CANADIAN FORCES
FLIGHT SAFETY INVESTIGATION REPORT (FSIR)

FINAL REPORT

FILE NUMBER:	1010-CH146420 (DFS 2-2)
DATE OF REPORT:	24 June 2005
AIRCRAFT TYPE:	CH146 Griffon
OCCURRENCE DATE/TIME:	182055Z July 2002
LOCATION:	5 Wing Goose Bay, Labrador, Newfoundland (NF)
CATEGORY:	‘’A’’ Category Accident

This report was produced under authority of the Minister of National Defence (MND) pursuant to Section 4.2 of the Aeronautics Act (AA), and in accordance with A-GA-135-001/AA-001, Flight Safety for the Canadian Forces.

With the exception of Part 1, the contents of this report shall only be used for the purpose of accident prevention. This report was released to the public under the authority of the Director of Flight Safety (DFS), National Defence Headquarters, pursuant to powers delegated to him by the MND as the Airworthiness Investigative Authority (AIA) of the Canadian Forces.

SYNOPSIS

The crew was tasked for a search and rescue (SAR) mission and launched from Goose Bay, NF after they had weather aborted their first attempt to reach the search location earlier in the day. The transit and search area weather allowed marginal visual flying rules (VFR) transit with ceilings ragged at 500 ft above ground level (AGL) and rain, mist or fog limiting visibility down to 1 mile in places. The crew refuelled at Seal Lake, a remote fuel cache, 350 degree magnetic (ºM) at 80 nautical miles (NM) from Goose Bay. After refuelling and while in transit to the search area, rescue coordination centre (RCC) Halifax cancelled the SAR mission because the target had been located. The crew started the return leg to 5 Wing and, at about 350ºM at 40 NM to Goose Bay, the tail rotor (T/R) departed the aircraft while in normal cruise flight at 2-300 ft AGL. The aircraft crashed at approximately 2055Z into hilly, tree-covered terrain about 400 meters down track from the T/R departure. The two pilots were killed instantly when the aircraft struck the ground with high vertical speed. Another crewmember was very seriously injured while the fourth crewmember sustained serious injuries. Despite his serious injuries, the fourth crewmember was able to use a satellite phone to notify RCC Halifax of the accident and their location after he rendered first aid to his crewmates. A 444 Combat Support Squadron (444 CS Sqn) rescue helicopter arrived on scene to evacuate the survivors to medical facilities within 3 hours. The aircraft sustained ‘’A’’ category damage.

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1. FACTUAL INFORMATION

General

The CH-146 Griffon aircraft is a military version of the Bell 412EP (listed as the 412CF on the FAA Type Certificate Data Sheet H4SW). CH146420 was a multi-person crew helicopter, operated by 444 CS Sqn in 5 Wing Goose Bay in the Combat Support (CS) role. The primary role for this unit is SAR response and standby for the allied forces that mostly conduct fighter operations at low level in the Goose Bay area. In this role, the normal crew is two pilots, one flight engineer and a SAR technician (SAR Tech). All 444 CS Sqn aircraft are equipped with a rescue hoist on the right side of the airframe.

1.1. History of the Flight

A standard four-person crew manned “Rescue 420” on 18 Jul 2002. The pilot-in-command was seated in the left seat and the co-pilot was seated in the right seat for this mission. The aircraft was configured with an auxiliary fuel tank in the left, outboard facing transmission seat area, with a night sun and rescue hoist mounted on the right side exterior and full CH146 SAR kit within the cabin. They were tasked by RCC Halifax to locate an overdue fishing boat last reported north of Goose Bay in the area of Nain. The crew attempted to reach the search area at 1515Z but returned about three hours later due to bad weather. They departed for a second attempt at 1825Z and reached a remote fuel cache near Seal Lake (350º M at 80NM from Goose Bay) to refuel. They departed the fuel cache heading north when RCC Halifax cancelled the SAR mission because the boat had arrived at destination.

The crew turned the aircraft south and began returning to Goose Bay, generally heading 170º M but manoeuvring at times to make their way past lower weather. Ceilings were about 500 ft AGL, except in higher terrain, and the visibility was 1-3 miles in rain, mist or fog. This weather was good enough to maintain close to 120 knots of indicated airspeed (KIAS) and a variable altitude of 2-300 ft AGL. The co-pilot had flown most of the flight but on the return leg the pilot-in-command had taken control of the aircraft. As they neared 40 NM to destination, in cruise flight along a valley, the tail rotor (T/R) departed the aircraft.

Though the crew quickly realized the nature of the emergency and attempted to transmit a Mayday, the right yaw associated with the loss of the T/R steered the aircraft towards rising rocky terrain that was covered completely in 30-40 foot high trees. Within seconds the aircraft was rotating uncontrollably about its vertical axis and descending rapidly. After losing the T/R, the aircraft travelled a further 400 meters along track. It also completed four 360-degree rotations before crashing into rising ground about 120 ft above a valley floor about 16 seconds after the T/R departed at 2055Z. The impact forces immediately killed both pilots while the SAR Tech received very serious injuries and the FE received serious injuries.

After getting his bearings and exiting the aircraft through the right rear hinged door, the FE attempted to administer first aid to his crewmates. Both engines were still running, so he attempted, unsuccessfully, to shut them off using the FIRE PULL handles (T handles). Then he tried the flight idle stop mechanisms, but both were jammed. Finally, he used the survival rifle to smash the break away valve on the number 2 engine which shut it off. The valve on the number one engine could not be accessed due to the deformation of the intake and cabin roof. Unable to shut down the number one engine, the FE removed the Co-pilot from the aircraft and extricated the SAR Tech as much as the tangled debris and the serious injury would allow. The pilot-in-command could not be extricated from the aircraft. The FE then called RCC Halifax on the Satellite phone to report the accident. After several minutes, grinding noises were heard and the number one engine finally stopped.

Using the GPS position provided by the FE, a second 444 CS Sqn rescue helicopter (CH146475 – R475) launched from Goose Bay and arrived on the accident scene at approximately 2330Z. Because CH146420's Emergency Locator Transmitter (ELT) antenna and cable were destroyed in the crash, R475 picked up the survival vest Personal Locator Beacon (PLB) set up by the FE at approximately 3 miles. The low visibility, the camouflage paint scheme on the aircraft, and the small size of the crash site made the aircraft difficult to see. The orange fly from the Arctic tent that was draped over the right hand side of the fuselage by the FE aided initial sighting of the crash site. The rescue helicopter was then "talked into" a suitable hoisting location by the FE using the hand-held "sabre" radio. The crew of R475 lowered personnel to the scene via the rescue hoist to evacuate the survivors. Extricating the SAR Tech from the tangle of wreckage and harness straps on the left side of the aircraft took some time, as his injuries required immobilization and immediate attention. The survivors and rescue crew were hoisted to R475 by 0035Z and the aircraft flew directly to the hospital in Happy Valley (Goose Bay), arriving at about 0110Z.

At 0845Z, personnel from 5 Wing were transported to the accident scene by a CH113 - Labrador helicopter, to secure the aircraft and await the coroner. The deceased crewmembers were later transferred to Goose Bay under the coroner’s supervision.

1.2. Injuries to Personnel

	Crew	Passengers	Other
Fatalities	2	Nil	Nil
Critical injury	1	Nil	Nil
Major injury	1	Nil	Nil

1.3. Damage to Aircraft

The aircraft, CH146420, sustained “A” category damage. The high vertical speed at ground contact caused extensive airframe damage, and tree or ground contact with the main rotor blades transferred very large forces to the main gearbox and associated drives, resulting in deformation and destruction of those components. Several trees punctured both the floor and ceiling of the cockpit and cabin. As the trees were forced through the floor, the aircraft fuel tanks were punctured but there was no post crash fire.

The T/R assembly was found about 280 meters up track of the main wreckage at the aircraft crash location. One full T/R blade was still attached to this piece but the other blade was missing about 18.5 inches of the tip. The tip of the second blade was located in one large piece and two smaller pieces a farther 100 meters up track.

1.4. Aircraft Salvage

The aircraft crashed into a remote uninhabited area of Labrador near a small creek that eventually flows into the Red Wine River about 3 NM away. The nearest road was 12 NM from the crash site. The investigation team assessed that recovery and reconstruction of the aircraft would be of little further value in analysing the accident so the wreckage was returned to 5 Wing's control on 26 July 2002 and appropriate clean up was initiated by the Wing's salvage team on their schedule. The aircraft held approximately 1700 lbs of JP-4 fuel at the time of the crash, most of which leaked out when trees punctured the fuel cells.

1.5. Personnel Information

	Pilot	Co-Pilot	FE	SAR Tech
Rank	Capt	Capt	Cpl	Sgt
Category/Expiry	Cat 1/ 15 Oct 02	Cat 3/ 18 Jun 03	SAR/ 24 Apr 03	Rotary Wing Team Lead
IRT Category/Expiry	Cat 1/ 15 May 03	Cat 1/ 2 Jun 03	N/A	N/A
Medical Expiry	14 Mar 03	30 Jun 03	4 Jul 03	25 Jul 02
Total flying time	3716.7	1475.5	579.6	3321.1
Flying hours on type	1608.8	87.4	529.9	1015.6
Flying hours last 30 days	35	33.1	27.2	21.8
Duty hours last 24 hours	16	16	18	16
Flying hours last 24 hours	6.9	6.9	6.9	6.9
Flying hours on day of Occurrence	3.8	3.8	3.8	3.8

The Pilot was the Sqn Standards Officer (Stds O), able to conduct all pilot check rides except SAR. He had recently conducted annual simulator training and was up-to-date for all squadron quarterly currency requirements.

The Co-Pilot was the Sqn Unit Flight Safety Officer (UFSO). She had recently completed the CH146 Operational Training Unit (OTU) and was in the process of completing squadron on the job training (OJT). She was up-to-date for all Sqn quarterly currency requirements.

The FE was up-to-date for all Sqn quarterly currency requirements.

The SAR Tech was on Temporary Duty (TD) from 439 Sqn, Bagotville, for a planned 2 week period to supplement the SAR Tech section on 444 CS Sqn during the busy summer flying schedule at Goose Bay. Examination of the records in 439 Sqn showed him to be current in all trade related qualifications.

1.6. Aircraft Information

1.6.1. Maintenance

An extensive review of aircraft records for CH146420 revealed no maintenance abnormalities. All scheduled inspections were carried out when required and the rectifications for the unscheduled corrective maintenance were logical and employed reasonable and acceptable repairs for the indicated unserviceabilities. Based on analysis of the historical aircraft record set, CH146420 was maintained IAW accepted CF CH146 maintenance practices and was considered to be serviceable prior to the accident flight based upon those accepted CF practices.

Investigation by laboratory personnel at Quality Engineering Test Establishment (QETE) revealed that the T/R failed due to fatigue. The outer 18.5 inches departed in flight, leading to complete loss of the T/R and eventual catastrophic loss of the aircraft (see para 1.16 and Section 2 for further details). The initiation site for this fatigue failure was a “nick”, with a depth of 0.008 inches that was located 18.5 inches from the tip of the T/R blade. Detailed post crash examination of the fracture surface and subsequent analysis revealed this damage had been present for about 76.86 flight hours prior to the accident. According to the Bell 412 maintenance manual current at the time, the maximum allowable depth of damage in this area of the T/R was 0.005 inch. Therefore, the actual depth of damage was beyond this limit and the T/R was not serviceable due to this damage.

The T/R blade maintenance procedure called for the T/R to be visually inspected by aircrew on the daily inspection before flight and by maintenance personnel every 25 flight hours. The pilot (or other qualified personnel) daily inspection is to "visually check condition and cleanliness" of the T/R blades. For the CF, this inspection was done from the ground and had no possibility of detecting anything but large-scale damage. The maintenance visual inspection was completed on the tail rotor to check for “whether damage is within limits.” Personnel using maintenance access stands in close proximity to the blade did this inspection. The investigation team determined both of these inspection types were carried out but they did not detect the damage in the 76.86 flight hours that the damage was present. The original and amended CFTOs are found in Annex H.

1.6.2. Maintenance Changes and Special Inspections

Normally, damage tolerances, inspection procedures and inspection intervals are the product of a continuous system of design, experience, validation and redesign. Helicopter manufacturers routinely adjust maintenance programs according to feedback and findings of incidents and accident investigations, to ensure that the maintenance program matches the helicopter design and operational parameters.

As soon as this T/R situation became known, the CH146 CF Technical Authority (TA) issued two special inspections (SI) for all CH146 T/R blades (NS SI 087 and NS SI 088) (Annex C) designed to ensure anomalies of this nature did not exist on any CH146 T/R blades in use at the time. Also, inspection methods and procedures were changed in an attempt to reliably detect any future damage of this nature on T/R blades in the critical area (see details in Annex D). These changes to procedures were the inspection methods used for the National Research Council (NRC) “Probability of Detection” (POD) study that it performed in early 2004 (Annex T). Further, the FAA issued a Special Airworthiness Information Bulletin (SAIB) in Nov 2004 detailing inspection procedures that were based primarily on these CF techniques (see details in Annex S).

1.6.3. Visual Inspection Types

Subsequent to the accident, Subject Matter Experts (SME) at Director of Technical Airworthiness (DTA) studied the visual inspection criteria contained in the Air Transport Association 2200 MSG -3 Logic (ATA iSpec 2200). It showed that there were differences in the details of visual inspection definitions.

A “detailed visual inspection” is defined as:

> *"An intensive examination of a specific item, installation, or assembly to detect damage, failure or irregularity. Available lighting is normally supplemented with a direct source of good lighting at an intensity deemed appropriate. Inspection aids such as mirrors, magnifying lenses, etc. may be necessary. Surface cleaning and elaborate access procedures may be required.*"

A “general visual inspection” is defined as:

> *"A visual examination of an interior or exterior area, installation or assembly to detect obvious damage, failure or irregularity. This level of inspection is made from within touching distance, unless otherwise specified. A mirror may be necessary to enhanced visual access to all exposed surfaces in the inspection area. This level of inspection is made under normally available lighting conditions such as daylight, hangar lighting, flashlight or drop-light and may require removal or*

> *opening of access panels or doors. Stands, ladders or platforms may be required to gain proximity to the area being checked.* "

The former definition more closely fits the amended and current CH146 T/R inspection procedures and the latter definition more closely fits the original CF CH146 T/R maintenance procedures.

1.7. Meteorological Information

The following are the forecasts and actual weather reports for the time-frame of the accident. CYYR is Goose Bay and CYDP is Nain.

CYYR 182000Z 36012KT 10SM –SHRA BKN021 OVC033 10/07 A2962 RMK SC6SC2 /WHITE/ SLP032 SKYXX=
CYYR 182023Z 34007KT 4SM –RA BR BKN020 OVC030 RMK SC6SC2/WHITE/ SKYXX=
CYYR 182026Z 35009KT 3SM –RA BR OVC019 RMK SC8 /WHITE/ VIS LWR W SKYXX=
CYYR 182036Z 34008KT 2 1/2SM –RA BR OVC019 RMK SC8 /GREEN/ VIS LWR W SKYXX=
CYYR 182100Z 35010KT 2 1/2SM RA BR BKN020 OVC040 09/07 A2965 RMK SC6SC2 /GREEN/ SLP043 51044 SKYXX=

AMD CYYR 181920Z 181918 34015G25KT P6SM –SHRA BKN015 OVC040 TEMPO 1903 P6SM NSW FEW015 BKN040 BKN090 BECMG 2123 34010G20KT
FM0300Z 33010KT P6SM BKN025 BECMG 0507 27005KT FEW030

AMD CYYR 182037Z 182018 34010G20KT P6SM –SHRA FEW013 BKN025 OVC040 TEMPO 2023 11/2SM –SHRA BR FEW008 OVC013
FM2300Z 34010KT P6SM –SHRA BKN015 OVC040 TEMPO 2304 P6SM NSW FEW015 BKN040 BKN090
FM0400Z 29008KT P6SM BKN025 BECMG 0507 SCT030

CYDP 181800Z 32025G31 14SM –RA SCT021 OVC070 08/03 A2964 RMK SC3AS5 SLP037=
CYDP 181900Z 32016G21KT 15SM –RA BKN024 OVC070 10/02 A2965 RMK SC5AS3 SLP041=
CYDP 181940Z 32013KT 15SM –SHRA BKN 024 OVC070 RMK SC6AS2 SKYXX=
CYDP 182000Z 32012G17KT 15SM –SHRA BKN024 OVC070 10/02 A2967 RMK SC6AS2 SLP048 SKYXX=
CYDP 182027Z 33009KT 15SM BKN024 OVC070 RMK SC6AS2 SKYXX=
CYDP 182100Z 31008KT 15SM BKN024 OVC070 10/01 A2969 RMK SC6AS2 SLP053 52016 SKYXX=

CYDP 181930Z 182023 32015G25KT P6SM –RA SCT020 OVC 070 TEMPO 2021 4SM –RA BR BKN020 OVC070

The 5 Wing weather office produced a synopsis of the crash site's weather shortly after being informed of the accident. The accident area was dominated by moderate instability following the passage of a cold front earlier in the day. Sharp cooling at all levels of the atmosphere allowed for towering cumulus (TCU) formation. However, no thunderstorm activity occurred within the area. Prevailing winds may not have been representative of localized sudden wind variations. Low cloud bases, along with poor visibility, created IFR or MVFR conditions. The weather office prediction for the site was:

Winds (in knots (kts))		Temperature (in degree Celcius)
Surface	35012G22 kts	8.0 C
FL025	34025 Kts	4.5 C
FL050	32025 Kts	-0.5 C
FL075	30025 Kts	-0.5 C

Cloud:	BKN/OVC 500'-1000' AGL, Tops 24000' TCU
Precipitation:	Showers and mist
Visibility:	1-4 SM
Freezing Level:	FL045 (~4500 ft above sea level (ASL))
Icing:	Moderate, possibly Severe in TCU
Turbulence:	Moderate, possibly Severe in TCU

Overall, the weather was within acceptable limits for a SAR mission of this type (ability to remain clear of cloud with at least ½ mile visibility).

1.8. Aid to Navigation

The entire mission was flown low level VFR since the Minimum Safe IFR altitude was above the freezing level. At this altitude (300 – 400 ft AGL) the only external aid to navigation available was GPS. The crew used GPS navigation as a backup to their map reading during the transit from Goose Bay to the fuel cache at Seal Lake, and from Seal Lake back towards Goose Bay. On the final leg of the mission, the crew had selected 168º on the horizontal situation indicator (HSI) track bar, which corresponds to the magnetic track from Seal Lake to Goose Bay.

1.9. Communications

The accident crew was in contact with RCC Halifax via HF phone patch through Military Aeronautical Communications System (MACS) Trenton. The crew also had a Satellite Phone on board the aircraft because they were conducting a SAR mission; this equipment is not standard on CH146 aircraft. The Satellite Phone was used by the FE to contact RCC Halifax after the crash.

The injured FE used a handheld "Sabre" VHF radio to "talk in" the rescue aircraft (R475) to a level hoisting location once on-scene. The FE also used this radio to relay communications between the SAR Tech, Flight Surgeon and R475.

1.10. Aerodrome/Alighting Area Information

The terrain at the crash site is sloped about 15 degrees, completely covered in 30-40 foot tall trees with thick moss covering rocks and undulations. There were no good landing or forced landing areas in front of CH146420 when the T/R departed the aircraft. All of the terrain forward of the aircraft sloped upwards. There was a small creek and pool of water to the right and slightly to the rear of the assessed point of T/R departure.

1.11. Flight Recorders

1.11.1. CVFDR

The CH146 carries a combined Cockpit Voice Recorder (CVR) and Flight Data Recorder (FDR), known as a CVFDR. The CVFDR was removed from the aircraft by a qualified technician and transported to 5 Wing Operation Centre after a telephone conversation with the Investigator in Charge (IIC) on the morning of 19 July 2002. The investigation team arrived on the afternoon of 19 July 2002 via CC144 Challenger aircraft, and the CVFDR was transported on the return flight back to NRC in Ottawa for downloading.

The data portion of the CVFDR (Annex E) contained a record of the aircraft’s performance for the last 24 flying hours, from the time power was applied to the time power was removed. Some information collected during the last 30 seconds of the accident flight is considered unreliable due to an Air Data Computer (ADC) input. The aircraft was flying well outside of the ADC's calibrated flight envelope (at a very large sideslip angle) after the T/R departed and thus the ADC produced erroneous data consistent with those conditions. The unreliable data included indicated airspeed, pressure altitude, outside air temperature and vertical speed for about 3-4 seconds.

The Voice portion of the CVFDR data was downloaded in its entirety. It contained the final 30 minutes of the crews’ conversations, captured on 4 separate channels as listed below, up to the point of impact:

Channel 1	Right Seat
Channel 2	Left Seat
Channel 3	Flight Engineer
Channel 4	Cockpit Area Microphone

Both sets of data were made available to the investigation team by 21 July.

1.11.2. HUMS

The CH146 is equipped with a Helicopter Health & Usage Monitoring System (HUMS) that has a system of sensors and recording mechanisms to record vibration data with the view to pinpointing problems early before they develop into major repairs. HUMS is an event based system for trend analysis; it is not focused on short term events nor is it intended to replace the maintenance program. The system is also used to help reduce or eliminate vibrations by allowing fine balancing of dynamic components, particularly the rotor systems.

The HUMS system data was successfully downloaded for analysis. The preliminary read outs indicated that HUMS (with the maintenance procedures associated with the system) did not have the opportunity to detect this failing T/R blade. From the information gathered from the Modular Data Acquisition Unit (MDAU), the vibration levels recorded in the T/R increased extremely quickly over the last 60 to 80 minute period prior to the accident (Annex F). Since HUMS data is normally downloaded approximately every 10 flying hours, there was no chance to forecast this failure with HUMS alone. Staff from NDHQ and the 403 Sqn HUMS cell evaluated the HUMS data from the MDAU (see section 2.2).

1.12. Wreckage and Impact Information

The wreckage area was very small, not much larger that the foot print of an intact CH146. From the damage pattern, the cut trees and impact marks from the main rotor blades, it was apparent the aircraft impacted the ground left side down (about 20 degrees), slightly nose low (about 5 degrees) but with high vertical speed. Three of the main rotor blades were badly damaged due to terrain and tree contact. The fourth blade indicated a very fast rotor stop because the spindle assembly was bent nearly 90 degrees and the blade made contact with the front right portion of the cockpit and door; though without penetrating them. The tail boom was generally aligned with its proper position but broken off its mounts at the body of the aircraft. Although it was in contact with many trees, there was not much rotational damage on either side of the boom or the vertical fin. There was no T/R blade damage noted at the main wreckage site because the T/R input shaft was severed and the T/R was not at the impact site. It had departed the aircraft several hundred meters before ground contact.

1.13. Medical

Both pilots were killed immediately upon aircraft impact with the ground. The SAR Tech received severe, life threatening injuries due to blunt trauma as he impacted the left cabin door. The prompt rescue effort and quick return to the Goose Bay hospital allowed appropriate medical attention to occur. He was wearing a “monkey tail” restraint harness rather than being strapped in to the normal seat harness. The FE received major injury but due to his seat position on the right side of the aircraft and the impact zone on the left side of the aircraft, his injuries were greatly reduced compared to the other crewmembers. The FE was also wearing a “monkey tail” rather than the normal seat harness.

Evaluation of all medical information did not reveal any medical elements as causal or contributing factors to this accident. All crewmembers tested negative for alcohol and drugs, other than for drugs administered in the ensuing rescue and medical triage.

1.14. Fire, Explosives Devices, and Munitions

1.14.1. Fire

There was no fire, but a tree that came to rest across the still-running #1 Engine's exhaust did begin to glow red. The #1 Engine spooled down on its own prior to the tree catching fire.

1.14.2. Explosive Devices

The aircraft carried the following flares (all were recovered):

a. 4 radar flares;
b. 2 day/night flares;
c. 1 signal kit with 7 pencil flares;
d. 1 aircraft flare gun with 4 cartridges; and
e. 4 survival vests with 7 pencil flares and 1 day/night flare each.

1.14.3. Munitions

The aircraft contained a 30.06 rifle with 26 rounds of ammunition. None of these munitions is considered a factor in the accident.

1.15. Survival Aspects

1.15.1. Front of the Aircraft

The high vertical speed at impact combined with terrain features (rocky, sloped, undulating, tree covered) generated forces during ground impact greater than the protection offered by the safety systems fitted to the aircraft. This was not a survivable accident for the crew in the front portion of the aircraft. Both of the pilot's seats fully "stroked" during the ground contact sequence and the seat stroking mechanisms were removed for further laboratory analysis (by Bell Helicopters). The cockpit roof collapsed downwards. The liveable space in the front portion of the aircraft was compromised to some extent, resulting in post mortem injuries to both crewmembers but the very large initial forces were the mechanism of death, with both pilots being killed instantly on ground contact. Both pilot's inertial reels and straps were examined with no anomalies noted. However, the left-hand (LH) seat pilot's inertial reel was badly damaged by contact with a tree during the crash sequence.

1.15.2. Rear of the Aircraft

The liveable space in the rear portion of the aircraft was somewhat compromised by trees entering through the bottom of the fuselage and exiting through the top. Neither of the rear crewmembers was injured by these events. Both rear crewmembers were attached to secure points in the rear cabin by "monkey tails". The SAR Tech was located on the LH side of the aircraft sitting on the crew seat but not strapped-in. The FE was on the right-hand (RH) side of the cabin sitting on the multi-person life raft. Due to the geometry of ground contact (impact was left side low – about 20 degrees, nose low - about 5 degrees), severe crash loads caused deformation of the left side of the fuselage creating the very severe injuries for the SAR Tech. This ground contact geometry limited the forces and resulting injuries for the FE because the RH portion of the rear cabin had the greatest room for airframe flexibility, allowing the ground contact forces to be dissipated over a longer period of time. Although the crash was survivable for the rear crewmembers, the forces created caused severe injury and only the prompt rescue response by the crew of CH146475 allowed the SAR Tech's injuries to be quickly treated.

1.16.Test and Research Activities

As mentioned in paragraph 1.3 above, the T/R assembly parts were found hundreds of meters away from the main wreckage. After receiving most of the T/R assembly from the aircraft on 21 July 2002, QETE began examination and tests to determine the failure mechanism. On 23 July 2002, the remaining 18-½ inch section from one of the blades was located and also sent to QETE for analysis (Annex G) that revealed the following:

a. The fracture surface of the root end of the T/R blade that was still attached to the T/R hub had two distinct zones consisting of a fatigue zone and an overload zone. The fatigue crack propagated from the initiation point both fore and aft. The fatigue portion constitutes approximately 60% of the total fracture surface. The remaining portion of the fracture surface was typical of overload failure.

b. The initiation point of the crack was a nick in the aluminium approximately 0.008 inches deep and 0.060 inches (1.5mm) long, running chord-wise along the T/R blade. Under ideal conditions such a nick would be visible to the unaided eye but considering the inspection methods in use at the time of the accident, the remote possibility of detecting this extremely small damage site (with depth as the critical dimension) prompted the CF to commission a POD study by NRC to validate the new CF inspection methodology and ensure the POD was appropriately high for the criteria associated with this critical inspection (see section 2.1.14). The nature of the nick and analysis of the deposits within the nick suggest that it was most likely caused by a stone. The aluminium skin on the T/R blade is 0.016 inches thick.

c. The three pieces that formed the18-½ inch tip portion of the T/R blade, were found in a separate location from the main crash site a long way from the remainder of the wreckage. These parts were examined and lead QETE to theorize that this portion of the rotor blade separated from the main T/R blade assembly in flight and was then struck by one of the main rotor blades. This is supported by evidence of contact between the main rotor blade and a contact mark on the separated part of the T/R. The separated 18-½ inch section was broken into several pieces as a result of this violent encounter.

The T/R blade configuration on this helicopter is designed such that to perform its' anti-torque function, forces are generated by "pulling" the tail of the helicopter. This means that with the damage on the inboard side of the T/R blade, forces on the site were predominantly tensile in nature.

1.17. Additional Information

1.17.1. OEM Actions

The Original Equipment Manufacturer (OEM) (Bell Helicopter) was involved and informed about the developments throughout this investigation. The company cooperated and provided engineering, investigation and technical resources and data to advance the investigation, which were essential in discovering important facts and determining the baseline reasons for the failure of the T/R blade on CH146420. As information was discovered, the OEM made changes to the “damage limits” and did issue an “Operations Service Notice (OSN)” drawing attention to the maintenance manuals about the limits and inspection requirements therein (Annex J). Of note, the Bell manual (Annex J2) calls for a visual inspection of the T/R blade and it is not commercial practice for OEMs to provide prescriptive maintenance procedures in areas that they feel are “Industry Standard” practice.

1.17.2. FAA Actions

The Federal Aviation Administration (FAA) in the United States of America (USA) issued the airworthiness certification for this aircraft type (Bell 412 series). The FAA was notified of the facts and research associated with this accident through the civilian Canadian airworthiness authority, Transport Canada (TC). Based on information passed to them and independent research about other accidents and T/R blade failures, the FAA issued a SAIB (number SW-05-10) on 5 November 2004. The bulletin contained information and recommendations on maintenance procedures to be employed for the Bell 412 series T/R (see Annex S) that parallel the procedures adopted by the CF. The FAA research found that there have been six additional confirmed T/R blade failures similar to CH146420; five on Bell 412 series helicopters and two on Bell 212 series. Five of the failures occurred between stations 30 and 33.5 on the T/R (17.5 to 21 inches from blade tip). Three of the T/R failures, including CH146420, have happened in flight. The six other T/R failures occurred before the accident on CH146420. The FAA recommendations in the SAIB are not mandatory.

1.18. Effective Investigation Techniques

During the investigation some questions arose regarding “best practice” for manually selecting the seat harness lock vice depending upon the inertial locking features for optimal aircrew security. Aerospace Engineering and Test Establishment (AETE) Escape Systems specialists were consulted about this question. They confirmed that locking the seat harness provides the best survival prospects (as indicated in technical studies by H. Koch et al). This portion of the investigation lead to an amendment to the DFS/AETE Memorandum of Understanding (MOU) for AETE to provide additional expert investigative support for examining all forms of crew seats rather than just ejection seats. Further, this consultation revealed a paper - “A2002-031 CH146 Armoured Seat Restraint” done by AETE where replacement of the existing CH146 inertial reel with a modern MA-16 type reel was suggested due to deficiencies found on the present system.

2. ANALYSIS

General

Examination of the wreckage pattern, with the T/R displaced several hundred meters up aircraft track of the bulk of the main wreckage, steered the initial investigation efforts. Preliminary analysis of the CVFDR quickly supported this action, because the aircraft's flight path and cockpit conversation indicated there had been a T/R failure emergency. Within 48 hours of the accident, QETE's examination of the T/R pieces revealed that the blade had failed as a result of a fatigue crack propagating from a small initiation site on the T/R blade skin surface.

2.1. T/R Blade Failure

2.1.1. General Description

The CH146 T/R blade is the same T/R blade found on many Bell helicopters, to include the CH146 (Bell 412CF), Bell 412, Bell 205, Bell 205B, Bell 212, "Twin Huey" CH 135 and UH-1H-II fleets. Of note, the Bell 412 series of aircraft have four main rotor blades, whereas the other fleets have two main rotor blades. All of these helicopters have the same two bladed T/R configuration. The T/R blade colour schemes vary in the area of the crack initiation. The paint colour for military UH-1s is usually olive drab green. The colour on 212, 412, 412HP, 412SP, and 412EP is high gloss white. The colour on 412CF, at the time of the accident, was black as specified by the CF. Subsequent to the accident the CF changed the paint scheme to white on CSS CH146s and to olive on the CF's Tactical Helicopter (Tac Hel) Sqn CH146s.

The T/R blade is an aluminium skin honeycomb core construction with a stainless steel Leading Edge (LE). The core, skin and LE are bonded together to form a single cell torque box structure. The 2024 aluminium skin is 0.016 inches thick and the LE stainless steel is between 0.032 and 0.040 inches thick. The T/R blade has a component life of 5000 airframe hours (AFH).

2.1.2 T/R Crack

The initiation site from which the fatigue crack grew was quite small, only 0.008 inches deep by 0.060 inches long. The T/R failure was the result of a fatigue crack that grew both forward and rearward (chord wise) from the original impact damage site. As the crack grew, the load shedding caused an increased load (and stress) in the stainless steel leading edge (LE) (spar). This caused a propagation of the crack into the LE spar. Eventually the fatigue crack progressed through most of the stainless steel spar and thereby finally reduced the strength of the blade structure sufficiently to allow the remaining section of the blade to fracture in overload.

The following is a summary of the sequence of events as they have been determined:

a. The nick on the T/R blade was produced likely following contact with a stone or a similar object;

b. Over the following flying hours, the nick developed into a crack, working its way through the thickness of the skin material;

c. Once through the skin thickness, the crack began growing simultaneously towards the leading and trailing edges of the aluminium skin;

d. As the crack grew, the load shedding caused an increase in load (and stress) in the stainless steel LE resulting in propagation of the crack into the LE spar;

e. The crack grew to such a size that the remaining structure could no longer carry the normal operating loads (critical crack length) and it failed in overload;

f. The18-½ inch portion of the T/R separated (at station 32.5) and flew up and forward striking a main rotor blade;

g. The departed 18-½ inch portion of the T/R blade caused an imbalance which led to an overload failure of the 90 degree gearbox shaft (T/R input shaft); and

h. As a result of this final failure, the T/R assembly departed the aircraft.

2.1.3 T/R Crack Propagation

Several initiatives were undertaken to glean more information about the fatigue crack, aircraft vibration spectra and the 412 T/R blades. Research to determine the fatigue growth rate included fractography analysis of the crack striation pattern and numbers using a scanning electron microscope (SEM) and a transmission electron microscope (TEM), crack debris analysis and a review of the Bell 412 baseline design spectrum and certification process. The preliminary assessment indicated that a fatigue crack would take approximately 56 airframe hours (AFH) to develop into a crack that resulted in blade failure from when the crack growth began. Bell Helicopters completed a more rigorous assessment of the "failure" time frame using the actual CVFDR data for the accident aircraft in comparison to the Bell 412 baseline design spectrum. This second analysis indicated that for the accident aircraft, from the initiation of crack growth, it took approximately 76.86 AFH for the crack to grow to the point where the structure of the blade was compromised resulting in failure. The analysis indicated the following crack propagation times (expressed in AFH):

60AFH --> Time to Crack through material thichkness

71AFH --> Crack reaches 0.10" length
74.5AFH --> Crack reaches 0.25" length
75.3AFH --> Crack reaches Critical Length of 4.14"
76.86AFH --> Complete Blade Failure

For this refined estimate of 76.86 hours total time for crack growth there were no significant changes in crack length for approximately the first 71 AFH. The crack grew through the thickness of the material, and not in length or in width. This means that during this 71 hours the visual inspections had to detect the original damage size, not a growing crack (length/width). Finally, in the 5-6 hours prior to the accident, there was rapid growth in the length of the crack in the T/R blade. Essentially, the visual probability of detection of the growing crack did not increase until, just prior to failure because the damage site was not increasing in length or width.

Another important point about the crack growth analysis and time available for discontinuity detection needs to be made. It is scientifically accepted that with fatigue cracks, there is an unquantifiable length of time between when the damage occurs and when the actual initiation of crack growth begins. Based on this scientific acceptance, it can be deduced that the damage site on CH146420 existed for longer than the crack growth time. Therefore, there was more than 76.86 AFH available to detect the original damage on CH146420’s affected T/R blade.

2.1.4 T/R Maintenance Procedures

Depending on the maintenance program, the OEM’s recommended visual inspection cycle for this component is every 25 AFH/30 day (which ever comes first) and daily. The CF CH146 maintenance program at the time of the accident used the 25 AFH visual inspection option (Annex H2). Examination of the aircraft record set (CF349s) confirmed that qualified CF maintenance personnel carried out these inspections at the recommended frequency. Also, a daily aircrew inspection “before flight” was conducted. However, this inspection was done from the ground and the T/R on the aircraft is about 10.5 ft off the ground. Neither of these inspection types detected the original damage or the developing crack during the estimated 76.86 AFH between crack initiation and T/R failure.

2.1.5 T/R Damage Criteria and Detectability

The initiation site from which the fatigue crack grew was only 0.008 inches deep by 0.060 inches long. The ability for maintenance personnel to reliably detect this size of damage without visual aid, special training and/or methodology was debated within the investigation team. By way of illustration on this point, field investigators required a 10X-magnifying lens to locate the initiation point once QETE had located the damage from the mating portion of the T/R during their initial laboratory examination and described the location to the field team.

The CFTO (C-12-146-000/MF-001), in use at the time of the accident, governing T/R maintenance was consulted for damage criteria (Annex H). This showed that the maximum "negligible and repairable" damage in the critical location and orientation was 0.005 inches deep and that blade replacement was necessary should damage exceed this limit. At the time of the accident, other locations on the T/R blade skin had smaller limits for the "negligible/repairable damage" classification (as little as 0.003 inches allowed). The maintenance procedure advocated in the manual to detect this damage was “visual inspection” and the inspection requirements were only expressed in depth, with various orientations and classifications of damage having different depth allowances.

2.1.6 CH146 Inspection Requirements vs Technical Training

To conduct meaningful inspections for damage limits of this small scale and specification (depth) requires specific detection methodology, measurement techniques and tools, particularly in consideration of the CF’s CH146 aircraft usage in military field operations where inspection access (10.5 ft off the ground), good lighting and clean surfaces are problematic. Also, the investigation team examined the training that CH146 technicians receive to determine if this information on T/R “negligible/repairable damage limits” and appropriate inspection techniques were part of CH146 technical training. The team found that there was not a match between the real inspection requirement and the technical training. There was no emphasis on the tight “negligible/repairable damage limits” in this area on this critical component and no measurement techniques were taught to confirm damage size. Therefore, the investigation team concluded that there was very low probability for detection of the problem. As soon as it became apparent that this situation existed, the Aircraft Engineering Office (AEO), in association with TAA advisors, initiated a series of SIs (Annex C) to confirm no other CH146 T/R had this kind of problem.

It should be pointed out that there is a constant emphasis in the CF maintenance community that CFTOs should be employed when conducting an inspection and the information with respect to the “negligible/repairable damage limit” existed in CF technical publications at the time of the accident. Further, an OEM does not generally teach Standard Maintenance Practices, particularly if the OEM believes that the maintenance action called for in the manual is “Industry Standard Practice”, as the OEM believes is the case for this T/R inspection. Normally, for CF day-to-day maintenance operations, dealing with awareness of crack sizes and tolerances are part of Standard Maintenance Practices taught to CF technicians in trade training. However, the specific teaching points about this T/R inspection, the extremely small tolerances and the unique aspect of depth as the critical criteria were not present in CF CH146 technician training prior to the accident. Subsequently, appropriate awareness training and a change of inspection procedures for CH146 technicians was undertaken to increase the probability of detection for this kind of anomaly on all future scheduled inspections of this rotor blade. The investigation team recommends that specific training be devised for CH146 technicians conducting this T/R blade inspection due to the inspection’s unique characteristics. This will ensure sustained inspection integrity and keep its effectiveness as high as possible.

2.1.7 T/R Inspection Methods and Other Users

The CF engineering staff (DGAEPM) plays an active role in the Bell 412 worldwide community by providing and receiving technical updates. Therefore, CF maintenance practices in use before the accident should likely have been consistent with other Bell 412 operators. Knowing this, the investigation team sought to determine whether a similar mismatch between requirements and procedures existed for other CH146 / Bell 412 operators worldwide. At the Bell 412 Military Users Group meeting in September 2002 held in Norway, all participating countries confirmed that they were not using specific inspection methods on their T/Rs (Annex I) to detect this small-scale damage. This user group included Canada (Bell 412CF), Norway (Bell 412SP), United Kingdom (Bell 412EP), Netherlands (Agusta Bell 412SP), and Sweden (Agusta Bell 412). The blade paint colour in the area of interest was white for models in the United Kingdom, Netherlands, and Sweden, olive drab green for Norwegian models, and black for Canadian models. It is noteworthy that the damage limits are the same for all of the blades regardless of colour and that the OEM certified all colour variations without restriction.

Inquiries to other Bell 212 and Bell 412 users regarding T/R inspection techniques confirmed that the inspection of T/Rs for this level of damage is not attuned to detection at this small scale and criteria (especially with depth being the critical dimension). While unable to check every Bell 412 user, it is reasonable to believe that this inspection deficiency is likely widespread if not common to every operator of the aircraft. (There are an additional 29 countries (beyond the user group mentioned) that have Bell or Agusta Bell 412s being used by their military forces. Further, there are 116 civil operators of Bell 412s worldwide and it is impossible for DFS to contact all of them). The investigation team concluded that the OEM does not place sufficient emphasis on the critical nature of the T/R blade inspection. While the tolerance is stated in technical publications, there was no specific emphasis on this item given by the OEM. Further, the team concluded that without a detailed and visually assisted inspection, the probability of detection is extremely low for this level of damage particularly since depth is the critical dimension for this T/R inspection.

2.1.8 T/R Inspection Damage Limit and Validity

Clearly the CF inspection procedures, equipment, training and awareness did not prepare CF technicians to discover this kind of minute damage. However, from the practical perspective, the use of visual inspections as a means to detect critical size defects has limitations. Post accident follow up consultations showed a wide variance in the “Industry Standards” for visual detection limits, with all standards examined having larger dimensions than the limits on this T/R and all expressed in length or width. Accordingly, the CF commissioned the National Research Council (NRC) Canada to conduct a POD Study to attempt quantification of the effectiveness of these types of inspections. This study used CF personnel and the new improved CF inspection methodology and associated resources (see Annex T). The objective of the study was to analyse damage type, size, and inspection techniques and make determinations on the statistical probability of damage detection. Secondarily, the study was to validate the assumption that the new CF techniques ensured a high POD and thereby validate the original CF Risk Assessments. This study and its implications will be discussed further in section 2.1.14. Of note, changes were made to the CFTO (and OEM approved maintenance publications) in 2004 with respect to damage limits (reduced to 0.003” depth) and description (now referred to as “repairable” damage limits).

2.1.9 T/R Damage Detection and Colour

The investigation concluded that the colour of the T/R might have played a role in this accident. The surface of the T/R blade on the accident aircraft was painted black and it is believed that the nature of the bonded blade structure would tend to “close” a developing crack when it was not under load (rotating). The combination of colour, structure and likely hidden nature of the crack unless under load, would make visual detection of the growing crack very difficult. However, despite being extremely small, the impact damage at the initiation site remained detectable. A lighter blade colour likely would have made damage detection easier as explained in section 2.1.14.

As the POD for T/R blade damage was examined and the aspect of blade colour was considered, the AEO / Weapon System Manager (WSM) decided to change the blade paint scheme to olive/red for Tac Hel Sqns and white/red for CS Sqns to aid in the detection of flaws. Further, the colour scheme geometries were also changed to preclude a colour change occurring in the critical zone.

2.1.10 Other Bell T/R Blade Failures

Soon after the accident, the investigation team searched for other T/R blade failures of this nature. A search of the FAA database revealed another Bell 412 T/R blade fatigue failure, but initiated by another means. In a Petroleum Helicopters International (PHI) accident in 1999, the crew had survived a ditching when the aircraft became uncontrollable after the T/R departed the aircraft. Several days after the crash, a piece of T/R blade tip about 17.5 inches long (station 33.5) was recovered. This blade tip had failed from an almost identical fatigue crack with the initiation site being a very small area of “pit corrosion” only 0.001 inches deep on the stainless steel LE portion of the blade (Annex R). Not-with-standing the on going effort to develop visually assisted inspections with high levels of POD for CFTO defined flaws beyond "negligible limits" there is serious doubts that flaws of this minuscule magnitude and location will be detected in the field.

With this additional information in hand (in 2003), the investigation team used all of the safety networks to which DFS had access for solicitation of similar circumstances from other users. This search exposed another T/R blade crack on a Bell 412 in 1996 where the Czech police force discovered a crack 8.31 inches long on a pre-flight inspection; it initiated at an indentation at “station 30” (21 inches from blade tip) 0.005 inches deep and 0.45 inches long (Annex R).

This type of damage was described in the CFTO and certified maintenance manual as “negligible/repairable” damage.

Comparison of these three failures, the only failures known at the time, showed they were relatively in the same location on the T/R blade (between stations 30 to 33.5 – 21 to 17.5 inches from the blade tip), all had very small damage initiation sites with large fatigue cracks and all were from the Bell 412 series of helicopters. Considering the millions of flying hours accumulated by all the helicopter types that use the same or similar T/R blades and the helicopter type involved in the reported T/R blade failures, the investigation team believed that this was most likely a problem with the Bell 412 fleet rather than all helicopter fleets equipped with similar T/R blade construction.

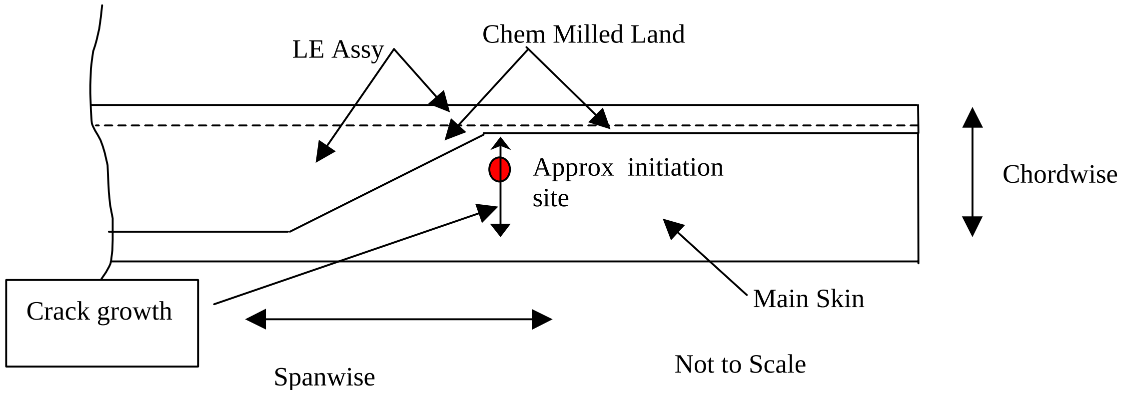
The three T/R reported occurrences came from three different organisations which utilised the aircraft in three different roles; the CF aircraft in a CSS role, the civilian aircraft used for transportation to oil platforms and the Czech aircraft used in police activities. Based on this observation, it is unlikely that differing usage spectra on CSS operations were solely responsible for crack initiation and propagation on CH146420. (Note: Subsequently, the FAA SAIB (Annex S), issued in November 2004, cited 4 other T/R blade failures for a total of 7 confirmed failures. The CF was unaware of these four additional failures until the FAA bulletin was issued.)

2.1.11 Crack Location and Blade Design

The investigation team examined the T/R blade design and the following original data for certification including:

a. T/R loads report,
b. T/R drawings,
c. T/R test reports (static and fatigue),
d. T/R design change history,
e. T/R stress analysis,
f. T/R fatigue assessment, and
g. FAR Part 29.571.

This review revealed the original analyzed points used by the OEM for determining the T/R blade life were not in the same location where the CF fatigue failure occurred. These OEM analysed points (at stations 26 and 16 - 25 inches and 35 inches from the blade tip) are to either side of the CF failure location and are assumed to be the “worst case” condition to arrive at a conservative analysis. The fact that all of the known failures occurred at similar locations which did not coincide with the OEM analysed points is convincing evidence that the analysis did not adequately identify the true critical area. It is important to note that, near the area of the know failures, there is a discontinuity of the blade structure.



Note: Chem Milled Land refers to the area where the chemical etching process is used to change the thickness dimension of the Stainless Steel LE to meet the aluminium material of the blade skin.

Specifically, there is a critical area near the CF failure location defined by a significant change in spar cross section. The structure of the leading edge becomes tapered (chord wise) and the run-out between the tapered portion and the constant cross section is made at a sharp radius creating a local stress concentration (Annex K). The investigation team is concerned that the OEM original design analysis did not predict the failure location. It would seem to be more than coincidental that in service failures have occurred at an area of structural discontinuity.

It should be noted that the area between Stn 30 to Stn 33.5, 21 inches from tip to 17.5 inches from tip, is where the 3 blade failures described in section 2.1.10 occurred. Further, the FAA SAIB mentioned in section 1.17.2 (see Annex S) noted that 5 blade failures (of 7 total verified similar failures) have occurred in this area and one other is within 2.5 inches of the area.

2.1.12 Initial CF Risk Assessments

Shortly after the accident, the TAA staffs started to prepare a Risk Assessment (RA) on the CH146 T/R blade. In preparing the RA, engineers used the total number of flying hours accumulated by the T/R blades on all similar helicopter fleets (412, 212 and 205 etc) to establish the occurrence rate and the probability of recurrence. However, when CF maintenance and airworthiness authorities were informed about the three Bell 412 T/R blade failures, the initial RA under consideration reduced the total AFH to only Bell 412 fleet hours. This had the effect of increasing the occurrence rate and thus the probability of a recurrence for the purpose of the RA.

At about the same time, the crack propagation rate was estimated using both classical fracture mechanics and crack growth analysis. As well, additional work was done using the TEM from Bell laboratories that used striation counting to recognize the later stages of crack growth from a very small crack to failure as something less than 5 hours. Of note, this method does not address the propagation of the crack when it is very small - the stage of crack growth where the greatest amount of time until failure is realized. A revised crack propagation rate of 56 hours was calculated in consideration of this point. This significant difference in the two initial reported propagation rates (5 vs 56 AFH) highlights the rapidity of crack propagation once the crack has reached through the thickness of the material. The initial estimation from all of these analyses for the crack propagation rate was 56 AFH from crack initiation to blade failure.

Based on this work and the increased probability of recurrence, the TAA and WSM concluded that the inspection cycle needed to be reduced to 12.5 AFH to raise the probability of detection to an acceptable level. The reduced inspection cycle increased the safety margin through the number of inspection opportunities (about 4 inspections would occur before blade failure). Of note, these RAs utilized the changes to CF maintenance procedures and assumed reasonably high POD (90%) levels for the inspections that reduced the RA level from medium to low.

Subsequently, further refinement of the crack growth analysis was completed with the crack propagation estimated to be 76.86 AFH from crack initiation to blade failure. The newly established 12.5 hr T/R inspection cycle was reviewed by the AEO based on this new data obtained from the OEM. After consideration of all factors, the AEO opted to retain the 12.5 hr interval to ensure an increased POD.

2.1.13 Inspection Objectives and Methodology

Generally, the purpose of conducting inspections on aircraft is to detect anomalies or conditions that may not be optimal for safe operations with the view to conducting prescribed maintenance actions to correct detected conditions. Obviously, the selected inspection technique must be designed so that the appropriately trained personnel can detect the abnormality reliably. In the case of the CH146 (and other Bell helicopters), the objective of T/R blade surface inspections is to visually detect anomalies as specified in “damage and repair limits” so that if damage is greater than specified, the appropriate maintenance action can take place. Damage is three dimensional in nature, having length, width and depth.

The damage types as described in the CFTO (and OEM certified maintenance manual) are “nick/scratch, sharp dents and non-sharp dents”. There are different allowable limits for the different damage categories depending on the location on the T/R blade. If a discontinuity is detected, it must be classified and measured and the T/R must either be repaired or replaced depending on the measurements. The maintenance inspection of the CH146 T/R calls for depth to be the only criteria that must be detected, and depending upon the category of damage, its location and its depth characteristic, certain maintenance actions are to take place such as rejection or repair.

CF specific inspection requirements at present require the use of visual aids, in bright light on a cleaned blade and employing “cheese cloth” to assist in feeling for imperfections. As described in paragraph 2.1.3 above, the crack growth characteristics make detection of the damage site critical since the length of the crack only changes in the last few hours of the growth cycle. This means the “target size” for the visual inspection is the original damage size for all but the last few AFH and the inspection frequency could easily miss the rapid change in crack size before ultimate failure.

2.1.14 POD Study

After the CF changed its maintenance procedures, frequency and initial technician awareness training, the TAA believed that the assumptions regarding high POD for the new visual inspection needed to be verified, especially since the detection of anomaly depth was critical to this inspection and the CF was unable to find any other “industry standard” using only this criterion. Consequently, the Institute for Aerospace Research (IAR) at NRC-Canada was engaged in a project to obtain estimates for the POD for damage on CH146 T/R blades using the new improved CF techniques and trained technicians (see Annex T). Of note, the damage limits were not reduced to 0.003” at the time the NRC POD field data was gathered so the POD study makes reference to 0.005”, the damage limit in the critical area on the blade at the time.

This research project revealed that there were several problems with the visual inspection and critical parameters associated with CH146 (and other similar Bell helicopters) T/R inspections. Some of the key findings are as follows:

a. the discontinuity size limits are specified solely in terms of depth but the detectability of nick/scratch discontinuities is not a function of depth;

b. inspectors had trouble differentiating between some categories of damage which is problematic since different categories of damage have different “repair/damage” depth limits;

c. sharp dents were correctly detected and classified only at a 50% POD for 0.005” and 80% at 0.015”. Even when the second inspection with the optical micrometer was utilized to correct category classification errors, the inspection only achieved 75% POD at 0.005”;

d. reference to the documentation of anomalies in the Maintenance Record Set (MRS) for continuous monitoring of existing anomalies (ie paint chips) is required; therefore, the MRS must be transported with an aircraft under inspection in the field;

e. one technician was not experienced with the inspection and had poor performance compared to the experienced technicians, highlighting the need for task specific training; and,

f. interviews with inspectors revealed green or white painted blades (opposed to black) were superior from a visual contrast criteria perspective for discontinuity detection.

2.1.15 Subsequent CF Risk Assessment

These findings caused the CF to revisit the RA associated with the CH146 T/R blade in late 2004 because the first series of RAs assumed a high POD for the visual inspection (at least 90% POD). Since the POD for some categories of damage were only 50% POD, the associated risk level was increased (from low to medium). The 50% POD was based on the damage limit of 0.005 and not 0.003. This new 0.003 limit will reduce the POD further (to roughly 40%) due to the reduced critical "target size".

An important point needs to be made as to the conditions in which this POD study was performed. The personnel involved in the detection trial were well informed about the project objectives, knew that the blades had damage on them and they were highly motivated to detect this damage. Lighting conditions for detection were good; maintenance stands were erected for easy access; cleaning supplies and optical devices were readily available and the aircraft was in a hangar under good climatic conditions. Added to these factors, was the recency effect of a fatal accident, which is believed to have supplied further motivation for the technicians to detect the damage on the trial artefacts. Field conditions, time, reduction in motivation and/or training will likely reduce these already low detection rates in the future. Rather than inspecting a blade with multiple damage sites, technicians in the field will be required to look for damage sites on a previously undamaged blade and a record of previously detected and repaired damage will be consulted before the inspection.

Further, the POD study demonstrates the problem with depth as the critical dimension for visual inspections as well as the need for task specific training. The study also validates a requirement to frequently inspect the T/R as a result of the low POD for some types of damage (thereby increasing the POD through a high inspection frequency). The IAR NRC study prompted the TAA to initiate further investigation into alternate inspection techniques that would complement the current visual technique with the goal being to increase the POD in some manner; however, this work is still ongoing. Of note, the results of this POD study were passed to the OEM, TC and the FAA.

In view of the very low POD for certain critical damage types as found in this study and the requirement to do so for safe continuous operations of this aircraft type, the investigation team believes that the FAA should re-examine the practicality and effectiveness of conducting this critical maintenance task.

2.1.16 Information Passage to Civilian Authorities (TC and FAA)

As the information about the Bell 412 T/R blade fatigue failures became known, it was transmitted through DTA (the CF TAA at the time) to civilian TC officials. Because the CF has a process of certification for the airworthiness of all CF aircraft fleets, appropriate risk assessments and changes to maintenance were undertaken for the CH146 to ensure the fleets' continued airworthiness and safe operations based on that Authority. For civilian fleets like the Bell 412, civilian authorities award the airworthiness certificate; in this case the FAA in the USA issued the Bell 412 original airworthiness certificate. Consequently, the CF requested that TC officials pass the information about CH146420 and the Bell 412 T/R blade design concerns and fatigue failure to the FAA. Subsequently, the aspect that other similar T/R blade failures had occurred (PHI and the Czech police) was passed to the FAA through the TC contacts.

Based on information passed to them and independent research about other accidents and T/R blade failures, the FAA issued a SAIB (SW-05-10) on 5 November 2004 (see Annex S). The bulletin contained information on seven T/R blade failures with similar failure mechanisms, five of which were in very close proximity to the blade failure location of CH146420. The SAIB included recommendations on maintenance procedures to be employed for Bell 412 series T/R (and T/R of like design on Bell 205 and 212 series helicopters), identified the critical location, discussed the “susceptibility” of the T/R blade to impact damage and expanded on some improved techniques. The FAA recommendations in the SAIB are not mandatory. The investigation team believes that a mandatory Airworthiness Directive should be issued by the FAA to reinforce the seriousness of this issue with all operators.

However, the FAA SAIB did not suggest changes to the inspection frequency to deal with the low POD of the visual inspection found in the NRC study. It is likely the SAIB was issued before the POD concerns were raised or fully considered and the investigation team will recommend that the FAA consider these facts and take appropriate action.

2.1.17 Additional Design and Certification Concerns

It is worth noting that the T/R blade on the Bell 412 series is exactly the same as that on the Bell 212 and several other variants in this Bell Huey-family of helicopters. Initially, this led to conclusions that the failure on CH146420 represented an extremely small failure rate overall given the vast number of hours on Bell 212 (and other similar) aircraft. However, AETE undertook some basic comparative analysis of T/R torque loads due to baseline aircraft characteristics (details are contained in Annex U). This showed that the T/Rs on the CH 135 / Bell 212 and CH146 / Bell 412 are subjected to different loading conditions and should not be considered similar for the purposes of failure analysis. This position is based on the differences in operating weights and power ratings between the variants.

For example, the CH 135’s maximum gross weight was 10,500 lbs, while the maximum gross weight of later Bell 212 variants was increased to 11,200 lbs. The CH146 / Bell 412’s maximum gross weight is 11,900 lbs. Similarly, referring to the performance information in the respective Aircraft Operating Instructions made a rudimentary comparison of the CH 135 and CH146 possible. On the CH 135, a combined engine torque of 100% corresponds to its transmission limit of 1290 shaft horsepower (SHP), whereas on the CH146, 100% mast torque corresponds to its transmission limit of 1370 SHP. Comparing the power required to hover out-of-ground-effect (OGE) at sea level standard conditions at the CH 135 maximum gross weight of 10,500 lbs shows that the CH146 requires less power for the same gross weight, undoubtedly due to improvements in the design of the main rotor. The CH135 requires 94%, or 1210 SHP, whereas the CH146 requires 79%, or 1080 SHP. The CH146, however, has a maximum gross weight of 11,900 lbs, at which it requires 92%, or 1260 SHP to hover OGE. Since the rotor speeds, tail boom and T/Rs are the same on both types, the anti-torque thrust required by the T/R is in direct proportion to the power required to hover. This means that the CH146 T/R is subject to more stress than the CH 135 T/R. This simple example is only representative of one flight condition.

The fatigue life of dynamic components depends overwhelmingly on the small proportion of time spent in the highest stress manoeuvres. It is for these reasons that the CF believes that a CH146 / Bell 412 T/R does not experience identical stress loading to a CH 135 / Bell 212 T/R. Though both aircraft may share a common tail boom and T/R, the CH146 / Bell 412 can be operated at higher power conditions, which, in the absence of evidence to the contrary, must be assumed to result in larger T/R loading than the loading on the CH135 / Bell 212. Also, in support of this point is that five of the seven T/R fatigue cracks identified to this point have been on CH146 / Bell 412 variants (as detailed in sections 1.17.2, 2.1.10, 2.1.16 and Annex S), with considerably less total fleet AFH than on the Bell 212 series of aircraft.

Another highly significant difference between the 412 and 212 helicopter types is the operating speed. The 412 has a higher speed rating, both cruise and VNE. In general aerodynamic loads are proportional to the square of the velocity even a small increase in speed can result in a large increase in loading. In the case of the loads on the tail rotor, higher speeds result in higher oscillating loads, which is the prime factor in causing fatigue failures. (Basic VNE for the CH146 at all up weight is 140KIAS to 3000 MSL, Max Cruise speed for Bell 212 is 120 KIAS)

2.1.18 T/R Certification Issues

The investigation team had several certification issues that could not be satisfactorily resolved during the investigation process. Consequently, several recommendations are offered to the certification authority for follow up actions.

The current T/R blade was designed to satisfy a 1965 issue of FAR 29, under which there was no requirement to consider environmental degradation or accidental damage or intrinsic flaws as there is today under FAR 29.571. The original Basis Of Certification (BOC) is thus old but the original means of certification were satisfactory to meet that BOC. However, the power comparison and T/R force comparison conducted by AETE indicates that the T/R of the Bell 412 family of aircraft is subjected to larger forces than previous versions of the aircraft. In addition, as can be seen from this accident, barely detectable random accidental damage can lead to catastrophic fatigue failure before it can be detected with sufficient confidence; even with a directed 25 hour inspection. Therefore, the acceptance of component life, damage limits and structure calculations by “like service” comparison to the Bell 205 / 212 series of aircraft should be an issue reviewed by the airworthiness issuing authority (FAA USA).

Second, the investigation team could not find a technical explanation, nor was the OEM able to provide the engineering substantiation for the assignment of the “damage” limits published in the maintenance manual. This is particularly important in the area of the failure because of the possible unaccounted stresses due to the location of original analysed points (as outlined in para 2.1.11 above) not being co-located with the underlying structure’s sharp radius form. From these two perspectives, the investigation team is concerned that the “Means of Compliance” for the T/R design, life and associated “damage limits” may not be consistent with the Basis of Certification (BOC) and should be re-examined by the Issuing Airworthiness Authority (the FAA in the USA).

Third, it is not clear if the FAA had information from the POD study when the SAIB (November 2004) was compiled. Consequently, the frequency of T/R inspections may not have been reduced in the SAIB as it was in the CF due to the low POD (effectiveness) of finding “out of limits” damage based solely on depth criteria, even using the special inspection techniques (see 2.1.14 above). The certification authority should reconsider the POD study findings, with respect to effectiveness/success rates, for frequency of inspection.

Finally, the practicality of properly carrying out this type of inspection, given its critical nature, a design that is exceptionally intolerant of damage and the low POD should form a part of certification re-examination. The practicality aspect of inspection is particularly challenging and of high concern given field operations and adverse inspection conditions one can expect in normal flight usage.

2.1.19 CF Airworthiness Investigative Authority (AIA) Safety Concerns

Given the multiple T/R blade failures, the CF AIA contends that the OEM must bring the critical design limitation and the nature of the extremely damage intolerant structure to the attention of all Bell 412 users. While the OEM did issue an “Operations Safety Notice” (OSN) (Annex J) following this accident, it is believed that there was insufficient direction on the methods needed to detect the damage reliably and no direction or information about the critical area location on the T/R blade included in the notice. The FAA SAIB did respond to some of these concerns but that bulletin is not mandatory and due to the critical nature of this issue, inspection methodology should be compulsory to ensure continued safe operations.

Further, the CF AIA contends that the inspection of the T/R blade structure needs improved *special methods* and training to reliably detect critical damage patterns given the low POD discovered in the NRC study for “detailed visual inspections” for depth damage detection.

The CF AIA believes that the FAA should re-visit the Bell 412 certification with respect to T/R blade design, inspection practicality and failure characteristics based on the information in this report as outlined in section 2.1.18.

Barring the development of a practical, deployable, reliable damage detection protocol, the CF AIA believes that T/R blade redesign and mandated inspection procedures are required to ensure safe operation of the CH146 fleet. Other users of the Bell 412 would also benefit from an improved design.

2.2. Health Usage Monitoring System (HUMS)

2.2.1. General Description

This aircraft's HUMS was successfully downloaded after the accident. Although still undergoing progressive development to refine the timing of when maintenance action is called for, the HUMS records data, primarily frequency spectra from various locations and sensors. This data is trended over a long time frame in order to predict failures of components before they fail in use. The HUMS data is continuously and automatically gathered according to an analysis schedule dependant upon flight regime and the parameter being monitored. Aircrew can also actively initiate recording of specific HUMS data by pressing the "take data" button. Certain events will trigger automatic recording of specific HUMS data as well. The HUMS component condition monitoring is done through setting vibration tolerance levels for the data gathering points that are being examined. Should the gathered data exceed the preset threshold level, further investigation is undertaken to ascertain the reason. Because the system was acquired primarily as a maintenance aid and a low false alarm rate could not be assured, no system was incorporated to notify the crew in flight when vibration exceeds the preset level. In its present configuration, HUMS is used to detect problems when the aircraft is on the ground after flight and maintenance personnel download and analyse it's collected data. It is important to remember that the CH146 (and the Bell 412) is a certified aircraft without the HUMS installed and that the HUMS is not a required item for serviceable flight.

Although HUMS will provide an automatic alarm to maintenance personnel when the data is analyzed on the HUMS ground support station, the automatic alarm for monitoring parameters is only triggered when there have been three (3) exceedences in the past five (5) measurements.

2.2.2. CH146420 Information

Using routine methods, the first download of CH146420 HUMS did not trigger the automatic alarms. The investigation team decided to have the HUMS data stripped and examined by the OEM. This allowed the data from the last few hours of the flight to be examined in more detail (Annex F) and showed that some vibrations detected by HUMS did exceed the preset tolerances. By the time the refuelling stop was concluded, about 25 minutes before the crash, the HUMS had recorded three vibration levels that exceeded the preset values. It is important to remember that the system as presently configured could not have given the crew a warning of these vibrations. Also, on the flight prior to the accident, CH146420 had recorded only one exceedence for T/R axial vibration and two exceedences for T/R radial vibration. Since the aircraft had not yet returned to base, this HUMS data had not been downloaded and analysed. Because these exceedences were recorded on different parameters and 3 of 5 measurements were not excessive, an automatic alarm would not have occurred on routine analysis. Only a focused review of the data by an experienced technician would have determined that the vibration data exceeded the preset values and alerted technicians to conduct a more intensive inspection of the T/R.

2.2.3. HUMS Warning Modification Considerations

The investigation team considered the possibility of various modifications to the HUMS so as to provide timely warning of impending failure to the crew. One possibility is to incorporate a caption (HUMS) on the Caution Annunciator System that illuminates when preset vibration parameters are exceeded. The investigation team discovered that this option was rejected in the delivered version of the HUMS because of high false alarm concerns as mentioned above. Unless annunciated cautions are highly reliable, such warnings can become a nuisance or even detract from safety, particularly if emergency procedures demand quick or extraordinary action by the crew. Further, a change of this type would likely involve fairly extensive aircraft modifications and corresponding costs. From experience with other HUMS systems, DTA estimated such a change would take at least 2 years and possibly cost over a million dollars to develop, before paying for unit installation costs.

Another option would be the use of an easily detectable trip (eg, a “cat’s eye” which changes colour when an excessive vibration level is detected on one of the HUMS electronic boxes). This kind of system would be checked after each flight, and if tripped, a HUMS download and appropriate maintenance action would take place before the next flight.

In the case of Ch146420, either of these HUMS modifications could only have been effective in preventing the accident if the 3 of 5 exceedence parameters were changed and if complete maintenance procedures occurred before the aircraft was released following the HUMS indication being tripped. It is worthwhile to point out that even a flight to the nearest maintenance location (sometimes authorized in cases of this nature due to the logistics involved with remote maintenance) would have resulted in an in flight failure in this case.

Technical authorities advocate that the HUMS technology available today is not refined enough to be used by itself to make a serviceability call on the status of the aircraft. If the CH146 Griffon were equipped with a light on the Caution Annunciator System to inform the aircrew of HUMS exceedences, many missions would be aborted for no valid reason. Regardless of this perspective, the investigation team concluded that further consideration for changes to the HUMS in these areas by the CH146 WSM is merited.

2.2.4. Reliance on HUMS

The investigation team looked at maintenance procedures to determine the degree to which HUMS data is used within the CH146 maintenance community to monitor component condition vice the use of other detection methods such as visual inspection. While the HUMS are being used to assess component condition, it is only one means being used for such predictions. There was no indication that the system is being relied upon as a sole source to find deteriorating conditions or to precipitate maintenance actions. The investigation team concluded that HUMS is a good tool and is being used properly by the CH146 maintenance community. However, the system merits further development, and work should continue to establish and refine vibration level tolerances.

2.3. Crew Reaction to the Emergency

2.3.1. Training Records

The investigation team examined the crew training records and files and determined that all training and readiness requirements were met and all crewmembers were considered current and proficient. The crew commander had an impressive file, was very experienced on this aircraft type and had achieved the status of Sqn Stds O, though he was relatively new to SAR operations. The investigation team concluded that no SAR operational considerations affected the outcome of this occurrence since the search had been stood down when the accident occurred.

2.3.2. CVFDR Analysis

The CVFDR data was retrieved and successfully downloaded by the experts at NRC within 24 hours of the accident. The preliminary interpretation of the data showed that the crew correctly analysed the problem and realized the T/R had failed within four seconds of its departing the aircraft. Further, the crew was reacting to the emergency condition but within a further four seconds, about eight seconds from the T/R failure, the aircraft began rotating about its vertical axis. Shortly thereafter, the rotation rate of the aircraft increased to about 210 degrees per second and a high rate of descent (approximately 4000 fpm) developed prior to tree and ground impact, which occurred within 16 seconds of the T/R failure (Annex E).

2.3.3. CVFDR System Limitations

Generally, the CH146 FDR data includes many parameters but the data has some limitations that hinder detailed flight dynamics analysis. First the sample rate is low, in some parameters only providing data points once per second (1 hertz). With the critical events for CH146420 taking place over 16-17 seconds, this rate provides only a few data points and much must be inferred from these points. Next, motion data is expressed in six degrees of freedom (longitudinal, lateral, vertical, pitch, roll and yaw). The CH146 FDR does not account for lateral or yaw motion so there is only four degrees of freedom to determine the actual flight profile of CH146420. Also, there is no longitude, latitude or throttle position recorded on the FDR so these parameters must be inferred from other means such as wreckage position, engine data and rotor RPM. Finally, the low data sample rate is further complicated by erroneous air data from CH146420 due to characteristics of the recording mechanism (the Air Data Computer) that rendered some airspeed, pressure altitude, rate of climb and outside air temperature points questionable. For example, IAS for some of the final profile is recorded as 448 knots – an impossible velocity for this scenario.

Although the IAS data point is invalid, an analysis of the recording system does yield factual information about the flight profile because the reading of 448 knots is actually an “error code” the ADC generates for various reasons. Analysis of the ADC and recording system showed this code was generated due to the extreme sideslip on the aircraft (about 60 degrees) caused by the loss of the T/R and continued torque produced from the main rotor.

2.3.4. CVFDR Derived Information

Detailed FDR data and system analysis allowed the determination of the approximate flight path, aircraft conditions and flight control inputs. This analysis showed the aircraft immediately yawed (side slipped) to the right by approximately 60-70 degrees and stabilized at a heading of approximately 230 degrees magnetic as the T/R left the aircraft.

At the time of the failure, the aircraft was about 300 ft AGL and just crossing a small creek and lake. The heavily treed terrain rose sharply, particularly to the right of aircraft track, effectively reducing altitude available for recovery. The aircraft captain, at the controls, attempted to correct the yaw with full left pedal but this was ineffective without a T/R. The very large yaw immediately started slowing the aircraft from the entry speed of 118 KIAS. The FDR showed a slight reduction in collective (about 5% of travel) initially and large cyclic inputs to control aircraft pitch in reaction to the changed C of G due to the T/R departure. Similarly, some small cyclic inputs were made to keep the aircraft flying forward but initially no throttle inputs were made.

After the second revolution about the vertical axis, when most of the forward speed had been bled by profile drag, the collective was reduced fully and remained in that position until ground impact. Almost at the same time that the collective was lowered to the bottom, the engine #1 torque decreased to 0% and engine #2 torque only decreased to approximately 20 %. This demonstrates that the flying pilot, sitting on the left side, was probably successful at reducing throttle #1 to idle; however, apparently he did not fully reduce the throttle #2 to idle. This is not unusual since the throttle #2 is a lot harder to control in the left seat because of the proximity of the seat structure and because of the design of the throttle linkage which makes throttle #2 harder to move compared to #1. While the command seat in the CH146 is the right seat and this problem is not present when flying from that seat, the left seat restriction to easy throttle movement suggests that practice autorotation and associated throttle movements should be practiced from both seats so that pilots are prepared to deal with this difficulty in an actual event.

Shortly thereafter, the aircraft contacted the trees at about 4000 FPM, was slowed to about 2500 FPM as the trees entered the fuselage and struck the ground with this high vertical speed but nearly no forward velocity and about 20 degrees left wing down attitude.

2.3.5. AOI, Checklist and SMM Precedence

The CH146 AOI was developed directly from the FAA certified model Bell 412 Aircraft Flight Manual, and thus is the authoritative document for CH146 aircraft operation. The CF CH146 "Checklist" is an aid for aircrew, constructed in lieu of AOI usage, because it is not practical to refer to a large book during flight operations, particularly during emergency situations. Ideally the Checklist should not deviate from the content of the AOI. The same is true for the Standard Manoeuvre Manual (SMM) or any other procedural reference used by aircrew.

2.3.6. AOI and Checklist Actions

The CH146 checklist for T/R failure emergency immediate reactions calls for "Collective - Reduce to Minimum. If yaw is uncontrollable, Throttles – Flight Idle, Airspeed – Autorotative glide 70 KIAS MINIMUM" (Annex L). The AOI has this procedure inverted as: "Close throttles and reduce collective. Attain an airspeed slightly above normal autorotative glide speed. If altitude permits with airspeed above 60 knots, throttle and collective may be gently applied to see if some degree of powered flight can be resumed. If any adverse yawing is experienced, re-enter autorotation and continue descent to a landing." The procedures in these two documents provide conflicting guidance and required actions are not completely clear, which may or may not have affected the reaction of the crew.

The "Loss of T/R Thrust in Level Flight procedure" in the Bell 412, 412SP, 412HP and 412EP Flight Manuals is only slightly different from the AOI and states: "Close throttles and reduce collective <u>pitch immediately</u>. Attain an airspeed slightly above the normal autorotative glide speed. If altitude permits with airspeed above 60 knots, throttle and <u>pitch</u> may be gently applied to see if some degree of powered flight can be resumed. If any adverse yawing is experienced, re-enter autorotation and continue descent to a landing."

2.3.7. AOI and Checklist Action Analysis

In a T/R failure emergency, collective must be reduced immediately to enter autorotation and remove the torque load from the Main Rotor regardless of throttle positions and thereby reduce the need for T/R anti-torque. Further, reducing engine throttles to flight idle provides additional assurance that minimal torque is applied to the main rotor as the procedure ensures the free wheel unit is engaged because the sprag clutch in the combining gearbox disengages. This combination of actions allows some directional control of the aircraft through cyclic inputs while the helicopter is in full autorotation. Last, throttle reduction sets up the aircraft to prevent the main body from spinning due to the mismatch of high Main Rotor torque and no anti-torque (T/R) when the collective is raised at the termination of the autorotation.

The airspeed requirement ensures the minimum rate of descent is achieved, about 1900 FPM (descent rate for 70 KIAS autorotation) (Annex O). Variation to the airspeed in either direction causes increased rates of descent (up to about 4000 FPM at zero airspeed).

Although the FAA certified Bell 412 Aircraft Flight Manual is the authoritative document, the order of the CH146 Checklist is more in concert with Human Factors and performance in emergency situations. The first reaction to this type of emergency must be collective reduction (to enter autorotation) because main rotor RPM and torque will quickly cause aircraft directional problems and associated control difficulties. Throttle reduction is important but is secondary to reduction of main rotor torque. Also, if throttle reduction is not accompanied with collective reduction, main rotor RPM will be lost, creating an even more catastrophic situation. Bearing this in mind, the investigation team concluded that an AOI amendment and associated recommendation to the Bell 412 Aircraft Flight Manual is required to reflect a more appropriate response to this critical emergency, which is properly reflected in the CH146 Checklist. Also, the checklist should be amended to ensure that “enter autorotation” is specified.

2.4. CH146 Autorotation

2.4.1. CF Autorotation Training Background

When the investigation team reviewed the history of autorotation training and practice in CF helicopter fleets, it became evident that training had been reduced and de-emphasized over a period of years. This was partly because all CF operational helicopters now have at least two engines. Only the initial helicopter flight training uses a single engine helicopter; the Jet Ranger. The likelihood of a double engine failure being remote and the fact that several practice autorotation accidents had occurred contributed to separate decisions that resulted in less emphasis on autorotation. This was done in primary helicopter training to conserve resources and it was carried over into operational squadrons because of the twin-engine logic. Unfortunately, this logic only makes sense from a power plant perspective. Most helicopters are still susceptible to T/R, gearbox and drive shaft malfunctions, and T/R control malfunctions, which would require autorotation as an emergency reaction.

2.4.2. CH146 Actual Autorotation Practice

Actual autorotation practice for most CH146 pilots consists of entering the sequence at about 1000 ft AGL and recovering by 150 ft AGL with power on both engines as dictated by the applicable orders. Autorotation practice is a quarterly requirement for CSS operations, and semi-annual requirement for Tac Hel operators. This training limitation rule does not allow most CH146 pilots to practice a very critical phase of flight for a successful autorotation, specifically the “flare, check, level, and cushion” of the landing phase. All checks and control movements must be completed in a very short period of time. This last part of an autorotation requires very good judgement, skill and coordination to be accomplished effectively and safely. It is also a very risky phase of the manoeuvre because a small error or omission can result in serious injuries and aircraft damage, as CF helicopter autorotation accident experience over the last 10 years has shown. The margin for error is small but previous CF training experience has shown practice autorotations can be accomplished safely when rigid controls, criteria and procedures are adhered to during the training sequences.

Of note, the focus for training should be on practice autorotations as a whole. The entry, profile management (i.e. max range/endurance/turning/etc) and landing are all critical. Until realistic autorotation training from entry to landing can be conducted (in aircraft, simulator, or both) the lack of proficiency in effective emergency response will represent a significant concern in CH146 operations.

2.4.3. CH146 Simulator Fidelity and Autorotation Practice

The lower, full flare and landing portion of an autorotation is flown only in the simulator, located in 403 Helicopter Operational Training Squadron (403 (Hel) OTS), at Canadian Forces Base (CFB) Gagetown, New Brunswick. While all CH146 pilots do get time in the CH146 simulator, it happens only yearly for most. The investigation team believes this is not enough exposure to maintain a reasonable level of proficiency in critical emergency handling and adjustments to the training protocol are merited.

To assess simulator fidelity, particularly for T/R failure scenarios, the investigation team examined the development process used by the original procurement and trials team of the CH146 simulator. One of the system developers, who had incorporated the flight model development process into his Masters thesis, stated that the simulator indications and flight path reactions were partly based on an aerodynamic model, but that the trial pilots, on a “gut feel” basis, had recommended that much of the original programming for the simulator be modified for the post T/R failure aircraft reaction scenarios. This was because there was no means of knowing how the simulator should react without comparing the simulator reaction to actual aircraft reaction to loss of T/R since this cannot be measured. Test pilots thus provided evaluations based on experience that was used during the development of the simulator reactions.

To further assess the simulator fidelity with respect to loss of T/R, the investigation team compared the actual flight data retrieved from the CVFDR to the CH146 simulator reaction to a T/R loss. The profiles proved to be remarkably similar; however, similarities between the estimated flight profile based on FDR data and the simulator must be viewed with caution. This is because any flight profile based upon the FDR data is only an estimate, based upon many assumptions and it cannot be known for sure how well this estimate reflects reality. Having noted this caution, it is still important to note the test pilot "estimated" inputs that created the simulation for this failure appear to have been generally good.

The investigation team concluded that the CH146 simulator T/R failure algorithm portrays the actual failure extremely well. Unfortunately, the simulator has a general weakness for fidelity and visual clues for the last 50-60 ft of altitude (Annex M). This means that the simulator can be used to demonstrate aircraft reaction to this kind of failure and the results of various control inputs at altitudes above the 50-60 foot level, but cannot accurately train pilots in the critical actions required near the ground for such emergencies. Improvement to the CH146 simulator visual fidelity is recommended to cover this deficiency.

2.5. Emergency Reaction

2.5.1. Actual vs Recommended Reaction

The flying pilot's reaction to the emergency depicted by FDR data was not as recommended in either the checklist or the AOI – collective was not immediately lowered and engine FDR data indicated that the throttles were not reduced until control had been lost. The extreme yaw reaction of the aircraft because autorotation was not established meant that the airspeed was not maintained at least 70 KIAS (see para 2.3.4 above). Had an autorotation been established, the pilot likely would have had more control over the airspeed. Given the pilots' high level of competence according to both training files and reputation, the investigation team attempted to ascertain whether CH146 baseline pilot training for this emergency was adequate.

2.5.2. Expected Aircraft Behaviour

Informal discussion and interviews with CH146 pilots revealed a widespread belief that it was possible and even desirable to fly a T/R stricken aircraft out of inhospitable terrain. Pilots believed that with enough forward speed, the aircraft would be controllable because the tail's vertical stabilizer would create enough sideward "lift" to compensate for a reduced torque, and the aerodynamic shape of the aircraft fuselage would assist in keeping the aircraft from spinning. Under these conditions, they thought it was possible to fly the aircraft to a suitable location where a "run on landing" of some sort or "autorotation to level ground" could be performed.

While the AOI (Annex L) does not explicitly recommend this procedure for a T/R failure, the final portion of the emergency states, "Carry out run on landing or autorotative glide landing as the situation dictates". Some pilots interpreted this, as "a fly-out was possible for T/R failures". Further, this interpretation may have been reinforced during conversion training given by Bell during CH146 acceptance, as some pilots recall having been counselled by instructors to first attempt to fly out by maintaining airspeed. Also, for the most part the single training scenario for T/R failure given in the CH146 simulator was where the crews were usually forewarned of the impending failure, the aircraft was usually high (more than 1000 ft AGL) and the terrain below close to ideal for “run on landings”.

For the best training experience the investigation team believes the emergencies for loss of tail rotor component and power loss failures should be seen throughout the simulator training session. Crews should not be forewarned and flight profiles should be representative of flight profiles flown by Tac Avn/CSS crews.

2.5.3. Weather and Geographic Factors

For this accident, other factors possibly affecting the pilot’s decision were the terrain and the relatively short time available (4-8 seconds) due to weather limiting the transit height. The adverse yaw immediately pointed the aircraft to the rising, heavily treed and rocky terrain to the right of the aircraft track, with a fairly desirable forced landing area just to the rear of the aircraft‘s track. A combination of the belief that a “fly out recovery was possible” and denial on the crew’s part about accepting the terrible landing area ahead due to terrain features possibly influenced the crew into delaying autorotation entry.

2.5.4. Crew Expectations

Another, more subtle factor potentially affecting this decision was an expectation that any emergency should result in a relatively undamaged aircraft, and of course the survival of the crew. While difficult to prove and impossible to measure, this expectation exists. It is reinforced by a number of elements including: the fact that emergency practice exercises in the air terminate with safe landings (in basic helicopter training all autorotations to landing are designed to be completed without damage), by wording in checklists and standard manoeuvre manuals that finish with a description of a safe landing, and by pilots’ personality. The horrific terrain in front of the accident aircraft rendered that expectation unrealizable without “flying out” of the emergency. In some circumstances, helicopter pilots must accept that the loss of major system such as a T/R turns the aircraft into a life saving device (“a parachute”) that must be sacrificed for survival and CF helicopter training should be adjusted to reflect this mindset.

Of note, the Standard Manoeuvre Manual (CFACM 40-46 (Annex N)) mentions very little about complete T/R loss and refers the reader to the loss of T/R thrust for more information.

2.5.5. Pilot Pre-disposition to “Flying Out”

There seemed to be another factor complementary to that discussed in section 2.5.4 above. It appears that CH146 pilots had a pre-disposition to ‘’fly out’’ of T/R emergencies. To verify this possibility, within days of the accident, the actual flight conditions and initial aircraft flight parameters obtained from the FDR were used to conduct several simulator trials. This simulation was to determine how other CH146 flight crews would respond to unforecast T/R failures in conditions similar to those experienced by the crew of CH146420 and to record aircraft reactions. Five different crews participated to this simulation and flew a total of 21 autorotations. Every crew reacted similarly to the crew of CH146420. Of the five crews presented with the scenario, not one reacted with an immediate entry to autorotation. All crews attempted to fly the aircraft out of the area to a more hospitable landing area or to descend under power to the ground. Even when given multiple opportunities with the scenario, crews were unable to fly the aircraft to a reasonable landing because they attempted to maintain powered flight. 20 of 21 crashed badly, the one relatively successful landing was followed on the next attempt (by the same crew) by one of the worst crashes. From this informal trial, the investigation team concluded that the CH146 aircrew community was, for a variety of reasons, pre-disposed to react to this kind of emergency, as did the crew of CH146420. The investigation team considers this situation unacceptable and concrete, affirmative action must be taken to ensure that Griffon pilots in particular and T/R equipped helicopter pilots in general do not consider the "fly out option" as a reliable reaction to T/R failures. Pilots must be able to recognize "complete T/R loss" and immediately establish an autorotative descent.

2.5.6. Complicating Factors in Landing

Given the aircraft's aerodynamic reaction to the T/R loss and the pilot's initial reaction to the emergency, four complicating factors greatly reduced the chance of success for the landing phase of this accident:

a. High rate of rotation about the vertical axis;
b. Somatic gyroscopic effect (disorientation);
c. Cyclic position; and
d. Physiological effects.

The delay in reducing the collective and rolling the throttles to flight idle resulted in a high rate of descent and high rate of rotation. This gave the aircraft so much momentum that substantial time and altitude would have been required to arrest the rotation to the right. The crew did not have enough time in this situation because of ground proximity.

With the aircraft rotating at about 210 degrees per second, the somatic gyroscopic effect likely completely disoriented the crew thereby making it very difficult if not impossible for the flying pilot to effectively fly the aircraft. The somatic gyroscopic effect is demonstrated to CF pilots during Aero Medical Training (AMT) using the Barani Chair. It is an extreme form of disorientation where movement about the vertical axis is translated to wild pitch sensations by the vestibular functions of sensory organs when movement in another axis is introduced. The stricken aircraft met all of these conditions during the last seconds of the flight, probably resulting in this effect, which associated "G" forces would have exacerbated.

In the flight simulator runs conducted for this investigation, the initial yaw from a loss of T/R progressed to a rapid increase in the rate of turn when the cyclic was positioned neutral or right of neutral. The FDR shows that the pilot was trying to overcome significant aircraft pitch changes and a left skid low attitude for the last 10 seconds of flight with right cyclic input and this may have made the rotation rate higher.

The crew most probably experienced the physiological effects of a high stress situation due to increased adrenaline. Some of those effects would be short focal distance, focused (reduced peripheral) vision, dilated pupils, higher blood pressure and higher pulse rate. These secondary effects likely reduced the flying pilot's ability to visually detect the rapidly increasing proximity of the terrain ("ground rush") during the last moments of the flight. Finally, the low rotor speed warning was sounding immediately prior to impact and this could have caused the crew to keep the collective lever lowered to attempt to regain main rotor RPM, particularly if disorientated and unaware of the ground proximity.

The combination of these complicating factors and the lack of CH146 autorotation practice, particularly in the landing phase, help explain why the pilot did not increase collective control input close to the ground.

2.5.7. Autorotation Airspeed and Available Landing Sites

Some very important points need to be made about this post accident analysis. First, even without a flare or collective pull at the bottom, quickly establishing full autorotative glide at 70 KIAS would have halved the rate of descent (1900 fpm vs 4000 fpm). Though this would not have been a guarantee of improved results because events such as dynamic aircraft upset, post crash fire, or failure of high-energy components such as main rotor blades could happen and may have had tragic results, it would have reduced vertical and rotational deceleration forces imposed on the crew.

The emergency autorotation profile limits landing sites to those within "gliding" distance. At low altitude that's a very small selection but aircraft control is retained. If autorotation is entered immediately (almost instinctively), some options remain, though in this accident, that would have only meant a choice of which trees to land on. With this point in mind, consideration should be given to teaching or discussing techniques to make undesirable landing sites more survivable. As examples of some thoughts on the subject, the French Army counsels initiating a very steep flare just above the trees to reduce groundspeed to zero and holding it till impact, using the tail boom as a cushion. Others opine that this action might induce last moment rapid rotation about the mast axis, possibly driving trees sideways through the cockpit and cabin; these pilots would enter trees at zero groundspeed in as flat an attitude as possible.

2.5.8. CH146 Autorotation Training Improvements

Analysis of this accident indicates that changes to CH146 training methods and philosophy, particularly for autorotations and emergency response, could improve the chances of survival in accidents like this one. First, the CH146 simulator should be utilized to practice multiple low-level autorotation scenarios and in particular for T/R loss malfunctions. The need to immediately enter autorotation and acceptance of the resulting landing terrain should be stressed. Associated with this would be emphasis on the fact that emergency autorotation is a survival situation and the aircraft should be sacrificed for the well being of the crew. As well, the CH146 simulator visuals need to be upgraded if it is to be depended upon as a primary tool for autorotation/emergency training (as detailed in section 2.4.3).

In addition to reinforcing the present checklist responses, it should be mentioned that 70 KIAS is the proper airspeed to achieve the minimum rate of descent in a steady state autorotation (Annex O). Further, the features associated with main rotor torque, rate of descent and tail fin force outlined in the chart at Annex P should be used as a tool to explain the emergency response for loss of T/R emergencies. Although this chart does not consider immediate aerodynamic changes associated with the adverse yaw and uncoordinated flight when a T/R is lost, it is useful to explain the dynamics and control inputs required. The chart graphically illustrates that the tail fin cannot be relied on to stabilize the helicopter after loss of tail rotor thrust.

Unfortunately, the lower portions of autorotations are not portrayed well in the present CH146 simulator due the inherent visual problems associated with the last 50-60 ft. This is a very important portion of autorotation training, some means of conducting full autorotation training through the use of actual CH146 flight profiles (with appropriate safe guards to avoid aircraft damage) should be considered. This type of training has been successfully accomplished in the CH124 community for some time and the investigation team believes similar procedures might be used in the CH146. However; should the CH146 rotor system not provide the ability to practice engine on autorotations due to over speeding the engine or other insurmountable problems, the fidelity of the simulator should be improved to provide a high level of proficiency in the close to ground portion of emergencies.

Finally, the attitudes or pre-dispositions against entering autorotation found in the CH146 community may be present in other communities (CH 149, CH139 and possibly CH124). In addition, fleets with other ‘’force landing scenarios’’ could benefit from a new look at how their crews are trained for emergencies, including the use of airborne emergency simulation, currency requirements, and simulator scenarios and requirements so that the most can be gleaned from this tragic accident.

3. CONCLUSIONS

3.1. Findings

3.1.1. The aircraft was serviceable from the perspective of CF maintenance practices in place at the time, prior to departure from Goose Bay other than for routine minor entries as noted in the aircraft maintenance set. (1.6.1)

3.1.2. The crew was qualified and current to perform the mission. (1.5) (2.3.1)

3.1.3. The pilot in control was flying from the left seat. (1.5) (2.3.4)

3.1.4. The weather was within limits for the SAR mission to be performed. (1.1) (1.7)

3.1.5. Weather ceilings limited the mission transit altitude to about 500 ft AGL but lower over higher terrain in the region of the accident. (1.1) (1.7)

3.1.6. The T/R blade and associated assembly departed the aircraft in-flight and fell into the forest about 400 meters before the aircraft crashed into rising heavily treed terrain. (1.1) (1.3) (2.3.4)

3.1.7. The T/R had about 18.5 inches of one blade tip fail and depart the T/R blade assembly due to a fatigue crack initiating from a small damage site on the skin of that rotor blade. (1.3) (1.16) (2.1.2)

3.1.8. The imbalance on the T/R blade assembly, due to the failure of the T/R blade tip, caused the failure of the T/R input shaft (90 degree gearbox shaft) and the departure of the entire T/R assembly from the aircraft. (2.1.2)

3.1.9. The CVFDR was recovered from the aircraft and personnel from NRC successfully downloaded the data that proved pivotal in understanding the accident sequence and the flight leading up to that event. (1.11.1) (2.general)

3.1.10. The characteristics of the FDR data made precise reconstruction of the flight path profile impossible because two parameters for the six degrees of motion were not available on this FDR (lateral and yaw planes). As well, the low sample rate and erroneous air data due to characteristics of the recording mechanism (the Air Data Computer) rendered some airspeed, pressure altitude, rate of climb and outside air temperature points questionable. However, detailed FDR data and system analysis allowed the determination of the approximate flight path, aircraft conditions and flight control inputs. (2.3.4)

3.1.11. The aircraft reaction to the loss of the T/R and associated assembly was a nearly immediate 70-degree yaw/sideslip to the right, a very significant nose tuck and likely quick loss of forward airspeed. Forward airspeed reduction due to the sideslip condition cannot be quantified due to the ADC data gathering mechanism generating an “error code” of 448 KIAS within 2 seconds. (2.3.3) 2.3.4)

3.1.12. The crew correctly identified the emergency within four seconds and attempted to control the aircraft. (1.1) (2.3.2)

3.1.13. Within seconds the aircraft was rotating about the vertical axis at about 210 degrees per second. (1.1) (2.3.2) (2.5.1)

3.1.14. The aircraft struck the trees and the ground at high vertical velocity (estimated between 4000 fpm and 2500 fpm, respectively) about 16 seconds after the T/R departed the aircraft. There was no evidence of control inputs to attempt to halt the high rate of descent prior to ground contact. (1.1) (2.3.4)

3.1.15. The two pilots were killed instantly in the accident, the SAR Tech was very seriously injured and the Flight Engineer was seriously injured. All injuries were attributable to the forces caused in the accident and ground contact. (1.1) (1.13) (1.15.1) (1.15.2)

3.1.16. All crewmembers tested negative for alcohol and drugs, other than for drugs administered in the ensuing rescue and medical triage. (1.13)

3.1.17. The FE was able to notify RCC Halifax of the crash by using the satellite telephone on the aircraft. In this instance, a satellite phone was available because of the presence of the SAR Tech. Satellite phones are not standard CH146 aircraft equipment. (1.1) (1.9)

3.1.18. The rescue helicopter (R475) used the GPS position and PLB signal to home in on the accident scene. The FE used the portable radio (Sabre radio) to "talk" R475 into a hoisting site. (1.1) (1.9)

3.1.19. Initial sighting of the accident scene was due to the orange arctic tent fly draped over the aircraft. The aircraft camouflage colour made it very difficult to visually acquire the accident scene. (1.1)

3.1.20. The surviving crewmembers were extricated from the accident scene, loaded on the helicopter by rescue hoist and transported to the Goose Bay hospital. (1.1)

3.1.21. The quick response by the rescue helicopter, the on board medical treatment and the subsequent quick delivery of the SAR Tech to the hospital permitted his survival and eventual recovery. (1.15.2)

3.1.22. The failed T/R blade was the end result of a fatigue crack that initiated from skin damage on the blade about 0.008 inches deep by 0.060 inches long, likely caused by a stone. When the fatigue crack reached its critical crack length, the rest of the blade tip failed in overload. (1.16) (2.1.2)

3.1.23. The T/R blade inspection in the CFTO at the time of the accident limited the size of damage for this orientation in this area of the T/R blade to 0.005 inches depth before the blade must be replaced. The OEM subsequently reduced the damage limit depth for this type of damage to 0.003 inches for the entire blade surface. (1.6.1) (2.1.2) (2.1.5) (2.1.8)

3.1.24. Though in consonance with those of other Bell 412 operators, CF CH146 T/R inspection and maintenance procedures were not sufficiently detailed to detect this level of damage with any degree of certainty, and no procedures were in place to measure this size of damage. (1.6.1) (2.1.4) (2.1.6)

3.1.25. CH146 inspection and maintenance procedures were immediately modified to attempt to achieve a very high probability of detection for T/R blade damage and techniques were put in place for measurement of detected damage. Inspection changes include use of magnification, cleaning the blades, use of “cheese cloth” and the requirement to use bright lights to inspect the critical zones of the blades. As well, the colour of the blades have been changed from matte black with a red-white-red tip to gloss white with two black bands for the CS Sqn aircraft and semi-gloss olive green with red-white-red bands for the Tac Hel Sqn aircraft. The colour schemes were also changed to preclude a colour change occurring in the critical zone. (1.6.2) (2.1.6) (2.1.9)

3.1.26. The OEM did not emphasize the T/R blade inspection procedures required, or the critical nature of damage to this component during conversion to type maintenance courses for CF personnel. (2.1.6) (2.1.7)

3.1.27. The damage limits are the same for all of the blades regardless of colour and the OEM has certified all colour variations without restriction. The black colour of the CF T/R blade may have made crack detection more difficult. (2.1.7) (2.1.9)

3.1.28. Seven confirmed T/R blade fatigue failures of this type have occurred on Bell helicopters (as detailed on the FAA SAIB of Nov 2004). Five of these failures were on Bell 412 type aircraft and five of the seven failures occurred at this location on the T/R blade. These failures occurred prior to CH146420. (1.17.2) (2.1.16)

3.1.29. The OEM issued an OSN to “All Owners/Operators of Bell 205, 205B, 212, 412, 412CF and UH-1H-II Helicopters” on 27 August 2002 to “remind operators of the importance of accomplishing a complete inspection of the T/R blades at specified inspection intervals.” Further reference to maintenance manuals is recommended in the OSN. (1.17.1)

3.1.30. The OEM has not provided guidance to worldwide users of the Bell 412 type helicopter on T/R inspection techniques required to avoid failures of this nature, or information on the critical nature and effect of a very small amount of damage on the T/R blade in this critical location. (2.1.5)

3.1.31. The FAA issued a Special Airworthiness Information Bulletin (SW-05-10, dated November 5, 2004) recommending specific maintenance procedures to accomplish improved T/R inspections. It included suggested techniques and follow on actions when damage is detected. However, FAA SAIB recommendations are not mandatory. (1.17.2)

3.1.32. The expanded detailed readout of the HUMS data showed there were three data points recorded by the system where the preset vibration limit was exceeded before the aircraft crashed. (2.2.2)

3.1.33. The present maintenance process for daily HUMS data retrieval would not have revealed the excessive vibrations recorded on the accident aircraft because the “flashing alarm “ parameters would not have been met (3 exceedences of 5 last recorded values in one parameter). An independent review of each parameter would have been required for such notification. (2.2.2)

3.1.34. The HUMS is not configured to give crew warnings in-flight when vibrations that exceed the preset limits are recorded. Development of an aircrew warning based on HUMS would involve detailed engineering assessment, design change to the system and evaluation methodology. (2.2.3)

3.1.35. The “normal” CH146 maintenance inspections are carried out conscientiously and inspections associated with the HUMS precipitated maintenance and troubleshooting is appropriate. The HUMS is not being relied upon by the CH146 community to the detriment of the other maintenance on the aircraft. (2.2.4)

3.1.36. The crew recognized the emergency condition quickly but did not reduce the collective to minimum until the second 360-degree rotation with forward speed close to 0 KIAS. Throttle number 1 was subsequently reduced to flight idle and throttle number two was reduced to about 20%. (2.3.4)

3.1.37. The checklist emergency procedure is not the same as the AOI procedure. The procedures in these two documents provide somewhat conflicting guidance, with the checklist correctly placing more emphasis on reduction of collective as the first and most important initial action. However, the checklist does not specify that immediate entry to autorotation is required. (2.3.6) (2.3.7)

3.1.38. CF helicopter training in general and the CH146 fleet in particular have de-emphasized autorotation scenarios. (2.4.1)

3.1.39. CH146 aircrew carry out in flight autorotation practice on a quarterly or semi annual basis but recovery from autorotative flight must be complete with both engines on line by 150 ft AGL. Crews conduct autorotation practice in the CH146 simulator at CFB Gagetown on an annual basis. (2.4.2) (2.4.3)

3.1.40. The CH146 simulator reaction to T/R loss was very similar to the flight profile estimated from the downloaded FDR data of CH146420 when flight control inputs were the same as registered on the FDR. (2.4.3)

3.1.41. CH146 simulator visual cue limitations for the last 50-60 ft of altitude reduce its effectiveness in training for the flare and landing phase of autorotation emergencies. (2.4.3)

3.1.42. The emergency checklist and AOI wording for response, “Carry out run on landing or …” may have been misinterpreted by flight crews as a “fly out is possible” for T/R loss failures. (2.5.2)

3.1.43. A "mind set" with respect to T/R failure procedures and autorotations in general predisposed CH146 crews to attempt to “fly out” of T/R emergencies, particularly when no desirable landing sites are available. This was reinforced in conversion to type training, CH146 simulator training and in actual autorotation flight training. (2.5.2) (2.5.3)

3.1.44. A “mind set” that autorotation emergencies, even for catastrophic reasons, will yield undamaged aircraft and crew survival may have been present in the CF helicopter community. This likely reinforced the unacceptability of an undesirable landing area and influenced flight control decisions made by the crew in this accident. (2.5.1) (2.5.4) (2.5.5)

3.1.45. During several simulator trials, different crews responded in a similar fashion as the crew of CH146420 did when presented with a T/R loss scenario under similar flight conditions. In 20 of 21 attempts, the trial crews crashed the simulator while trying to “fly out” of the presented scenario. (2.5.5)

3.1.46. The high rate of rotation in combination with the large pitch oscillations probably caused somatic gyroscopic induced disorientation in the crew. Other physiological based effects were likely present in the crew thereby making appropriate reaction to the emergency difficult. (2.5.6)

3.1.47. The pilot made no collective input as the aircraft reached the ground. This can be explained by pilot disorientation, physiological complications, lack of realistic experience with the final “ground rush” phase of autorotative landings, the low rotor warning aural warning sounding or a combination of those factors. (2.5.6) (2.5.7)

3.2. Causes & Contributing Factors

3.2.1 While in cruise flight, the T/R of CH146420 failed due to a fatigue crack initiating from a small damage site on the skin of the rotor blade about 18.5 inches from the tip of one blade. That section of one blade then flew off; the resulting imbalance of this dynamic component caused the T/R input shaft to fail instantly and the entire T/R to depart the aircraft.

3.2.2 The aircraft's inherent response to the loss of T/R thrust and the change to the aircraft’s centre of gravity with loss of mass of the T/R created a nearly instantaneous and extreme out of normal flight condition which was compounded by the low altitude, terrain, and weather conditions.

3.2.3 While the damage for the initiation site of the fatigue crack was greater than the CFTO stated limit for damage to the “critical zone” portion of the T/R blade skin, the maintenance procedures in place before the accident in the CF CH146 units and amongst Bell 412 operators worldwide had a very low probability for detection of the damage. Furthermore, there is no hard engineering evidence to support the current allowable limits in the publications and awareness of the criticality of damage was also low throughout the Bell 412 community. Complicating this situation was the paint colour of the damaged area (black) and the blade structure (likely closing the fracture surface when not under flight load), which made detection of the developing crack even more difficult.

3.2.4 The pilots’ reaction to the loss of T/R resulted in the aircraft impacting the ground at very high vertical velocity and reduced the survivability of the crash. The following are all probable reasons for this reaction:

3.2.4.1 There is evidence that emergency response philosophy and training methods then extant within the CF and CH146 community predisposed pilots to attempt a “fly out” to a suitable landing area on loss of T/R. Likely contributing to an apparent “fly-out” decision was lack of landing areas and low altitude/time to respond.

3.2.4.2 Reduced emphasis on autorotation training in the CF helicopter community and the resultant reduction in realistic autorotation training opportunities reduced the pilots’ propensity to use the autorotation option for T/R loss and to subsequently respond instinctively to the “ground rush” as the aircraft neared the ground.

3.2.4.3 Disorientation and other physiological complications, resulting primarily from a high rate of rotation, reduced pilot capacity to react as the emergency developed.

4. SAFETY ACTION

4.1. Safety Action Taken

4.1.1 The failure of the T/R blade on CH146420 and subsequent examination and preliminary findings by QETE prompted two SIs(NS SI 087 and NS SI 088) to be issued by the CH146 WSM for all T/R blades in the CH146 fleet. SI 087 called for a detailed visual inspection using appropriate cleaning, lighting and magnification (10X) methods. SI 088 was a Non Destructive Inspection (NDI) using a combination of x-ray and eddy current methods for assessment. T/R blades in operation on the CH146 fleet had to successfully pass both of these SIs.

4.1.2 The CH146 WSM issued instructions (11500GR-276-3 (DAEPM(TH)) 14 August 2002) to all CH146 Units mandating a daily download and analysis of the HUMS information. By tracking the HUMS information on a more frequent basis (at least for the interim), a better picture of the health and trends of the T/R will be possible. Where the HUMS equipment may not be available for a particular aircraft, units are to pursue every option available to avoid operations without HUMS equipment.

4.1.3 The CH146 WSM issued instructions (11500GR-276-3 (DAEPM(TH)) 14 August 2002) to re-emphasise to maintenance personnel the importance of taking special attention in the event of any reported T/R vibrations (as reported by the aircrew or through HUMS analysis). In particular, close inspection of the entire T/R assembly is required in advance of any action to balance the T/R. Successive T/R balancing actions in a short period of time or the inability to balance the T/R within two or three attempts is an indication that balancing is only masking a fault in the T/R that is unrelated to the actual balance condition of the rotor.

4.1.4 The Comd 1 Cdn Air Div issued orders (COMD 124 - 251903Z JUL 02 and 261354Z JUL 02) directing that all CH146 aircrew and ground crew be fully briefed on the airworthiness risk assessment and be updated on the ongoing DFS investigation. Flight profiles and manoeuvres involving higher T/R loads were to be reviewed and discussed.

4.1.5 The DTA, in his capacity as the TAA for the CF, formally informed Transport Canada Civil Aviation - Continuing Airworthiness office (1010-2-146-1 (DTA 2-4) 2 August 2002) of the T/R blade failure, the follow-on SIs and changes to CF maintenance activities for the T/R inspections. This information was formally transmitted to the FAA in the USA as the State of Design responsible for the rotorcraft on 14 August 2002 (via e-mail).

4.1.6 Members of 444 CS Sqn were briefed on the investigation twice between 22 –25 July 2002. These briefing centred on the T/R fatigue failure information and the inspection techniques and methods associated with the small size of the initiation site. Further, the WComd, OpsO, CO of 444 CS Sqn and standards pilots were fully out briefed on the preliminary findings and proposed recommendations of the investigation team on 28 July 2002.

4.1.7 DFS notified other military and civilian users of similar type aircraft on the information discovered in this investigation through various information sharing venues. Similarly, information was solicited from other Bell 412 users (or similar type aircraft) on maintenance practices, T/R blade problems observed and crew training philosophy. This information was used as part of the "lessons learned" passed on to users of this aircraft, both in the CF and on a worldwide basis.

4.1.8 CS Sqn aircraft are being painted in standard search and rescue configuration, mostly yellow with red high lighting, to make them easier to sight (Annex Q).

4.1.9 CH146 inspection and maintenance procedures (C-12-146-000/MF-OOl) were immediately modified to attempt increasing the POD for T/R blade damage and techniques were put in place for measurement of detected damage. Inspection changes include reduction of inspection frequency from 25 to 12.5 hours, use of magnification, cleaning blades, use of "cheese cloth" and inspection in bright light for the critical location. (2.1.3) (2.1.6)

4.1.10 The critical area on the blade was identified and the colours of the T/R blades were changed from black to olive green or white with the colour scheme designed so the transition zones are not in the critical zone. (2.1.4)

4.1.11 The OEM issued an OSN to "All Owners/Operators of Bell 205, 205B, 212, 412, 412 CF and UH-1H-II Helicopters" on 27 August 2002 to "remind operators of the importance of accomplishing a complete inspection of the T/R blades at specified inspection intervals." Further reference to maintenance manuals is recommended in the OSN. (2.1.5)

4.1.12 Optical micrometers were purchased and distributed to each CH146 unit to ensure that a precise tool is used in order to measure any defects in the blades.

4.1.13 DAEPM(TH) contracted Bell Helicopter to provide a one time only blade seminar to some experienced Aircraft Structures (ACS) technician in order to educate them on the construction of the blades (both T/R and main rotor), damage assessment, the refinishing and the repair procedures.

4.1.14 A POD Study was initiated in coordination with NRC, DTA and DAEPM(TH) 6. The intent of this study was to assess new CF procedures associated with T/R blade inspections and the effectiveness of detecting damage based on the properties of the damage. Also, its purpose was to help in improving the detection ability of the technicians by pointing out the best conditions under which they will be successful in finding damage.

4.1.15 A thorough review of the T/R blade maintenance, inspection and life criteria was performed in consultation with Bell and DTA. As a result of this review, Bell Helicopter will change the T/R blades chapter in the maintenance manual and the component repair and overhaul manual.

4.1.16 Since the accident, emphasis has been placed on training crews on how to react to such an emergency (high speed, low level T/R failure) during their annual simulator re- currency training. All CH146 pilots attending their annual CH146 simulator re-currency training are exposed, in great detail, to these types of emergencies and are trained to react appropriately, which is to immediately enter autorotation as per the C-12-146-OOO/MB-OO2. Further, T/R loss emergencies at various points throughout the CH146 flight envelop are practiced in the simulator sessions.

4.1.17 An amendment to the DFS/AETE MOU was made to provide additional expert investigation support for examining all forms of crew seats rather than just ejection seats.

4.1.18 The OEM changed the T/R rejection damage limit to 0.003 inches deep (from 0.005”) and changed the terminology for damage for less than this amount to “repairable” (from “negligible and repairable”) to clarify the nature of damage and consequence for detected damage.

4.1.19 The FAA issued a Special Airworthiness Information Bulletin (SW-05-10, dated November 5, 2004) recommending specific maintenance procedures to accomplish improved T/R inspections. It included suggested techniques and follow on actions when damage is detected. The recommended actions are not mandatory.

4.1.20 HUMS interim release software was introduced and is in use at 400 Sqn Borden that includes lower Tail Rotor vibration alarm thresholds, and alarm triggering for every data point that is above limits for tail rotor vibration.

4.2. Safety Action Recommended

It is recommended that:

4.2.1 DAEPM(TH) 6 continue the work at developing a usage spectrum for the various operations conducted by the Griffon helicopters with the view to be able to compare these spectrums to the original Bell design spectrum and to evaluate the present maintenance program.

4.2.2 The review, already underway, of CH146 T/R blade maintenance, inspection and safe life criteria (as a result of the accident findings), damage tolerance analysis and crack propagation data in consultation with appropriate authorities (QETE, Bell Helicopters, DTA, WSM, OAA etc) be completed. This should include definitions of “detailed visual inspection” and “general visual inspection” with appropriate guidance in the CH146 maintenance publication. (1.6.3)

4.2.3 The WSM investigate the feasibility of modifying the HUMS to provide warning cues for vibration exceedences of critical rotating components. Incorporation of systems that provide an immediate impending component-failure advisory is warranted and a design requirement for system malfunction detection with proven system reliability is desirable. Further assessment of HUMS should continue; potentially in conjunction with a CH146 Life Extension Program.

4.2.4 The OEM must bring the critical design limitation and the nature of the extremely damage intolerant structure to the attention of all Bell 412 users.

4.2.5 The FAA (USA) re-visit the Bell 412 inspection/maintenance procedures of the T/R blades to mandate appropriate means and frequency of inspection, in order to detect minor damage in the “critical location”, likely by issuing an Air Directive. Since detection of damage depth is the parameter that is required by the maintenance instruction and the POD for this criteria is not predictable in all damage classifications nor very high for the tolerances stated, the practicality and effectiveness of techniques called for should be part of this re-examination. This is essential to ensure that such damage does not result in catastrophic failure of the kind observed in this accident, and on 6 other fatigue failures (occurrences) on T/R blades of this type.

4.2.6 The FAA (USA) re-visit the Bell 412 certification, particularly with respect to T/R design, paying particular attention to the "means of compliance" utilized to validate the damage criteria to meet the Basis of Certification, and the T/R failure characteristics, based on the seven T/R blade failures observed. Analysis at the critical points due to underlying structure of the blade, actual forces on the Bell 412 series aircraft and practicalities of maintenance procedures for damage detection should be part of the re-evaluation. Appropriate changes to the design (with damage tolerance in mind) and/or current maintenance program must be determined and mandated to ensure recurrence of this failure mode associated with damage in the “critical area” is adequately addressed.

4.2.7 Guidance and techniques for pilots facing loss of T/R emergencies as well as methods for training in these techniques be reviewed and improved in light of lessons learned from this accident. DFS is prepared to work with whichever agency is assigned this task to ensure that all of the lessons learned from this accident are fully considered. The OEM could play a key role in this kind of activity.

4.2.8 The discrepancy between the AOI and checklist procedures for loss of T/R emergencies should be rectified. The outcome of this accident suggests that the most critical actions should be first and immediate (lower collective) to enter autorotation. Corrections to the Checklist or AOI may require subsequent amendment to the FAA certified Flight Manual through the appropriate airworthiness authority and procedures.

4.2.9 A “streamlined” process be developed or negotiated with OEM, FAA, TC and CF to keep all pertinent publications updated so that CFTOs, Checklist, AOIs etc will contain the most accurate and best possible information.

4.2.10 Autorotation practice (frequency, scenarios, procedures, flight parameters, from both pilots seats) in the CH146 simulator and in actual flight be re-assessed to ensure optimal transfer of autorotation entry, flight control and throttle movements and flare/landing skills and instincts. Part of this assessment should be to adjust the simulator to react more realistically based on the fight data from CH146420, to include rate of onset, yaw/sideslip rate adjustments, rapid loss of airspeed and severe nose tuck to simulate the loss of the mass of the T/R gear box. Rectification of the CH146 simulator visual fidelity deficiencies in the lower altitude regimens should be pursued to provide optimum pilot skill improvement.

4.2.11 CF autorotation and forced landing philosophy and procedures should be re-assessed with respect to emphasis, both overt and subtle, placed on saving the aircraft versus crew survivability. Subjects could include techniques for undesirable landing sites, management of flight path trajectory, and configuration of the aircraft, all with the purpose of increasing crew survivability. This training assessment should not be limited to any particular aircraft fleet or group, and input could be sought from helicopter manufacturers and large operators worldwide.

4.2.12 The mechanism of the injuries be more completely analyzed to determine if better survivability can be built into the Griffon helicopter and associated Aircrew Life Support Equipment, and perhaps into other helicopters.

4.2.13 The policy on seat belt usage (opposed to “monkey tails”) when sitting in the cargo area be reviewed. Further, recommendations to aircrew regarding “best practice” for locking seat harness rather than depending on the inertial features of the locking mechanism should be promulgated. The recommendations in A2002-031 CH146 Armoured Seat Restraint paper done by AETE for replacement of the existing inertial reel with a modern MA-16 type reel should be re-visited.

4.2.14 The investigation team recommends that specific training be devised and required for CH146 technicians conducting CH146 T/R blade inspections due to the inspection’s unique characteristics. This will ensure sustained inspection integrity and keep the effectiveness as high as possible, given the limits outlined in the NRC POD.

4.2.15 The deficiencies associated with the FDR data sample rate, the six degrees of motion missing parameters and alternate air data measurement systems to correct or improve air data at low airspeed, hover and wind data be investigated for system improvements.

4.3. Other Safety Concerns

4.3.1 While searching for the crew of CH146420 was made difficult by weather and light conditions, the colour of the aircraft made this more so. Similarly, the dark flight suit colour for most members of the SAR crew did not promote easy visual acquisition, a situation that will be exacerbated when all aircrew are dressed in the new olive green flight gear. The question of flying suit colour for all personnel in the SAR role should be re-examined for optimal effect. Further, Aircrew Life Support Equipment (helmets, winter flight suits, life vests etc) should be part of this assessment.

4.3.2 The aircraft ELT antenna cable and upper antenna where destroyed in the crash. Although the ELT had tripped, without the antenna attached, the signal is reflected back into the device rendering the ELT useless. The remote antenna on the CH146 is held in place by two plastic clips that do not adequately secure this component in place. Post-crash, the FE was unable to locate this antenna in the wreckage. This deficiency needs to be rectified.

4.3.3 Each crewmember in 444 CS Sqn carries a PLB in their survival vest and the FE activated his PLB which R475 was able to pick up, although not until within 3 miles. The SAR Tech had a 406 beacon that was also turned on. Most units and Sqns do not have sufficient quantities of these radios to include in survival vests. Satellite phone for remote helicopter operations should be considered as well. This situation should be assessed and sufficient equipment recommended for improved detection by rescue resources should be carried in survival vests.

4.3.4 The addition and retrofit of GPS encoded ELT' s for CH146 and other CF aircraft fleets should be investigated.

4.4. DFS Comments

The investigation into this accident has been lengthy, exhaustive and complex. In addition, a number of agencies including the OEM, QETE, DTA, NRC and, DAEPM (TH) have played a critical role in completing this investigation.

As can be seen in this report, a number of recommendations have been developed and forwarded for consideration. It must be understood that some of these recommendations are contentious and are not universally supported by all Persons of Direct Interest who reviewed earlier drafts of this report. In particular, it is anticipated that this report's recommendations concerning the airworthiness of the T/R will be challenged. Despite these differing opinions, it is strongly felt that, barring the development of a simple, reliable and practical non-destructive test for this component, the practicality of continuing to safely operate the CH-146 fleet with this damage intolerant T/R in field conditions in which the CF normally operates is highly questionable. While there are a number of variables that influence this issue, the development and certification of a more robust CH-146 T/R merits serious consideration.

The investigation of this accident highlighted concerns with rotary wing training deficiencies. Autorotation training in particular needs to be closely reviewed and rationalized in all rotary wing fleets. Similar training problems were identified in the FSIR into the crash of CH-12401 onto the deck of HMCS Iroquois in Feb 2003. In addition, anecdotal inputs from the field indicates that the rotary wing community may be developing a culture that questions the requirement for autorotation training due to power plant redundancy in almost all CF helicopter fleets. However, all current CF rotary wing fleets are tail rotor (as opposed to dual rotor) configured and, as we have seen in the CH-146 and CH-149 fleets, there are many areas in which these types of aircraft are vulnerable. In almost all cases, the best defence against these vulnerabilities is realistic autorotation training. Ideally this training would be done in the actual aircraft but it is recognized that this carries an elevated risk of serious occurrences. Accordingly, the option of completing this training in high fidelity simulators should be aggressively pursued for all helicopter fleets.

Finally, this accident highlights a major concern with information flow within the aviation community. While DND was aware of two other T/R failures on the Bell 412 family of aircraft, the CF investigation team was unaware of another four failures of this type of T/R until well over two years after this accident. While it is understood that not all nations and aviation organizations embrace free and open reporting, this poor flow of information is very disturbing. It is therefore extremely important that the CF and DND continue to support international initiatives such as the Global Aviation Information Network (GAIN) to improve the flow of flight safety information between all concerned organizations.

A.D. Hunter
Colonel
Director of Flight Safety

LIST OF ANNEXES