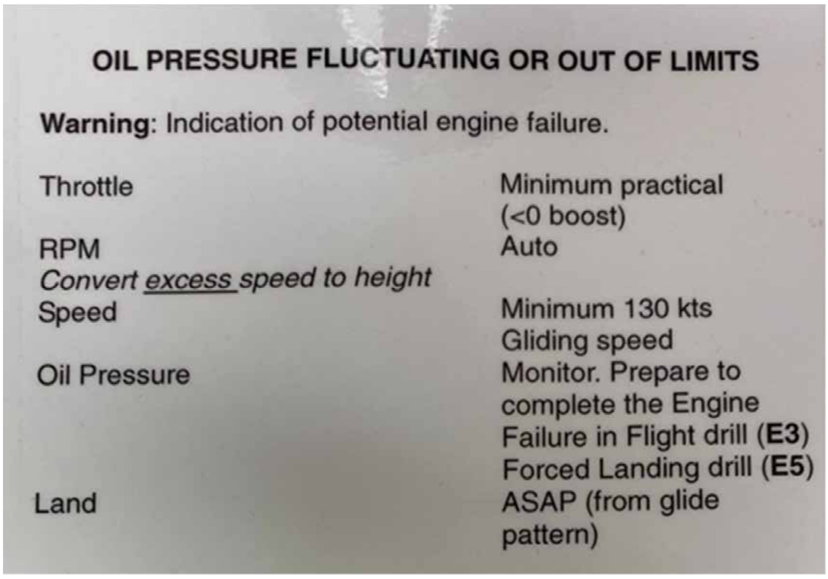
Pilot notes, maintenance manuals, engine manuals and checklists were based on the original naval military documents. The operators of G-RNHF had an extensive manual suite for the servicing and maintenance of the aircraft.

Emergency checklists

The operator of G-RNHF had developed a set of Flight Reference Cards (FRCs) which contained the normal checklist, as well as actions to be taken in the event of an emergency.

These emergency checklists included 'Oil Pressure Fluctuating or out of limits', 'Engine Failure in Flight' and a 'Forced Landing Drill'.

The operators FRCs checklist for oil pressure fluctuating or out of limit is:



OIL PRESSURE FLUCTUATING OR OUT OF LIMITS

Warning: Indication of potential engine failure.

Throttle	Minimum practical (<0 boost)
RPM	Auto
Convert excess speed to height	
Speed	Minimum 130 kts Gliding speed
Oil Pressure	Monitor. Prepare to complete the Engine Failure in Flight drill (**E3**) Forced Landing drill (**E5**)
Land	ASAP (from glide pattern)

Figure 7

FRCs Actions for Oil Pressure

The FRCs required the aircraft to be landed as soon as possible from a glide approach.

In this accident, on noticing the oil pressure issues, the pilot immediately initiated a return to Yeovilton. He did not consider that there were any mechanical signs of a failure and opted to leave the throttle where it was already located, minimising the change. Given his limited flying on the type, he decided to return to Runway 04 although this was a longer routing. Landing on Runway 08, whilst a shorter track distance, would have meant a reasonable crosswind which the pilot considered to be of a greater risk than the extra time to reach the into wind runway.

As the pilot flew the aircraft around the base turn for landing, he closed the throttle as he considered that he was too high and it was very shortly after this that the engine failed. He was unable to feather the propeller and a very high rate of descent was required to maintain the aircraft speed. Although the FRCs contained a forced landing drill, there was only around 10 seconds between the engine failing and the aircraft striking the ground. The pilot did not have the time to consider or complete the drill. This meant that both canopies were locked closed, rather than jettisoned or locked open as required by the forced landing checklist.

Whilst the FRCs required a glide approach to be flown, the seizure of the engine and propeller with no ability to feather would have rendered any glide approach path inadequate for the rate of descent that was required to maintain a suitable speed.

Engine examination

The propeller and engine cowlings were removed along with three cylinders from the rear row which revealed that the master rod and crankpin bearing had broken up, leaving the rear crankpin journal exposed (Figure 8). The remains of fractured articulated rods and pistons were visible in the bottom of the rear crankcase.

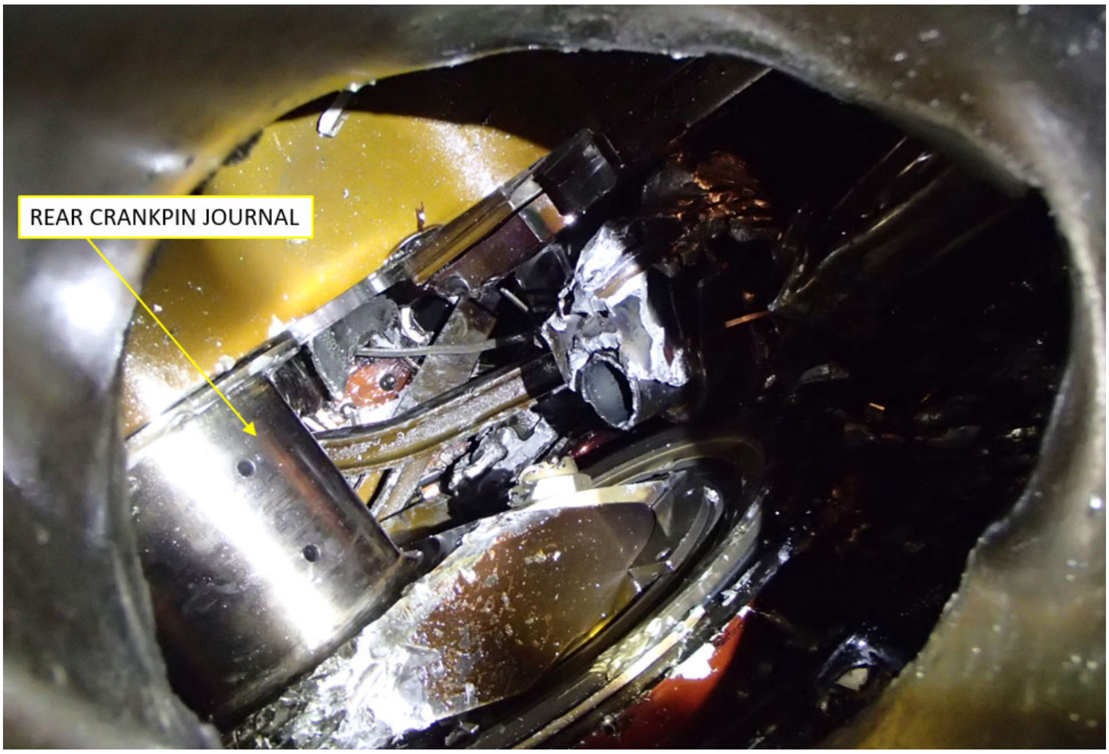


Figure 8

View inside the rear crankcase, looking down the No 17 cylinder

The engine was disassembled which showed that the front row components were largely intact, with only minor impact damage evident from debris liberated by the rear row that had entered the front row through the crankcase lightening holes. The rear master rod and articulated rods were fractured in multiple locations (Figure 9).

The fractured sections of the master rod big end showed evidence of overheating and a large number of cracks were present on the face of the master rod big end bore (Figure 10). The front master rod bore exhibited similar cracking. Examination of the cracks in the rear master rod bore showed that they were intergranular, following grain boundaries, and were coated with tin. Metallurgical assessment of the cracks noted that they were likely caused by liquid metal embrittlement (LME) of the master rod steel material with molten tin from the crankpin sleeve bearing. Three conditions are required for rapid crack propagation in steel due to LME with tin; the steel must be in a state of tension, with the steel surface free of oxidation and the liquid tin must intimately wet the steel surface. All three conditions were present in the master rod big end bores during the engine failure.

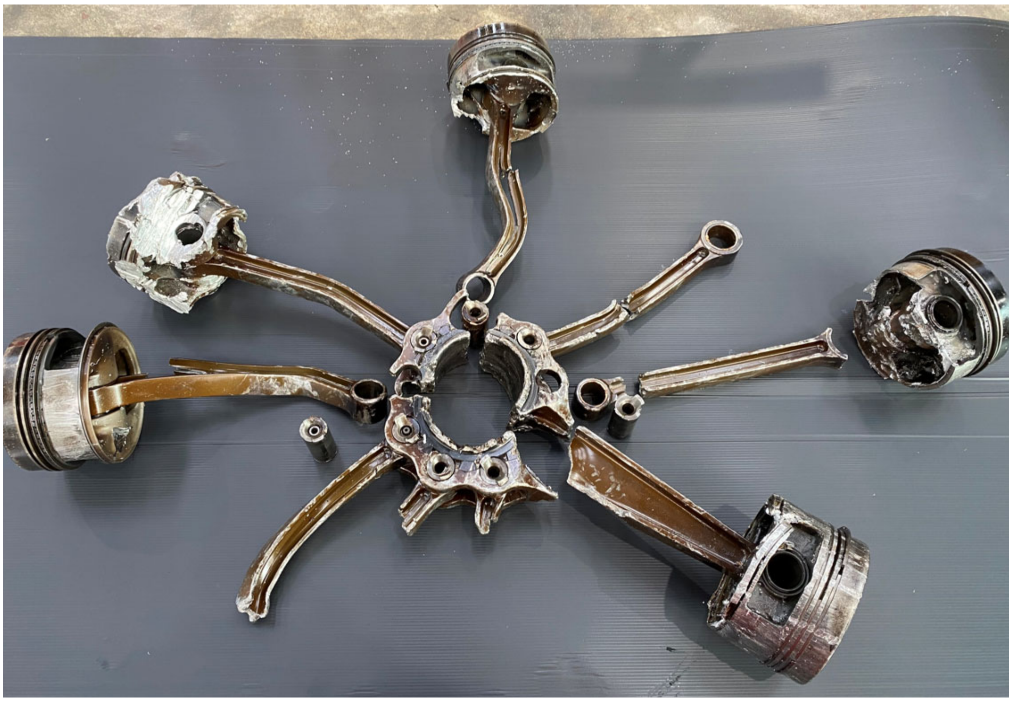


Figure 9

Front view of reassembled components of the rear row master and articulated rod assembly

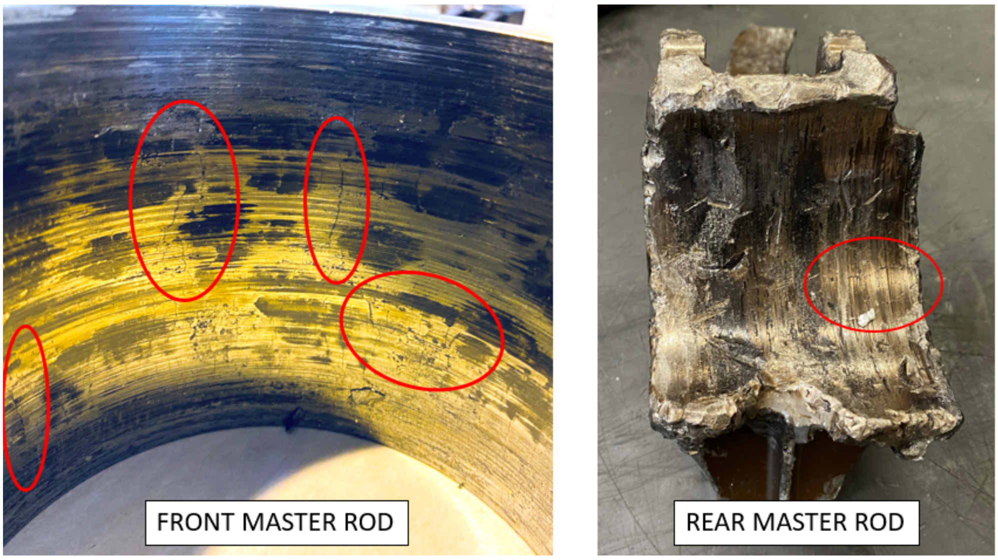


Figure 10

Cracks (circled) in the front and rear master rod big end bores

The fractures to the rear articulated rods were inspected and determined to be consistent with mechanical overload. There was no visible evidence of any progressive crack propagation, although smearing of some of the fracture surfaces during the engine failure prevented a complete examination.

The rear half of the crankshaft was bent and the rear maneton joint had slipped, opposite to the direction of crankshaft rotation, due to contact between the rear counterweight and debris within the rear crankcase liberated during the engine failure. Fretting marks were present on the mating surfaces of the rear maneton joint (Figure 11). The crankshaft rear main roller bearing had failed in overload.

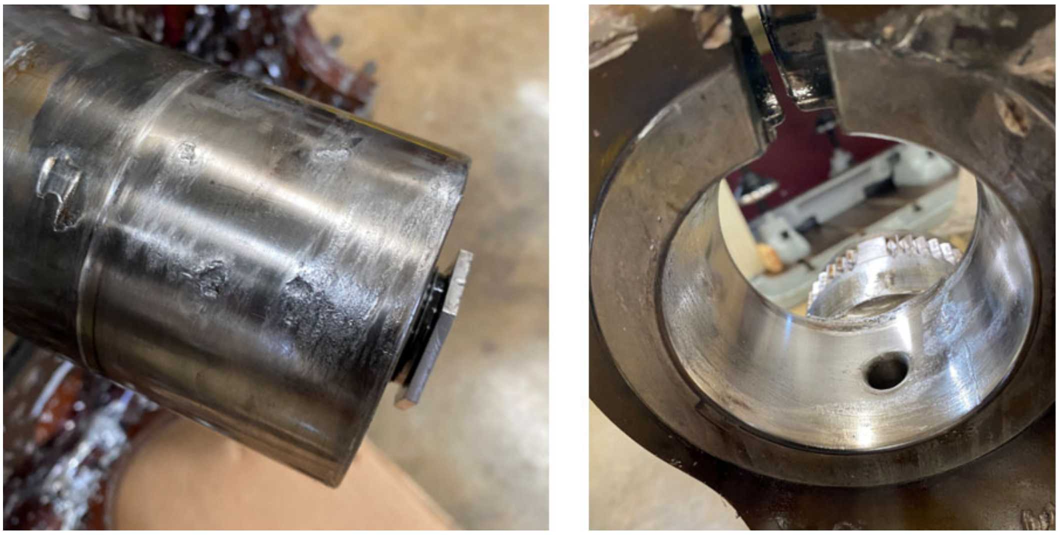


Figure 11
Fretting damage to the rear maneton joint

Both rear maneton bolts were mechanically damaged due to impacts. The degree of stretch present in the rear maneton bolts was measured during disassembly and found to be 0.009” for the rearmost bolt and 0.004” for the adjacent bolt. This was lower than the specified range of 0.013” - 0.015”, which was recorded as being applied to both rear maneton bolts in the engine overhaul records. The elemental composition and hardness of the maneton bolts were analysed, which showed that they were manufactured from BS S97 steel rather than BS S65 steel as specified on the bolt’s part drawing. BS S97 has similar mechanical properties to BS S65. The bolts were found to geometrically conform to drawing requirements.

The rear crankpin sleeve bearing was broken into three pieces (Figure 12). The sleeve’s locating dogs were sheared off and it had spun on the crankpin. The sleeve had overheated, causing the white metal bearing layer to melt and little bearing material was left on the sleeve.

Metallurgical analysis of the rear crankpin bearing confirmed the elemental composition of the white metal bearing material, along with lead bromide deposits, which are formed during the combustion of avgas fuel containing tetraethyl lead. The examination also revealed a small deposit of cadmium that had melted and resolidified on the bearing’s surface, indicating that the bearing temperature exceeded 321°C during the engine failure. The source of the cadmium was considered to be a fragment of cadmium plating from elsewhere within the engine, liberated during the failure sequence.

Figure 12

Front and rear crankpin sleeve bearings

The front crankpin bearing had missing regions of white metal bearing material adjacent to the oil entry holes (Figure 13). Examination of the missing bearing material under a scanning electron microscope showed that an antimony-tin phase of the white metal had melted due to contact with oil in excess of 232°C, leaving behind a copper-tin phase of the material which remained due to it having a higher melting point of 344°C. Some of the bearing material had been smeared, due to contact with the master rod bore once the lubricating oil-film was lost. The sleeve's locating dogs were intact and it had not rotated on the front crankpin.

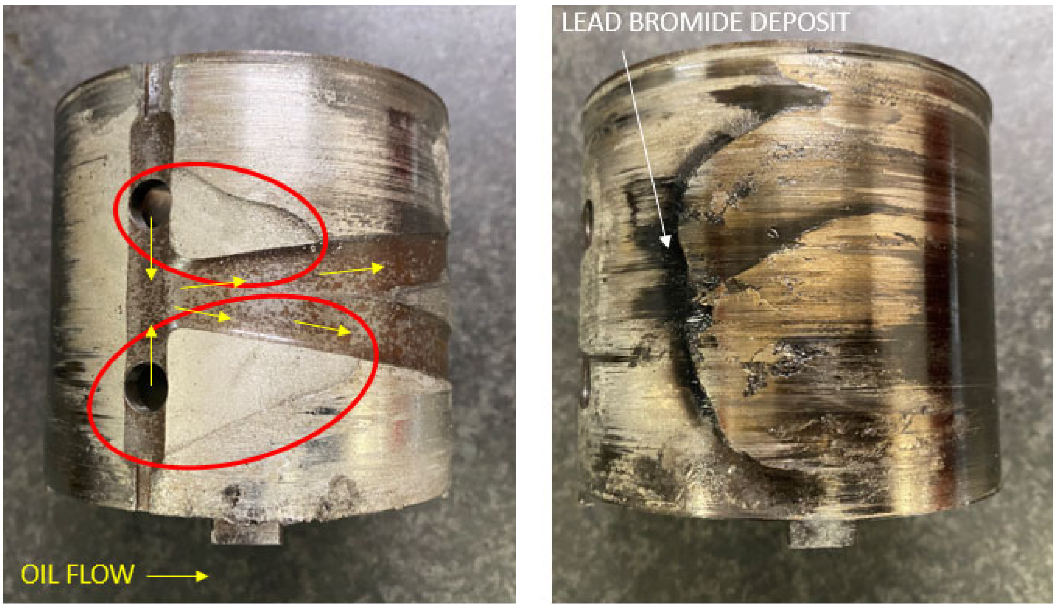


Figure 13

Front crankpin sleeve bearing, with missing bearing material circled

The rear row sleeves were all damaged at their bottom ends due to impacts received during the engine failure (Figure 14). The sleeve drives for cylinders 3, 5 and 9 had failed in shear overload and 11 had failed in bending due to an impact. The front row sleeves were largely undamaged apart from cylinders 6, 12 and 14 which had received light impact damage at their bases. The sleeve drives for cylinders 10 and 14 had failed in shear overload. All of the sleeves in both rows of cylinders exhibited elliptical scoring marks on their outer surfaces, indicating that they were all being driven normally whilst metallic debris was circulating in the engine oil system. No significant corrosion was observed on any of the engine components.

Figure 14

Typical impact damage to bottom end of a rear row sleeve (No 7 shown)

The magnetos were removed and run on a test rig. Whilst the left magneto operated normally, the right magneto sparked erratically. This magneto was disassembled, revealing that impact distortion to the casing had caused the points gap to close up, causing the erratic sparking. The ignition cable harnesses did not have any evidence of pre-accident defects, and all 36 spark plugs were in good condition with no damage observed to their electrode tips or ceramic insulation.

The pre-impact positions of the engine controls in the front and rear cockpits could not be established due to disturbance of the control rods and cables when the engine separated from the fuselage in the accident. The supercharger control valve was examined, however it was not possible to establish the supercharger gear selection at impact as the spool within the control valve is moved to the low gear position, under spring loading, once oil pressure is lost.

Oil system examination

Oil samples recovered from the oil tank, sump and crankcase all contained fine metallic debris and larger debris was trapped in the sump strainer and scavenge pump screens. A greater amount of debris was present in the forward crankcase scavenge pump screen than the rear. This could be attributed to drive to the rear scavenge pump having been lost during the engine failure sequence due to an impact of its sleeve-drive driving gear, whilst the front scavenge pump continued to be driven until the engine eventually seized.

The oil supply and return pipes between the engine and oil tank had parted in overload when the engine broke away from the fuselage. All engine oil pipes and hoses were examined and no blockages or other pre-existing deterioration was observed. The oil cooler was flushed and pressure-tested, and apart from the presence of metallic debris generated by the engine failure, no abnormalities were noted. The anti-surge, thermostatic and pressure control valves were disassembled and no defects were evident.

Mechanical drive between the crankshaft and oil pump was confirmed. The oil pump was disassembled revealing that its internal components were in good condition, including the HIOP and pressure relief valves. The crankshaft oil gland seal was installed in the correct orientation and was slightly stiff, but otherwise in good condition. The oil centrifuges were opened and a small amount of oil sludge was present. The oilways within the engine, including the crankshaft oil passages were clear of blockages and the required sealing between casings was present. The oil jets on the front crankshaft counterweight and centre bearing retaining bolt were free of obstructions, however the rear counterweight oil jet was too damaged to determine its condition prior to the engine failure.

Oil analysis results

The aircraft operator and maintenance organisation each sent engine oil samples to different laboratories for analysis (Figure 15). Oil samples were taken either from the oil sump drain point or the oil tank, and occasionally from both points. The operator's laboratory reported the results without reference to limiting values, whereas the maintenance organisation's laboratory provided warnings when the levels of certain elements exceeded thresholds set by that laboratory.

The oil analysis results were monitored by the maintenance organisation and did not give cause for any unscheduled maintenance or other investigation. Levels of tin above the warning level were ascribed to 'bedding in' of the sleeve-drive gears, which had been tin-plated during the engine overhaul. Relatively high levels of lead in the oil, thought to originate from tetraethyl lead in the avgas fuel, were seen to reduce to normal levels following an engine oil change. No warning level had been set for lead concentration level.

The maintenance organisation sent an oil sample from an oil centrifuge for analysis in July 2019, for comparison against oil drained from elsewhere within the engine oil system. This sample contained levels of metallic elements that were significantly higher than for previous oil samples. This result was interpreted by the maintenance organisation as confirmation that the centrifuges were successfully removing debris from the oil system, as was intended by their design.

Following the accident a sample of engine oil was analysed which showed that, aside from metallic particles present in the oil due to the engine failure, the oil conformed to a reference sample of unused AeroShell Oil W100 apart from the Total Acid Number (TAN). The sample TAN was 0.140 mgKOH/g, which was higher than the reference sample value of 0.016 mgKOH/g. The laboratory noted that TAN rises in engine oil during normal engine running, and that a value 1.0 mgKOH/g is regarded as an acceptable upper limit for W100 oil.

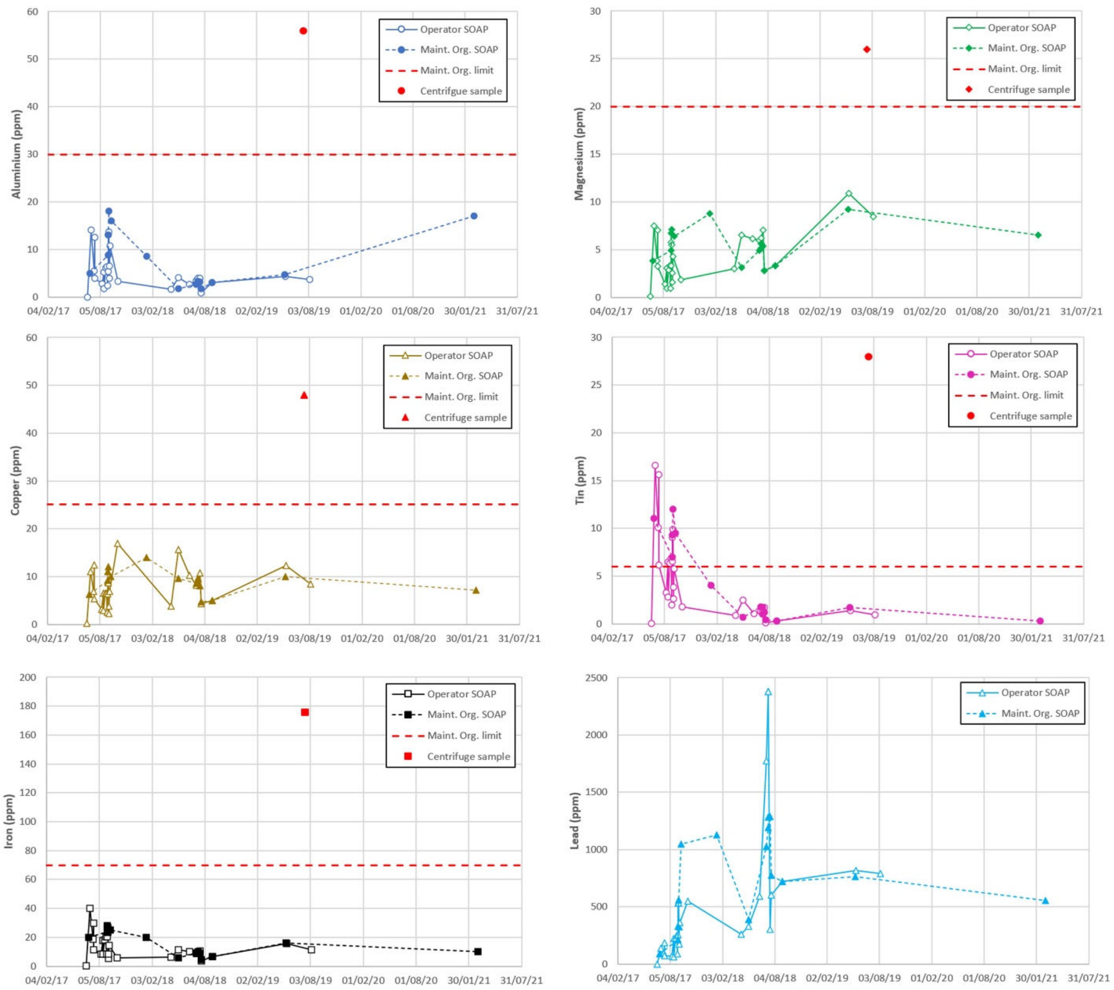


Figure 15

Summary of SOAP programme data

Other information

Sources of airworthiness information

The design standard and sources of information relating to the continued airworthiness of an aircraft operating on a National Permit to Fly (NPF) are defined in its Airworthiness Approval Note (AAN). The AAN for G-RNHF[15] was issued by the CAA in September 2010, following a review of the aircraft, its documentation and a design report submitted by the applicant. G-RNHF's NPF was issued by the CAA in 2011 and required an annual airworthiness review to remain valid, through a process resulting in the issue of a Certificate of Validity (CofV).

Footnote

[15] CAA Airworthiness Approval Note No. 29215, 15 September 2010.

The aircraft's maintenance organisation holds CAA approval under CAP 553 BCAR A8-25, permitting the organisation to conduct the airworthiness review and issue CofVs. G-RNHF's last CofV was issued on 9 April 2021 and was therefore valid when the accident occurred.

G-RNHF's AAN stated that the basis of approval for the aircraft included service experience with the type on the basis of precedence, along with an assessment of modifications as listed in AP4018C Volume 2, Part 1, which listed manufacturer's modifications applicable to the Sea Fury. The AAN further stated that this modification list had been assessed by the applicant and those considered relevant to the airworthiness, classified B/2 or above, had been applied. AP4018C relates to airframe modifications and does not contain modification data relevant to the engine.

Section 5.5 of the AAN provided a list of required manuals for the maintenance of the aircraft and its engine (Figure 16). The AAN stated a required amendment status for two of the manuals, but not for the others.

5.5.4 <u>Maintenance</u>

The following manuals are to be employed:

AP4018C Vol 1 AL39	Sea Fury T Mk20 General and Tech
AP4018C Vol Pt 1	Sea Fury T Mk20 Spare Parts
AP4018-5C/G/KL	Sea Fury Basic Maintenance Schedule
AP101B-7501-5V	Sea Fury "Structural Exam Requirements"
AP4158A Vol 1	Gen and Tech (AL11)
Bristol Centaurus:-	Aero Engine Care and Maintenance
AP4146B Vol 2 Pt3	Repair and Conditioning

Figure 16

List of required manuals from G-RNHF's AAN

In addition to the required manuals, the maintenance organisation had a copy of *Centaurus Aero-Engines Modification Lists*[16], which contains a tabulated list of Centaurus engine modifications. The title of each modification is listed, along with its Class and Repair Modification Category, but no additional description or embodiment instructions for the modifications are provided. The maintenance organisation also had a 1958 copy of the Centaurus XVIII *Illustrated Parts Catalogue*[17], which contains amendments to part numbers affected by issued modifications at that date.

Centaurus engine modifications are generally classified by a Ministry of Supply scheme of a combination of a letter and a number. The letter denotes the Repair Modification Category and the number denotes the Class of the modification. Repair Modification Categories vary between A and D (Table 1) and Class categories vary between 1 and 4 (Table 2).

Footnote

[16] AP2039, Amendment List 8, January 1963.
[17] Bristol Centaurus 18 and 57 Engines, Illustrated Parts Catalogue, Amendment List 12, January 1958.

Repair Modification Category	Meaning
A	Essential. Engines not to be dispatched without.
B	Essential when material available, on complete overhaul.
B*	As B, but must also be fitted on partial overhaul.
C	As material available.
D	Only when existing parts are worn out.

Table 1

Ministry of Supply Repair Modification Categories

Modification Class	Meaning
1	Safety modifications requiring immediate and compulsory embodiment in all engines of the type and/or mark, pending which flying is suspended.
2	Modifications of an operational character or of sufficient importance from a safety point of view to justify compulsory embodiment in all engines of the type and/or mark, but flying will not be restricted in the meantime. These modifications should be embodied before the issue of engines or aeroplanes to squadrons and similar units.
3	A desirable modification, the embodiment of which is discretionary. Commands are not entitled to refuse to accept engines which may be issued to them without these modifications embodied.
4	Modifications carried out only at maker's works and at repair depots.

Table 2

Ministry of Supply Modification Classes

In addition to modifications classified as above, a significant number of the available modifications were instead classified as Salvage, relating to the re-working of obsolete parts to a later modification standard.

The engine's modification status listed by the maintenance organisation when the engine was overhauled was compared against the list of available modifications for the Centaurus XVIII. Two Category A modifications were stated as embodied, against a total of four available Category A modifications however examination of the engine by the AAIB confirmed that all four Category A modifications were present. Sixty-nine modifications classified as B/2[18] and listed as available for the engine were not stated as embodied at overhaul, although the maintenance organisation had noted that other modifications of a later date may have been embodied, but could not be proven due to a lack of technical information or part number marking.

Footnote

[18] Repair Category B modification that was Modification Class 2.

Examination of the part numbers stamped on the sleeves revealed that two of the rear row sleeves, on cylinders 5 and 7, had been subject to salvage modification E.3338. This involved reapplying nitriding to the surface of the sleeves and stamping the modified sleeves with an additional part number[19]. The modification title for E.3338 stated that such modified sleeves were not to be used for master rod cylinders (number 7 and 8 on the Centaurus XVIII).

The operator held a copy of *Historic Centaurus Mk 18 and 58 Modification Leaflets*[20] on file, which had originally been held by the MOD before being transferred to the operator by the MOD on 1 January 2021[21]. This document had not been shared with the maintenance organisation by either the MOD or the operator, and the maintenance organisation was unaware that the operator had a copy of it. The operator stated that as the aircraft had been declared airworthy by the maintenance organisation, there was no perceived need to share the document with them.

The document contained detailed information relating to 86 modifications for the Centaurus XVIII, issued between June 1946 and April 1955. The information provided in each leaflet included the reason for the introduction of a modification, lists of required parts, embodiment instructions and illustrations. The maintenance organisation noted that whilst certain parts listed in a Modification Leaflet might no longer be available, the information contained in the leaflets was very useful in determining whether a particular modification was embodied, or was relevant to the airworthiness of the engine.

Analysis

Once the pilot and passenger had strapped into G-RNHF for a staff continuation training sortie, the engine was started normally and was described as running well by the pilot. The after start and before takeoff checks were completed on the ramp with the chocks in place as was normal practise. Although the supercharger check was missed by the pilot in his normal sequence, he was prompted by the rear seat occupant to complete it before the aircraft was taxied to the runway. There were no abnormal indications during or after the engine start.

As the aircraft approached the runway, the pilot noticed that the oil pressure was indicating 60 psi which was below the minimum limitation. This reading was confirmed by the rear seat occupant, but as the pilot increased the engine rpm to 1,200 the reading immediately recovered to a normal level. The pilot considered at the time that this might have been due to the oil being hotter than normal after the checklist items were completed. It is possible that this may have been the first indication of a problem with the engine.

Having departed from RNAS Yeovilton, the pilot began to head east towards clearer weather when he noticed that the oil pressure was low. He informed the tower at Yeovilton and

Footnote

19 SAL FB193081 for the rear row sleeves.
20 AP 102B-7501-2, July 2013 (superseding AP 4146B Vol.2, Part 1).
21 This transfer of documents coincided with the transfer of a number of historic aircraft from the MOD to the operator.

turned for the airfield. He considered that although the main runway (08) was closer, the crosswind presented a greater hazard to the aircraft and crew than the longer route to position for Runway 04.

The pilot was faced with a dramatic and complete engine seizure on the base leg turn to Runway 04. The aircraft position and height at the time of the failure, combined with the very significant increase in drag with the unfeathered propeller meant that it was not possible to reach the runway and the pilot was left with no choice but to attempt a forced landing from a very high rate of descent.

It is possible that, had the pilot decided to land on Runway 08, the engine might have still been running at touchdown but it is far from certain. There is no way to predict what caused the final failure and whether the cause may have occurred sooner had the aircraft throttle position been altered earlier in manoeuvring to Runway 08. Whilst the shorter pattern might have been considered a better option given the known outcome, the pilot was concerned about the crosswind when he had so little recent experience of the aircraft. The decision to proceed to Runway 04 was a reasonable one given that although the oil pressure was low there were no other indications of engine difficulties together with the pilot's lack of recent flying on type. Although the checklist required a glide approach to be flown, clearly given the rate of descent required once the engine had seized, any such glide approach pattern would have been rendered irrelevant as the aircraft height would still have been insufficient to reach the runway.

The time between the engine failure and the aircraft striking the ground was around 10 seconds. Although there was an emergency landing checklist that required the pilot and rear seat occupant to jettison or lock open their canopies, there was no time to complete these actions. Fortunately, both the pilot and the rear seat passenger were able to extract themselves from the wreckage as the front canopy had smashed and the rear canopy had slid open in the accident. The fact that both occupants were wearing helmets almost certainly saved them from any serious head injuries despite the cockpit coming to rest almost inverted.

Engine failure

The failure of the rear master rod resulted from overheating of the rear crankpin bearing, which caused its white metal bearing layer to melt. Increased friction between the crankpin bearing and the master rod bore was sufficient to shear the bearing sleeve's dogs, allowing the sleeve to spin on the crankpin journal. The molten tin liberated from the overheated bearing caused LME of the rear master rod big end. This promoted rapid crack propagation in the big end, leading to its eventual fracture into three main sections under the high loads imposed on it whilst the engine was running.

The damage sustained by the front crankpin bearing was caused by excessively hot oil flowing to it through the rear crankshaft, which had been heated by the failed rear crankpin bearing. This shows that some oil was still circulating within the high-pressure oil system whilst the rear crankpin bearing failure was underway. The overheated oil caused the partial melting of the front crankpin bearing, leading to similar LME-cracking of the front master rod big end although these cracks did not grow to a critical length and the front master rod remained structurally intact.

The breakup of the rear row connecting rods, pistons and sleeves occurred whilst the undisturbed front row continued to produce power, resulting in the very significant disruption observed within the rear row crankcase. The engine eventually seized when the rear maneton joint slipped, due to impacts between the rear counterweight and debris within the rear crankcase. Loss of alignment of the rear maneton joint caused sufficiently large radial loads on the rear main bearing that it failed in overload.

Despite the re-nitriding of the rear row's number 7 sleeve, which was not permitted under modification E.3338, there was no evidence to suggest that this contributed to the rear crankpin bearing failure. The sleeve had not seized in the cylinder bore and the lug at the base of the sleeve remained attached to its sleeve crank drive. All sleeves within the engine exhibited similar elliptical surface scoring due to contact with metallic debris in the engine oil whilst the sleeves were moving through their normal range of movement. Therefore the initiating event in the engine failure sequence preceded any subsequent failure of the rear row sleeves.

It is uncertain whether the loss of oil pressure observed by the pilot preceded the overheating of the rear crankpin bearing, or whether it occurred as a result of the bearing failure due to another unidentified cause, which then allowed oil to leak from it resulting in a loss of oil pressure. The remains of the bearing were too badly damaged to allow a determination of the cause of the bearing failure. It is possible that mechanical failure or rapid wear of a component within the engine, unidentified by this investigation, generated debris that circulated within the engine oil system. In this scenario any debris would reach the rear crankpin bearing first, due to the direction of oil flow within the crankshaft, and could cause rapid wear of the bearing, leading to its failure.

No pre-accident defects were identified in the engine oil system or its associated components. An unusually large number of oil samples were analysed for the SOAP programme, however after an initial 'wear-in' period, the oil analysis did not show any adverse trend that would have prompted the maintenance organisation to carry out unplanned maintenance or investigative activity.

Modifications

The maintenance organisation's assessment of the modification standard of the engine was hampered by a lack of relevant information, in particular in not having access to a complete set of Modification Leaflets covering all the issued modifications for the engine. The AAN for the aircraft only contained a requirement to consider the airworthiness implications of airframe modifications classified as B/2 or above, which the maintenance organisation complied with. The list of engine modifications embodied in the overhauled engine was therefore incomplete, however this information was accepted by a CAA surveyor when an audit visit occurred prior to operation of the aircraft with the overhauled engine.

The maintenance organisation's lack of access to Centaurus XVIII Modification Leaflets could have been partially alleviated if the operator or, prior to 1 January 2021, the MOD had shared those it held on file, however this did not occur as the maintenance organisation was unaware that they were potentially available and therefore had not asked for them.

As the investigation was unable to identify the cause of the rear crankpin bearing failure, no link can be drawn between the engine failure and the engine's modification standard. However since B/2 modifications relate to the improvement of an engine's safety or reliability, it is important that maintenance organisations have access to this information when assessing if an engine has a particular modification embodied, and if not, what the impact on its airworthiness may be.

Enquiries made by the AAIB during the investigation indicate that difficulties in access to relevant information for historic piston and turbine engines, particularly in relation to identifying engine modification status and modification data, is a systemic problem.

As a result of this investigation the CAA have agreed to meet with the engine manufacturer to discuss whether Modification Leaflets for the Centaurus XVIII can be made available to maintenance organisations servicing these engines, despite the restrictions imposed by the manufacturer's Historic Engine Policy.

Conclusion

The aircraft's engine failed shortly after takeoff on the second flight following a long period of aircraft storage. Examination of the engine identified that the rear crankpin bearing had overheated, leading to fracture of the rear master rod and destruction of the rear cylinder row components. Due to the severe engine damage, the investigation was unable to identify why the rear crankpin bearing overheated.

The point at which the engine seized on the base leg for landing left the pilot with no choice but to complete a forced landing short of the runway. Despite not having time to jettison or open the canopies, both pilots were able to vacate the cockpit once the aircraft had come to rest.

The investigation identified the difficulty maintenance organisations have in accessing technical information for historic engines, in particular that relating to engine modifications. The CAA have agreed to meet with the engine manufacturer to discuss whether Modification Leaflets for the Centaurus XVIII can be made available to maintenance organisations servicing these engines.

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