Inquiry 11-005: Boeing 747, engine compressor surges
18 September 2011

Final Report

Aviation inquiry 11-005: Engine compressor surges

18 September 2011

Approved for publication: 24 July 2013

Transport Accident Investigation Commission

About the Transport Accident Investigation Commission

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

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

Photographs, diagrams, pictures

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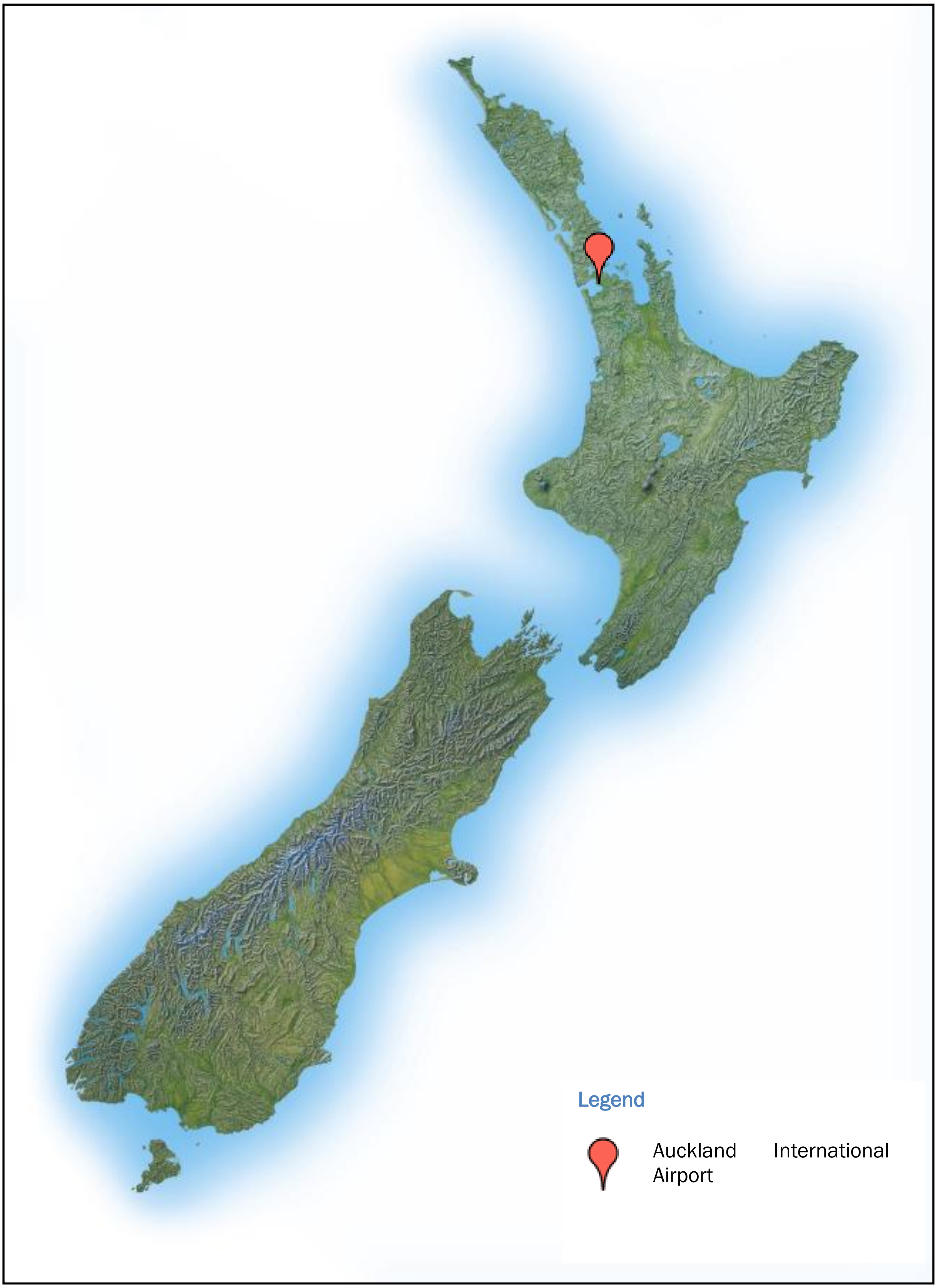
Boeing 747-419 ZK-NBT



Source: mapsof.net

Location of incident

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Abbreviations

°C Celsius

CAA	Civil Aviation Authority of New Zealand
Commission	Transport Accident Investigation Commission
ECU	engine control unit
EGT	exhaust gas temperature
EICAS	engine indication and crew alerting system
MEC	main engine control
RNZAF	Royal New Zealand Air Force
VIGV	variable inlet guide vane

Glossary

abradable lining	material on the inside of a turbine engine between the casing and the rotor tips, which is designed to wear away with use
component life	a predetermined limit for a component, often expressed in flying hours, cycles or time, after which it must be inspected or replaced, as required
component soft life	a predetermined figure, normally expressed in either hours or cycles, after which it is recommended that the component be inspected if the engine or the component is subject to other engineering work that facilitates the additional inspection. Should such an opportunity not arise, the component may continue to remain in service until its component life is reached or a fault occurs
compressor stall	the disruption of normal airflow through the compressor of a turbine engine resulting from a stall of the aerofoils. The event may vary from a minor power loss that occurs too quickly to be seen on engine instruments, to a complete breakdown of airflow through the compressor (surge) requiring a reduction of fuel flow to the engine
compressor surge	an un-commanded surge of pressure through an engine, often associated with banging or popping noises and possibly flames out of the exhaust. In more severe cases the pressure surge may move forward, causing flames to come out of the engine air intake
on-condition maintenance	sometimes called "condition-based maintenance" or "predictive maintenance", on-condition maintenance allows an engine to continue in service provided its performance remains within strict tolerances. The programme requires close monitoring of the engine with prompt trend and fault reporting, and redundancy
uncontained failure	an engine failure where a component or components detaches from and leaves the engine in an uncontrolled manner, possibly at high speed
variable inlet guide	a device usually located at the front of a turbine engine that directs the air into vane the engine at the required angle. Normally closed while the engine is starting and at low speed, it progressively opens as turbine speed increases. The vane helps to prevent compressor stalling
yaw	the movement of an aircraft around its vertical axis. Observed as the nose of the aircraft moving left or right from the direction of flight

Data summary

Aircraft particulars

Aircraft registration:	ZK-NBT
Type and serial number:	Boeing 747-419, 24855
Number and type of engines:	4 Rolls-Royce RB211-524GT turbofans
Year of manufacture:	1990
Operator:	Air New Zealand Limited
Type of flight:	scheduled air transport

Date and time	18 September 2011, 2040[1]
Location	Auckland International Airport
	latitude: 37° 00´ 29" south
	longitude: 174° 47´ 30" east
Injuries	nil
Damage	confined to compressor blades and lining

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

1. Executive summary

General

1.1. On 16 September 2011 an Air New Zealand Boeing 747-419, registered ZK-NBT (the aeroplane), was on approach to land at San Francisco when the crew was alerted by the crew of another aircraft that flames were coming from the number 4 engine.[2] There was no indication on the flight deck of the condition. After an uneventful landing and shutdown, the local engineer inspected the engine in accordance with the published procedure. After some additional checking and engine running, he released the aeroplane back to service. The aeroplane completed a further 2 sectors without incident. On the next sector, while on approach to land at Auckland, the number 4 engine surged and it was shut down by the crew. The aeroplane landed safely on 3 engines.

1.2. The cause of the surge at Auckland was not identified and it could not be determined whether the San Francisco occurrence contributed to the more severe occurrence at Auckland. The actions of the San Francisco engineer in following the prescribed maintenance procedures, and completing some additional checks before releasing the aeroplane back to service, were considered appropriate.

1.3. Engine compressor stalls and surges can be dramatic, especially for passengers. However, a review by Rolls-Royce of reported RB211 engine surge events showed that while a stall could result in damage or having to shut down the engine, the safe operation of the aeroplane should not be affected. In both incidents the crews acted correctly in dealing with the surges.

1.4. The Transport Accident Investigation Commission (Commission) became aware of another 2 recent engine failure/shutdown occurrences in Air New Zealand's (the operator's) fleet of aeroplanes. Although these incidents had involved different aeroplane types, each type, like the Boeing 747, had been scheduled for replacement in the short to medium future.

1.5. The inquiry found no link between the 3 engine occurrences and nothing to suggest that the operator was accepting lower engineering or safety standards as the 3 aeroplane types neared replacement.

Key lessons

1.6. No new safety lessons were identified.

[2] The right outboard engine.

2. Conduct of the inquiry

2.1. The incident that initiated this inquiry was the surge event that occurred at Auckland on 18 September 2011. The Commission first became aware of the incident through the news media on 22 September. Initial enquiries identified that the same aeroplane and engine had had a similar event 2 days earlier. An investigation was commenced as a result.

2.2. The Commission's inquiry was assisted by the Royal New Zealand Air Force (RNZAF), which had engineering expertise with the engine, as a version of the RB211 was fitted to RNZAF Boeing 757 aeroplanes.

2.3. In consultation with the operator and the RNZAF, the Commission agreed a work scope package to manage the inspection of the engine and its components. Several components, principally those related to the airflow control system, were removed for bench testing and examination. A boroscope[3] inspection of the inside of the engine was also completed.

2.4. The engine manufacturer, Rolls-Royce, provided advice on component operation, interaction and reliability. Supporting information was also obtained from the Civil Aviation Authority of New Zealand (CAA).

2.5. In November 2011, 2 senior Air New Zealand Limited engineering staff gave a presentation to the Commission on the maintenance of aeroplanes operated by Air New Zealand.

2.6. On 22 May 2013, the Commission approved the draft final report for circulation to Interested Persons for their comment. Submissions were received from Air New Zealand, the RNZAF, Rolls-Royce and the CAA. The Commission has considered all submissions, and changes have been made to this report where considered appropriate.

2.7. On 24 July 2013 the Commission approved the final report for publication.

[3] An optical device with a lens at one end and an eyepiece at the other, normally connected by a flexible tube.

3. Factual information

3.1. Narrative

3.1.1. On the evening of 16 September 2011, ZK-NBT, a Boeing 747-419 operated by Air New Zealand, was on approach to land at San Francisco International Airport. At between 600 and 700 feet on final approach, as the power was increased slightly, the crew heard muffled "popping" noises. The crew initially thought that the noises were coming from the nose landing gear area. At the same time the pilot of another aeroplane on approach to a parallel runway radioed that flames were coming from the tailpipe of the number 4 engine. The crew checked the engine instruments and noted that everything was within limits and all appeared normal. As power was reduced the noise stopped and an EICAS (engine indication and crew alerting system) advisory message "ECU ENG 4" (Engine Control Unit – Engine 4) was displayed. With no other warnings or cautions, an uneventful landing was completed without the use of reverse thrust on any of the engines. The aeroplane was taxied to the gate and shut down.

3.1.2. An engineer who was employed by another airline that had a contract to provide engineering support to Air New Zealand at San Francisco met the flight crew and was briefed on the incident and EICAS message. The other airline also operated the Boeing 747 with the same engine type. The engineer inspected the engine and found no damage or obvious cause, such as a bird strike, for the flames and EICAS message. He then followed the actions detailed in the Boeing Fault Isolation Manual, which led him to examine a particular pneumatic line. The line was disconnected and inspected. No obvious blockages were recorded as being found, but the possibility of a partial blockage could not be excluded. The pneumatic line was then reinstalled and checked.

3.1.3. In addition to the required actions, the engineer contacted the control tower, which confirmed that a crosswind had been blowing at the time the aeroplane landed. The engineer had the aeroplane towed to a remote area to perform a high-power ground run. This included several rapid throttle movements from idle to full power and back again to check the acceleration and deceleration of the engine. The original fault could not be reproduced.

3.1.4. The engineer contacted the operator's maintenance operations centre in Auckland, and briefed the duty staff on the fault and the maintenance work completed. They agreed that, having followed the manufacturer's instructions, checked the pneumatic system and performed additional testing, the aeroplane could be released for service. The aeroplane completed a normal service to Auckland the next day.

3.1.5. On 18 September the aeroplane operated from Auckland to Sydney and return. The leg to Sydney was completed without incident. At 2040 and at about 500 feet on final approach to land at Auckland, the number 4 engine stalled and surged.[4] The crew noted that the engine's exhaust gas temperature (EGT) reading began to increase, and as it started to exceed the temperature limit the engine was shut down using the fuel control shut-off switch. Several EICAS messages related to the engine temperature were also displayed at this time. An otherwise uneventful 3-engine landing was completed.

3.1.6. Following the incident, the number 4 engine was removed from the aeroplane and quarantined as part of the investigation.

3.2. Aircraft information and damage

3.2.1. ZK-NBT was a Boeing 747-419, serial number 24855, manufactured in the United States in 1990 and immediately leased by the operator. The aeroplane was powered by 4 Rolls-Royce RB211-524GT turbofan engines (see Figure 1). The incident engine, serial number 13261, was owned by the operator and had accrued 65 371 hours and 6988 cycles[5] since new, and 29 415 hours and 3926 cycles since its last overhaul.

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[4] See section 3.4 for a full description of engine operation and surge information.
[5] A cycle is one start.

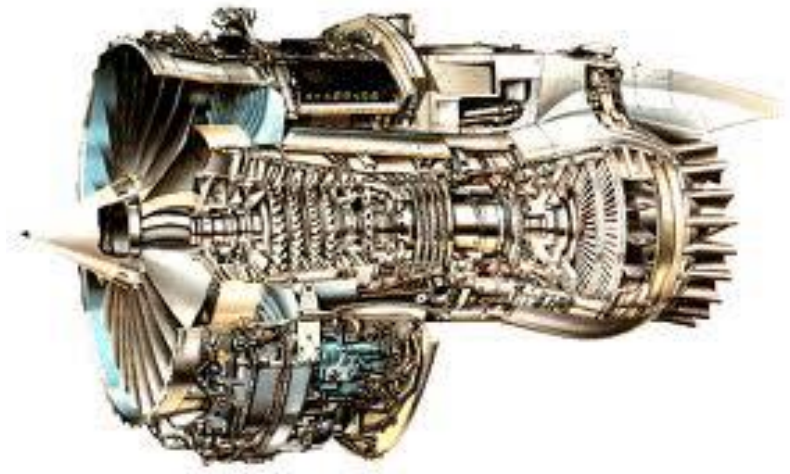

Figure 1
Rolls-Royce RB211

3.2.2. The operator was in the process of decommissioning its fleet of Boeing 747 aeroplanes, but still had 4 aeroplanes available for flying at the time of the incident. The 4 aeroplanes included 2 that were powered by General Electric CF6-80C2-B1F engines and 2 that were powered by RB211s. The RB211-powered aeroplanes were leased to the operator and were the next to be withdrawn from service. To support the Rolls-Royce-powered aeroplanes, the operator owned 5 spare engines, including the incident engine.

Engine and damage assessment

3.2.3. All engines were maintained in accordance with the Rolls-Royce maintenance schedule. All service bulletins that were required to be embodied on the incident engine at the time of the incident were recorded as having been completed. Another service bulletin, SB72-D574, concerned wear between the intermediate-pressure and high-pressure stages of the compressor, an area nicknamed the "birdmouth" (see Figure 2). The bulletin advised that wear in this area "can allow contact between stage 1 blades and abradable lining resulting in lining loss, increased rotor tip clearances, and a reduction in surge margin". The area was subject to regular inspections as part of the monitoring of the condition of the engine. However, the bulletin was not of sufficient urgency to require immediate action and could be incorporated into an operator's regular maintenance programme. The incident engine, one of 2 engines yet to have this service bulletin embodied, was scheduled for this work at the "next shop visit" before compliance date.

3.2.4. The Boeing 747 fleet decommissioning schedule had the Rolls-Royce-powered aeroplanes ceasing service with the operator in February 2012 in order to allow time for the 2 airframes and 8 engines to be returned to the lessor's specifications by May 2012. To help facilitate this, the operator's own engines were being put on the aeroplanes while the leased engines were put through the maintenance workshop to ensure they met the lessors' requirements. For example, some components might have needed changing to ensure that they had the required minimum service lives remaining.

3.2.5. A review of the engine history showed that it had last been overhauled in 2000, when it was upgraded to GT status.[6] During the next 9 years the engine had been installed at various times on different aeroplanes, with no major faults being reported during that time. In May 2009 the engine had been removed from an aeroplane that was being retired from service and used to support the maintenance workshop visit programme as part of the decommissioning of the B747 fleet. The engine was held in storage between each aircraft fitment. The operator's engine storage conditions were inspected and found to exceed the minimum specifications recommended by the manufacturer. Stored engines were sealed in a

[6] Modification of the engine by the installation of the Trent 700 high-pressure compressor. This resulted in a weight reduction, improved fuel efficiency and reduced emissions.

controlled environment that included data recording of environmental conditions for the periods of storage.

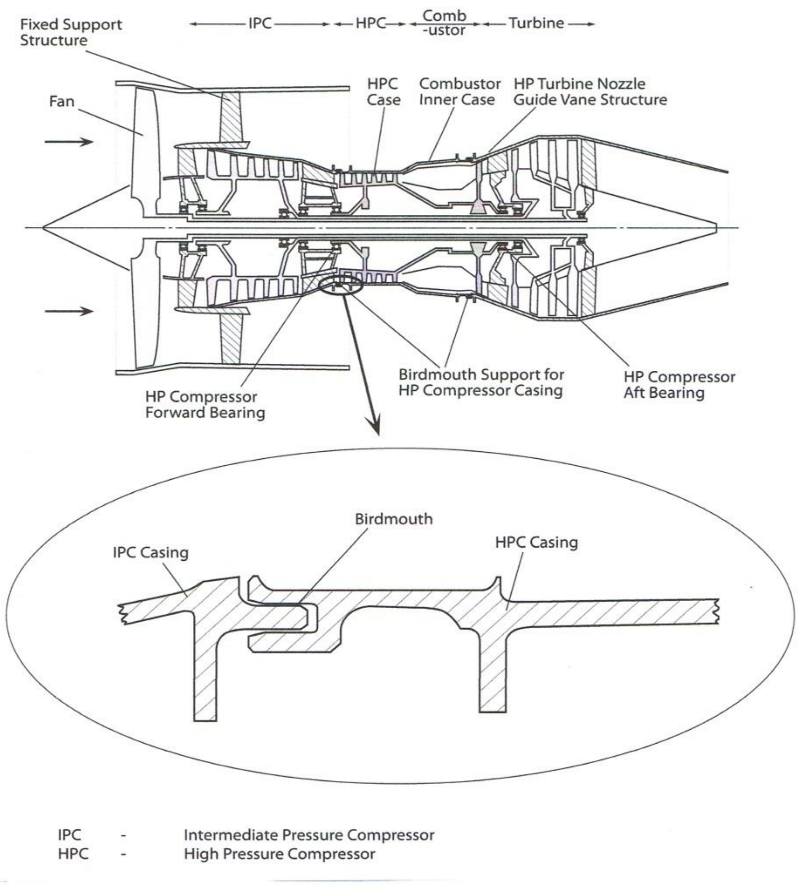

Figure 2
RB211 diagram

3.2.6. On 9 September 2011 the engine was installed on ZK-NBT in the number 4 position. Installation documentation showed the engine had an EGT margin of 33 degrees Celsius (°C) on fitment. EGT is the primary measure of engine health. The difference between the EGT produced at full power and the maximum permitted EGT is the EGT margin. The minimum margin allowed was 0°C.

3.2.7. The incidents at San Francisco and Auckland were regarded as being related in that they both displayed characteristics of a compressor stall and possible surge. (See section 3.4 for a full explanation of engine stalls and surging.) Because of this, in addition to inspecting the condition of the engine, attention was directed to the airflow control system.

3.2.8. Digital flight data recorder information for the 2 incidents was downloaded and reviewed. The data confirmed that a stall had occurred during the approach to San Francisco. The engine manufacturer also confirmed that the EICAS message and associated central maintenance computer message referring to the pneumatic line had been generated by the stall and surge. The messages had not preceded the surge.

3.2.9. After the engine had been removed, a boroscope inspection showed that several high-pressure compressor stage 1 blades were bent and there was tip curl on 6 of the stage 2 blades. Sections of the high-pressure compressor case liner were also seen to be missing (see Figures 3 and 4). The amount missing was considered to be in keeping with the age of the engine, but not excessive.

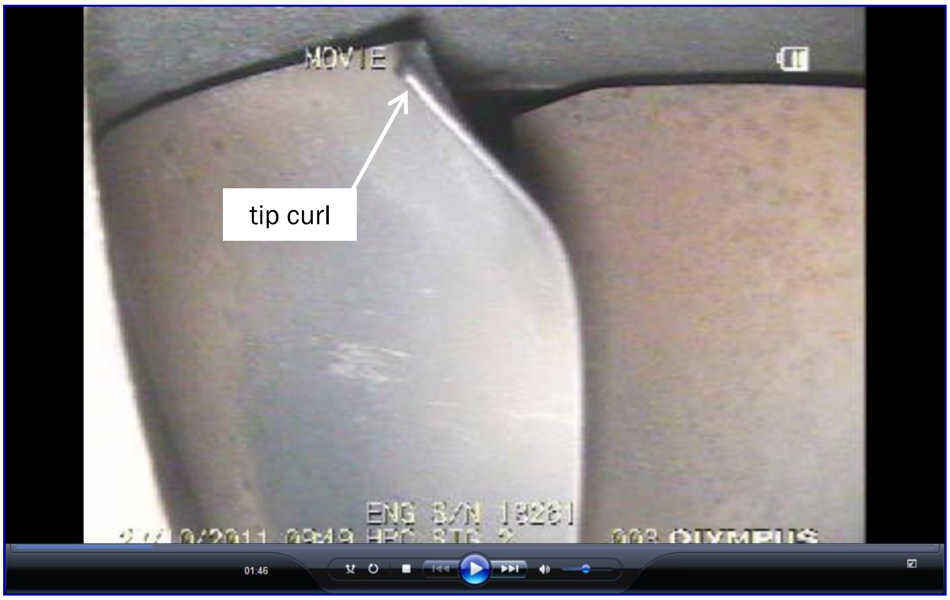

Figure 3
High-pressure compressor stage 2 tip curl

Figure 4
High-pressure compressor stage 1 compressor lining

3.2.10. RNZAF engineering opinion was that aside from the blade damage observed during the boroscope inspection, the general condition of the engine was consistent with its high life and "there was no engineering reasons that this engine could not be fitted to the aircraft or remain on wing until the over-temp event" at Auckland. Further, it was considered that the damage "was caused by a significant surge, but cannot be determined when. A reasonable assumption is this occurred on the surge into [Auckland]".

3.2.11. The RB211 engine, like most other modern large-turbine engines, was operated and maintained "on-condition". Records for the incident engine showed that all life-limited components were within their limits. The variable inlet guide vane (VIGV) controller had a "soft life" of 7000 hours and had accrued about 15 000 hours. There was, however, no requirement to remove it while the engine continued to meet performance specifications.

3.2.12. After the incident, the VIGV controller, actuator and rams were removed for testing. The controller settings were found to be within limits with some negative settings.[7] Normally as engine life increases the settings are moved towards the positive to maintain the required rotor speed. However, negative settings did not in themselves indicate anything untoward.

3.2.13. The VIGV rams had a life of 15 000 hours and at the time of the incident had accrued 14 000 hours. On testing, the rams were found to be outside the bench-test limits for new and overhauled rams. This was not considered uncommon for rams that were nearing the end of their lives. As there had been no recorded anomaly or indication that the rams were outside their operating limits while fitted to the engine, there had been no reason to remove them earlier.

3.2.14. Other inspections and tests that were carried out included the following:

- fan blade tip to fan track attrition lining inspected and measured – found within limits
- intermediate- and low-pressure ducting checked for security – found secure
- intermediate- and-low pressure bleed valves checked – no defects found
- intermediate- and low-pressure control valves checked – no defects found
- magnetic plugs inspected – no debris found
- oil pressure and scavenge filters removed and inspected – no contamination found
- fan blade set and associated hardware inspected – no defects found
- splitter fairings removed, VIGV unison ring and hardware inspected – no defects found
- VIGV controller fittings and rigging tested – no defects found
- inter-services plumbing inspected for leaks and integrity – no defects found
- intermediate pressure pneumatic check valve removed and inspected – no defects found.

3.3. Engine reliability

3.3.1. The investigation identified that 3 other in-flight shutdowns had occurred on the operator's B747 fleet since January 2000. One had involved an oil filter and scavenge pump fault; the second an engine vibration and exceeding the EGT limits. The third, in 2008, had been an engine surge after take-off, which also resulted in the EGT exceeding limits. The cause of the third event was traced to the failure of a stage 1 high-pressure compressor blade in the blade root area. The manufacturer had since developed a modification to reduce the risk of that failure.

3.3.2. As part of this investigation, the engine manufacturer completed a reliability study of the RB211 engine for in-flight shutdowns. The rate of shutdowns for the operator's fleet of RB211 engines was calculated to be 9.32×10^{-6} per engine flying hour. This was better than the 12-monthly rate of in-flight shutdowns for the worldwide RB211-524G/H-T fleet of 12×10^{-5}.

3.3.3. The manufacturer advised that compressors were designed with a tolerance or margin to ensure that unstable operation was avoided. But over time, wear in the compressor and/or airflow control system components could reduce the surge margin, and therefore the chance of a stall would increase. Engine overhaul periods were set to ensure that components were overhauled or replaced before significant reductions in surge margin took place. Engine health monitoring could record trends and provide advisories and alerts regarding decreases in compressor performance.

3.3.4. The San Francisco incident, like the subsequent Auckland incident, was reported to the CAA as part of the operator's normal in-service defect-reporting system. The engine manufacturer, as part of its airworthiness programme, overseen by the CAA in the United Kingdom, relied on operators around the world to provide engine reliability data, typically through their field representatives. Air New Zealand and Rolls-Royce advised that events like the surges at San Francisco and Auckland would be reported to the engine manufacturer in support of their airworthiness programmes.

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[7] Adjustments on the VIGV that enable the engine to meet its performance criteria.

3.3.5. The manufacturer confirmed that if the symptoms of an initial surge were not addressed, there was a risk of a further surge. However, many minor surges were initiated by environmental conditions, for example crosswinds, wake turbulence or gusty conditions on final approach, for which no corrective action was possible and that did not affect the likelihood of a future surge. If an initial surge resulted in compressor damage, the risk of a further surge would likely be increased. The manufacturer noted that there had been incidents of second surges after engines had been cleared to return to service. There had also been incidents where no obvious causes of surges were found and the engines returned to service with no further reoccurrence.

3.3.6. The manufacturer reported that there had never been any "uncontained" failures as a result of engine stalls and surging. Damage resulting from surges, including high-power surges, typically included compressor blade tip curl, vanes clipped by damaged blades and rotor path lining damage.

3.3.7. The manufacturer advised that the aircraft's maintenance manual and damage limits were subject to periodic review. The limits were only relaxed when there was sufficient evidence that they would not result in a greater risk of a surge. Should the incidence of surges increase as a result of relaxed limits, the limits would be reviewed. The first RB211 engine had entered service in 1972 and undergone extensive modifications since then. There had been no change to the limits for the RB211-524G/H series of engines, used on the Boeing 747-400 aeroplane since 1989.

3.4. Engine operation and surge information

3.4.1. As air passes through each stage in an engine compressor, the pressure and temperature of the air increase. In the combustion section fuel is added and ignited. The resultant high-pressure hot exhaust passes through the turbine section. The turbine drives the front fan (which provides the majority of the thrust), the compressor and accessories, and directs the residual thrust to help propel the aeroplane.

3.4.2. The modern turbine engine is fitted with a control system to help ensure that the engine is operated within its designed limits. The control system will typically receive inputs such as shaft speeds, engine temperatures, oil pressures and actuator positions. When a pilot selects a power or thrust setting, the system then sets a combination of fuel flow, variable stator vanes and bleed valve positions.

3.4.3. Engine operating temperatures are a primary indicator of engine health. Thermocouples or temperature sensors are mounted on various parts of an engine according to the manufacturer's requirements. On the RB211 the engine temperature was taken near the rear and was known as exhaust gas temperature or EGT.

3.4.4. A compressor stall is the disruption of airflow through the compressor. The airflow may recover naturally, but if not the stall may increase to the point where the airflow surges through the engine. The surge may begin to oscillate, typically at a frequency around 5 times a second. Because of the airflow disruption, fuel may not be fully burnt in the combustion section, so burning fuel may be seen coming from the rear of the engine. The surging and possible flames coming from the rear are often associated with what is commonly described as a "popping" of the engine. In more extreme cases of engine surging, the airflow may reverse and flames will come out of the front of the engine.

3.4.5. There are a number of possible reasons for the airflow through the compressor being disrupted. They include: foreign object damage, for example bird strikes; disturbances to the flow of air entering the engine, for example gusting crosswinds or wake turbulence; and faulty engine components. These may include worn components or faulty inlet guide vanes that direct the air on entry.

3.4.6. In the event of a stall continuing, a reduction in the thrust setting will often allow a smooth airflow to re-establish. In more extreme surge events an engine shutdown is normally required.

3.4.7. An engine surge can appear dramatic, with possibly loud popping or banging noises and partially burnt fuel and flames coming from the exhaust. However, if correctly handled, it is unlikely to be dangerous. Aircraft performance requirements and operating procedures cater for the loss of an engine during the most performance-critical phase of flight – the take-off. Modern engine design requirements also ensure that should an engine stall and surge occur, any damage is contained within the engine. Thus an engine surge would not cause a multiple engine failure situation.

3.4.8. In the event of an engine surge or stall, crew checklists generally direct the pilot firstly to retard the thrust lever until engine operating parameters remain within limits and any abnormal noises or other indications cease. If the abnormal or out-of-limit indications continue, the engine shutdown checklist would be completed. The crews on both the incident flights followed the required actions directed in the Boeing 747 checklist described above.

3.5. Other incidents

3.5.1. The Commission's inquiry considered 2 other recent in-flight shutdowns involving the operator's aeroplanes. Although both occurrences involved different types of aeroplane and engine, the aeroplane types were, like the Boeing 747 fleet, programmed for withdrawal from service in the next 5 years.

Boeing 737, equipped with CFM International CFM56-3C-1 engines

3.5.2. On 8 May 2011, ZK-NGD, a Boeing 737-3U3, was flying from Auckland to Wellington when there was an audible bang, the aeroplane yawed and the right engine failed. The engine was shut down and the aeroplane diverted to Hamilton for a successful single-engine landing. The engine was removed for detailed examination.

3.5.3. The engine had accumulated 34 239 hours and 25 310 cycles since new, and 8115 hours and 7993 cycles since the most recent workshop visit. It was therefore considered to be about average for the operator's CFM56 engine fleet. The engine had been installed on ZK-NGD in December 2007 and was next scheduled for removal for maintenance in March 2012. As part of a "C" Check carried out in January 2011, engineers had examined the engine's vibration system following reports of vibration reference shifts.[8] The examination, which included in-flight assessments, found no abnormal vibrations and the engine performed well within limits.

3.5.4. The failure was traced to the "No 3 bearing", which displayed evidence of "skidding". CFM International advised the operator that this had been only the third failure for the CFM56-3 series of engine in 6 million operating hours worldwide involving some 4500 engines. The CFM56 engine had been developed in 1974, with more than 22 000 built. The engine has flown more than 470 million cumulative hours and is one of the most common engines in service.[9]

Boeing 767, equipped with General Electric CF6-80C2 engines

3.5.5. On 9 June 2011, ZK-NCJ, a Boeing 767-319, took off on a scheduled flight from Auckland to Perth. Passing about 1500 feet the crew experienced a compressor stall on the left engine. The crew heard an audible bang, which was accompanied by an aircraft shudder and N1 fluctuations.[10] The captain retarded the thrust lever for the engine and as he did so the engine stalled a further 2 times. It was therefore shut down. A PAN[11] call was made and the aircraft returned to Auckland and landed. The engine, a General Electric CF6-80C2, was subsequently removed and sent to an overhaul facility for examination.

3.5.6. The engine had had a bird strike on 31 May, so the operator requested that the overhaul facility also examine the engine to look for evidence of any bird strike damage. Although

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[8] Changes in the baseline vibration readings, but still within limits.
[9] CFM International website – www.cfmaeroengines.com.
[10] N1 – low pressure rotor speed.
[11] An "urgency" call indicating a condition concerning the safety of an aircraft, or of some person on board or within sight, but that does not require immediate assistance.

limited signs of organic residue were found, no damage caused by the bird strike was evident. The only damage found was blade-to-blade tip contact, termed tip clang, on stage 4 of the high-pressure compressor rotor, and this was attributed to the engine stall.

3.5.7. The main engine control (MEC) and compressor inlet temperature sensor were removed and tested. The MEC operated normally but some of the settings, in particular for the variable stator vanes, were "out of rig". The operator determined that "rigging errors when the MEC was installed in February 2011 reduced the engine stall margin and was [a] significant contributing factor in the engine stall event". The engine had accumulated 79 666 hours and 14 693 cycles since new, and 265 hours and 60 cycles since the installation of the MEC in February.

4. Analysis

4.1. The Commission inquired into this incident to answer 2 questions:

- was the decision to release the aeroplane back into service after the engine surge in San Francisco appropriate, given that a second, apparently related and more serious, surge occurred several days later?
- did the 3 in-flight shutdowns in a little over 4 months, although involving different aeroplane and engine types, indicate a reduction in the standard of maintenance of aeroplanes nearing the end of their service lives with the operator?

Engine stalls and surges

4.2. An engine stall or surge can be frightening for those on board and is potentially damaging for the engine. However, modern engine design requirements and operating practices have reduced the frequency and severity of these events, as shown by the high levels of reliability. A minor engine stall should correct itself before any crew intervention can take place. In some cases, a momentary reduction in thrust setting will allow a stable airflow to be re-established. In more serious cases an engine may need to be shut down, either manually by the pilot or automatically by the engine control system.

4.3. In the most severe cases of RB211 compressor stall, there has not been any secondary damage outside the engine. The performance requirements for multi-engine aeroplanes are such that even after a severe engine surge the safety of continued flight will not be compromised if correctly handled. Although an engine stall or surge may cause engine damage, or reduce performance if the engine has to be shut down, provided pilots follow the prescribed flight manual procedures, as they did in these incidents, such events are not critical flight safety hazards.

> **Finding**
>
> 1. Engine surges, while potentially alarming for passengers and possibly requiring an engine to be shut down, are not critical flight safety hazards.

4.4. The San Francisco surge occurred on final approach during thrust or power adjustments at a low speed. The locally based engineer was familiar with the RB211 engine and correctly followed the recommended procedure for the indicated fault. No damage was found. To satisfy himself that the aeroplane was airworthy, he went beyond the published requirements and checked the weather conditions and conducted a high-power ground run on the engine. The engine performed as required and, in the knowledge that gusty winds and turbulence from other aircraft could contribute to a stall, the aeroplane was returned to service after consulting the operator's maintenance control.

4.5. The surge at San Francisco was considered by Air New Zealand to be minor and the aeroplane completed another 2 flights without incident, and engine performance data confirmed that the engine operated correctly during that time. The Commission therefore determined that, with the information available to him at the time, the San Francisco engineer had made an appropriate decision to release the aeroplane to service.

4.6. The surge event during the approach to land at Auckland was more severe and resulted in the EGT exceeding the maximum limit. This necessitated the shutting down of the engine. Expert advice was that due to the severity of the surge event on approach to Auckland it is probable that most, if not all, of the internal compressor damage was caused during this event. However, it is possible that the less severe San Francisco event caused some minor compressor damage that was undetected prior to the Auckland event. If such minor damage occurred during the San Francisco event, the engine may have had a slightly lower surge margin and therefore been more susceptible to surges thereafter. This is not always the case, however, and one instance of a surge does not necessarily mean that others will follow; refer manufacturer comment in paragraph 3.3.5.

4.7. The San Francisco event was likely a result of environmental influences on a high-time but serviceable engine; similarly for the Auckland event. If the missing high-pressure compressor liner material had been lost during normal operations or as a consequence of the San Francisco event, the surge margin would have been reduced. The non-embodiment of the 'birdmouth' service bulletin could have reduced the margin further. However, because of the continued good EGT margin there was unlikely to have been any predictor of a surge or another problem that might have led to a surge.

4.8. The crew acted correctly in shutting down the engine to minimise further damage. The operator acted appropriately in removing the engine for examination.

4.9. These stall events were unrelated to the 3 other engine in-flight shutdown events since 2000 that had involved the RB211. The review of RB211 engine surge events showed that on average the rate of occurrence for the operator was below the average for the worldwide fleet. Noting the operator's relatively small fleet, even a single event would have varied the average occurrence rate significantly.

Findings

2. Prior to the surge, the RB211 engine had been operating within its design performance limits and there had been no indication that a stall or surge could occur at either San Francisco or Auckland.

3. With the information available to him at the time, the San Francisco engineer made an appropriate decision to release the aeroplane to service.

Standard of maintenance on retiring fleets

4.10. The 2 other engine events that occurred between May and September 2011 concerned different aeroplane types, different engine types and different circumstances.

4.11. The bearing failure on the Boeing 737 aeroplane was the first of its type for the operator and only the third worldwide. There was no evidence that maintenance practices might have precipitated this failure. The engine was not high time, having accumulated about the average time for the operator's fleet of CFM56 engines. The reports of engine vibrations had been properly investigated and been found to be within limits.

4.12. The Boeing 767 stalls occurred under high power demands shortly after take-off. The MEC had been fitted some 4 months earlier and had operated correctly for the next 60 cycles and 265 hours. It also operated correctly during post-incident bench testing. However, after extensive testing the rigging of the MEC during fitment remained the most likely cause of the incident, possibly initiated by some other event. The bird strike some 10 days earlier may have been such a factor, but this could not be substantiated.

Finding

4. The spate of engine shutdown events between May and September 2011 involved 3 different engine types. There were no related circumstances and no evidence that the operator's maintenance practices contributed to any of the events.

5. Findings

5.1. Engine surges, while potentially alarming for passengers and possibly requiring an engine to be shut down, are not critical flight safety hazards.

5.2. Prior to the surge, the RB211 engine had been operating within its design performance limits and there had been no indication that a stall or surge could occur at either San Francisco or Auckland.

5.3. With the information available to him at the time, the San Francisco engineer made an appropriate decision to release the aeroplane to service.

5.4. The spate of engine shutdown events between May and September 2011 involved 3 different engine types. There were no related circumstances and no evidence that the operator's maintenance practices contributed to any of the events.

6. Safety actions

General

6.1. The Commission classifies safety actions by 2 types:

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

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

6.2. There were no safety actions taken.

7. Recommendations

General

7.1. The Commission may issue, or give notice of, recommendations to any person or organisation that it considers the most appropriate to address the identified safety issues, depending on whether these safety issues are applicable to a single operator only or to the wider transport sector.

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

Recommendations

There were no recommendations made.

8. Key lessons

8.1. No new safety lessons were identified.

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