NATIONAL TRANSPORTATION SAFETY BOARD
Office of Aviation Safety
Washington, D.C. 20594

October 30, 2018

AIRWORTHINESS GROUP CHAIRMAN'S FACTUAL REPORT

NTSB No: ERA16FA311

A. ACCIDENT

Operator:	AAR Airlift Group
Aircraft:	Sikorsky S-61N, Registration N805AR
Location:	Palm Bay, Florida
Date:	September 6, 2016
Time:	1340 eastern daylight time

B. GROUP

Group Chairman:	Chihoon Shin National Transportation Safety Board Washington, District of Columbia
Member:	Ryan Bellamy Federal Aviation Administration Orlando, Florida
Member:	Kirk Gustafson Federal Aviation Administration Burlington, Massachusetts
Member:	Jill Browning Sikorsky Aircraft Corporation Stratford, Connecticut
Member:	Javier Casanova Sikorsky Aircraft Corporation West Palm Beach, Florida
Member:	David Gridley General Electric Aviation Lynn, Massachusetts
Member:	Bruce Widzgowski AAR Airlift Melbourne, Florida

Member:	Glen Pruden UTC Aerospace Systems Hartford, Connecticut

LIST OF ACRONYMS

AGB	accessory gearbox
ALF	aft looking forward
ATT	aircraft total time
CFP	centrifugal fuel purifier
CMM	coordinate-measuring machine
EDT	eastern daylight time
FAA	Federal Aviation Administration
FL	Florida
FOD	foreign object debris
ft-lbs	foot-pounds
FWU	freewheeling unit
GE	General Electric
GPS	Global Positioning System
IGV	inlet guide vanes
MLB	Melbourne International Airport
MRB	main rotor blade
Nf	power turbine speed
Ng	gas generator speed
NTSB	National Transportation Safety Board
PCL	pitch change link
PRV	pressure relief valve
P3	compressor discharge pressure
S/N	serial number
STC	Supplemental Type Certificate
SVA	stator vane actuator
TRB	tail rotor blade
TRDS	tail rotor drive shaft
T2	compressor inlet temperature
T5	power turbine inlet temperature
UTAS	UTC Aerospace Systems
VGV	variable guide vanes
3D	three-dimensional

C. SUMMARY

On September 6, 2016, about 1340 eastern daylight time (EDT), a Sikorsky S-61N helicopter, N805AR, was destroyed when it impacted a field near Palm Bay, Florida (FL). An airline transport pilot, a commercial pilot, and a maintenance crewmember were fatally injured. The helicopter was registered to EP Aviation LLC and operated by AAR Airlift Group as a postmaintenance flight conducted under the provisions of 14 *Code of Federal Regulations* Part 91. Visual meteorological conditions prevailed and a company flight plan was filed for the local flight that departed Melbourne International Airport (MLB), Melbourne, FL, at 1324 EDT.

According to the operator, the helicopter's fore/aft main rotor servo was recently removed and replaced. Subsequently, three separate maintenance check flights were performed on the day of the accident, with the accident occurring on the third maintenance check flight. Ground witness videos recorded the helicopter performing maneuvers near the accident site uneventfully, about 100 feet above ground level. The helicopter then flew an orbit around the accident site about the same altitude before the video ended. There were no known witnesses to the accident impact sequence.

The helicopter came to rest upright in a field with no debris path noted. The wreckage was oriented about a magnetic heading of 190 degrees. A postcrash fire consumed the cockpit and cabin. The tail boom transition section exhibited partial thermal damage, but the majority of the tail boom remained intact. The root ends of the five main rotor blades (MRB) and five tail rotor blades (TRB) remained attached to their respective rotor hubs and exhibited signatures consistent with low rotational energy.

D. DETAILS OF THE INVESTIGATION

1.0 HELICOPTER INFORMATION

1.1 HELICOPTER DESCRIPTION

The Sikorsky S-61N helicopter has a five-bladed main rotor system that provides helicopter lift and thrust. A five-bladed tail rotor provides thrust to counteract main rotor torque effect and control helicopter yaw. The helicopter was equipped with two General Electric (GE) CT58-140 turboshaft engines mounted side-by-side, forward of the main gearbox input housing. The helicopter was equipped with a reverse-tricycle wheeled landing gear. The Sikorsky S-61N is type certificated under Federal Aviation Administration (FAA) type certificate data sheet No. 1H15 as a Transport Category helicopter under Categories A and B.

The terms "left", "right", "up", and "down" are used when in the frame of reference of looking forward from the aft end of the helicopter, i.e. aft looking forward (ALF). All locations and directions will be viewed from ALF unless otherwise specified. Additionally, clock positions are in the ALF frame of reference unless otherwise specified.

1.2 ENGINE DESCRIPTION

The GE CT58-140-2 is an axial flow, free turbine engine with a maximum one-engine inoperative (2.5 minute) rating of 1,500 shaft horsepower. The gas generator comprises a 10-stage compressor, an annular combustor, and a two-stage turbine. Inlet guide vanes (IGV), comprising variable stators, are in front of the first stage compressor. Three stages of variable guide vanes (VGV) are located between the first and fourth stage compressors. A hydromechanical fuel control meters fuel to the combustor. A single-stage power turbine provides engine power output to the high speed shaft.

1.3 HELICOPTER HISTORY

The accident helicopter, serial number (S/N) 61717, was manufactured in 1974. According to helicopter records, the helicopter accumulated an aircraft total time (ATT) of about 40,296.2 flight hours and a Hobbs time of 4,800 hours at the time of the accident. The No. 1 (left) engine, S/N 295122C, was installed on the accident helicopter on November 25, 2015 and accumulated a total time of 23,234.8 hours at the time of the accident. The No. 2 (right) engine, S/N 296010, was installed on the accident helicopter on January 26, 2016 and accumulated a total time of 26,258.6 hours at the time of the accident. The Nos. 1 and 2 engines accumulated about 248.4 and 237.7 hours, respectively, since installation on N805AR. The helicopter was estimated to weigh about 17,029 pounds at the start of the accident flight. Additional information on the helicopter maintenance can be found in the Maintenance Factual Report in the docket for this investigation.

1.4 POST-MAINTENANCE CHECK FLIGHT

The accident helicopter had recently undergone a replacement of its fore/aft main rotor servo and was performing a flight check of the main rotor control rigging in accordance with Table 601 in Section 65-40-0 of the Sikorsky S-61N maintenance manual No. SA 4045-80. Table 601 contained various criteria, including a forward center of gravity aft control rigging check. The aft control rigging check required sufficient control travel during a hover turn and at least 2.0 inches of minimum cyclic stick travel remaining when in rearward flight. The rearward flight criteria were 20 knots rearward airspeed at an altitude of 0-1000 feet.[1] An excerpt of Table 601 can be found in **Attachment 1** of this report.

2.0 WRECKAGE DOCUMENTATION AT THE ACCIDENT SITE AND AFTER RECOVERY

On September 7, 2016, members of the Airworthiness Group convened at the accident site to document the wreckage.[2] The wreckage was confined to the crash site with no evidence of an inflight breakup. All major components were observed at the crash site. Ground impact marks consistent with the tail wheel and the tail boom underside antenna was observed about 12 feet to the east of the resting position of the tail boom. The wreckage was recovered the same day to a hanger in Fort Pierce, FL. On September 8, 2016, members of the Airworthiness Group documented the recovered wreckage.

2.1 STRUCTURES

2.1.1 AIRFRAME DESCRIPTION

The helicopter structure comprises the fuselage, pylon, horizontal stabilizer, doors and windows. The fuselage is a semi-monocoque design composed primarily of aluminum, with skin plating composed of titanium and stainless steel in the engine area. Certain fairings, access doors, and access covers are constructed of reinforced fiberglass.

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[1] According to the operator, the crew would normally utilize a Global Positioning System (GPS) display in the cockpit that showed the helicopter's groundspeed for the rearward flight portion of the aft control rigging check.

[2] Photos of the accident site taken by first responders were provided to the NTSB. These photos showed pools of water adjacent to the main wreckage site consistent with firefighting efforts.

The fuselage contains the cockpit, cabin, engine compartment, transmission compartment, cargo compartment, lower fuselage (containing the fuel tanks), and rear fuselage (tail boom). The pylon supports the intermediate and tail gearboxes, the tail rotor, and horizontal stabilizer; the pylon acts as a vertical stabilizer in forward flight. The sponsons, mounted on the left and right side of the helicopter, houses the main landing gear.

2.1.2 FINDINGS

The helicopter came to rest upright with a heading of about 190 degrees magnetic (**Figure 1**). The majority of the airframe forward of the tail boom was consumed by the postcrash fire. The cabin was partially consumed by the postcrash fire and the lower fuselage (normally housing the fuel tanks) had crushed from ground impact. The left side of the tail boom remained attached to the aft end of the main fuselage and did not exhibit evidence of thermal damage. The forward portion of the right side of the tail boom exhibited thermal damage. The horizontal stabilizer remained attached to the vertical fin. The trailing edge of the horizontal stabilizer tip end exhibited distortion, but the remainder of the horizontal stabilizer exhibited no anomalous damage. The underside of the tail boom and vertical fin attachment area exhibited wrinkling of the skin and crush damage consistent with ground impact. The tail rotor driveshaft covers remained installed from the aft portion of the main fuselage up to the vertical fin. The tail rotor driveshaft covers forward of the tail boom were thermally damaged and partially consumed by the postcrash fire.

Figure 1. The accident helicopter.

The tail wheel was found inside the forward end of the tail boom and exhibited thermal damage. The left main landing gear strut was found upright and embedded into the ground near its normally installed location. The right main landing gear strut was found laying on its side near its normally installed location. The left and right main landing gear wheels and hubs were separated from the struts and exhibited thermal damage. The main landing gear wheels and hubs were found loose near the wreckage and exhibited thermal damage.

2.2 MAIN ROTOR SYSTEM

2.2.1 SYSTEM DESCRIPTION

The main rotor comprises a rotor head assembly and five MRBs. The rotor head assembly contains a swashplate assembly and a hub. The five MRBs are identified by color, presented in the order of advancing rotation (when seated in the pilot seat and observing the blades pass from right to left): ‘red’, ‘black’, ‘white’, ‘yellow’, and ‘blue’. The five MRBs attach to the hub via sleeve-spindle assemblies and damper assemblies, and to the swashplate assembly via adjustable pitch change links (PCL). The MRBs are of composite construction and installed under FAA Supplemental Type Certificate (STC) No. SR01585NY.

The main rotor is driven by a main gearbox which is mounted directly to the airframe. The main gearbox is driven by two input pinions which connect to the engine output high speed shafts (also known as input drive shafts). Freewheeling units (FWU) are located at each input pinion. A hydraulically-activated rotor brake is located between the two input pinions. An accessory section, located behind the main gearbox, drives primary and auxiliary hydraulic pumps, the rotor tachometer-generator, torque meter oil pump, main gearbox oil pump, a direct current motor-generator, and two alternating current motor-generators.

2.2.2 MAIN ROTOR FINDINGS

All five MRBs remained attached to the main rotor hub via blade grip and spindle assemblies. All five MRB tips remained attached to their respective blade. The majority of the blade span for all five MRBs did not exhibit evidence of shattering or multiple spar fractures that would be consistent with high rotational energy impact damage. The majority of the blade afterbody[3] of the ‘yellow’ and ‘blue’ MRBs were consumed by the postcrash fire. The composite spars of the ‘yellow’ and ‘blue’ MRBs exhibited thermal damage and separation of their carbon fibers consistent with exposure to the postcrash fire. The inboard section of the ‘red’ MRB exhibited thermal damage and a portion of its afterbody was consumed by the postcrash fire; the leading edge of the outboard section of the ‘red’ MRB remained intact and its trailing edge exhibited thermal damage in localized areas. The inboard section of the ‘black’ and ‘white’ MRBs exhibited thermal damage but its outboard section remained largely intact. The ‘yellow’, ‘red’, and ‘black’ MRB PCLs remained attached to their respective pitch horns and rotating swashplate attachment lugs. The ‘blue’ MRB PCL was separated at its upper end, with its upper end still attached to the ‘blue’ MRB pitch horn. The ‘white’ MRB PCL remained attached to its pitch horn but was not attached to the rotating swashplate; a fracture was observed on the lower-inboard area of leading rotating swashplate attachment lug. The ‘blue’ MRB damper piston was separated from its housing, but both ends of the damper remained attached to the ‘blue’ MRB spindle and the hub. The remaining four MRB dampers remained attached to their respective MRB spindles and the hub. The stationary and rotating scissors remained installed with no evidence of fractures or disconnection.

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[3] The blade afterbody is the structure behind the spar which includes the blade skin and core.

2.2.3 MAIN ROTOR DRIVE SYSTEM

The main gearbox housing remained whole with evidence of thermal damage to its exterior. The input and accessory housings remained attached to the main gearbox housing. All four gearbox mount feet remained attached to remnant, thermally damaged pieces of airframe. Both input pinion splined couplings did not exhibit evidence of anomalous wear but exhibited evidence of thermally degraded grease. Both high speed shafts (also known as the engine output shaft) remained attached at their forward ends to the engine, but were not attached to their respective input pinions. The aft end of the left high speed shaft had one bolt hole fractured, one bolt hole significantly elongated, and two bolt holes slightly elongated. The aft end of the right high speed shaft had two bolt holes fractured and two bolt holes significantly deformed; all four bolt hole flanges were bent in the forward direction. Neither of the high speed shaft tubes exhibited evidence of fractures.

Manual rotation of the rotor brake disk resulted in corresponding movement of the main rotor head, tail takeoff pinion and No. 1 tail rotor drive shaft (TRDS)[4], and the two input pinion splined couplings (normally attached to the aft end of the high speed shafts). However, the degree of rotation of the rotor brake disk was limited due to interference with a fractured main rotor damper restricting free rotation. The hydraulic pumps and generators remained attached to the aft section of the main transmission.

2.3 TAIL ROTOR SYSTEM

2.3.1 SYSTEM DESCRIPTION

The tail rotor comprises a hub assembly and five TRBs. The five TRBs are identified by color: ‘red’, ‘blue’, ‘yellow’, ‘white’, and ‘black’. The TRBs are attached to the hub via hinges and spindles. The TRBs are constructed of a one-piece all-metal wrap-around skin, bonded to a solid leading edge spar and a honeycomb core. The TRBs are attached to the pitch change beam via adjustable PCLs.

The tail rotor drive train is driven by the tail take-off pinion of the main gearbox through the tail take-off FWU. There are four TRDS. The forward end of the No. 1 TRDS attaches to the main gearbox tail take-off and the tail rotor drive train continues down the tail boom via the Nos. 2 and 3 TRDS. The aft end of the No. 3 TRDS attaches to the intermediate gearbox input flange. The No. 4 TRDS is located between the intermediate and tail gearboxes.

2.3.2 TAIL ROTOR SYSTEM

All five TRBs remained installed on the tail rotor hub. The ‘red’ TRB exhibited a chordwise fracture about 15.5 inches from the blade attachment bolts. The ‘red’ TRB airfoil outboard of the fracture was separated and found on the ground adjacent to the tail rotor. The ‘blue’ TRB exhibited a partial chordwise fracture about 9 inches from the blade attachment bolt. The ‘blue’ TRB tip was embedded into the ground. A ground scar

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[4] To facilitate the wreckage recovery, the tail rotor drive train was separated at the flange attachment between the No. 1 and No. 2 TRDS.

with a width consistent with a TRB chord was observed between the resting positions of the ‘red’ and ‘blue’ TRBs. All five PCLs remained attached between their respective TRB and pitch change beam.

2.3.3 TAIL ROTOR DRIVE SYSTEM

The TRDS remained attached to the tail takeoff pinion of the main gearbox. The tail rotor drive train remained continuous from the tail takeoff pinion to the tail gearbox. All attaching hardware between the TRDS and flexible couplings remained installed. The flexible coupling and TRDS flange connection near the forward end of the tail boom (where it attaches to the main fuselage) exhibited axial deformation, with one of the tri-lobe flanges fractured. The tail rotor drive train forward of this area exhibited evidence of thermal damage.

The intermediate and tail gearboxes remained installed on the airframe. Evidence of oil was observed via the oil sight glasses on both the intermediate and tail gearboxes.

2.4 FLIGHT CONTROL SYSTEM

2.4.1 SYSTEM DESCRIPTION

The main rotor flight controls comprises a cyclic stick, collective lever, and pedals for each pilot. The left and right pilot controls are interconnected. The cyclic and collective inputs are combined into a mixing unit and transmitted to the swashplate assembly via mechanical linkages. The controls are power assisted via two hydraulically operated flight control servo systems. The pedals contain toe-operated brakes for wheel braking.

2.4.2 FINDINGS

The collective sticks for both the left and right seated pilots were found loose in the wreckage. The cyclic sticks for both the left and right seated pilots remained attached to their respective bases. The head on the right cyclic stick was fractured. The left cyclic stick was thermally damaged and partially consumed by the postcrash fire. The auxiliary servo and mixing unit were found loose near the cockpit wreckage and exhibited thermal damage. Attaching hardware remained installed within the fractured rod end connections. The fore/aft, left lateral, and right lateral main rotor servos remained installed on the stationary swashplate and main gearbox housing. The main rotor servo input rod linkages remained attached to their respective bellcranks.

The pedal set for the right seated pilot was observable in the cockpit wreckage and the right pedal was in the full forward position. The pedal set for the left seated pilot was observable in the cockpit wreckage and both pedals were in the same (neutral) position. The tail rotor pitch control push-pull tube on the underside of the vertical fin was attached at the tail gearbox end but was fractured at the rod end of the pivot bellcrank. The rod end remained attached to the pivot bellcrank. The push-pull tube routed to the large bellcrank within the tail boom was fractured at the rod end of the pivot bellcrank. The rod end remained attached to the pivot bellcrank. The tail rotor pitch control cables were continuous from the tail boom bellcrank to the radiator, where the left cable exhibited a fracture at its turnbuckle. The right cable and the left cable forward of the turnbuckle, remained continuous forward of the main gearbox, where the cables fed into crushed wreckage.

2.5 POWERPLANTS

The two engines remained installed on the engine deck (located forward of the main gearbox). The resting position of the engine deck was about one foot lower than the resting position of the main gearbox. As mentioned in section 2.3 of this report, both engines were mechanically disconnected from the main gearbox due to separation of the aft end of their respective high speed shafts from main gearbox. The conical engine inlet screens were found loose near their normally installed position (**Figure 2**). No evidence of significant blockages was observed on the conical screens. The engine control levers were found loose in the cockpit wreckage, precluding determination of lever position, and exhibited thermal damage (**Figure 3**).

Figure 2. The engines and conical inlet screens at the accident site (No. 2 engine partially viewable).

Figure 3. The engine control levers found on scene.

2.5.1 NO. 1 ENGINE (S/N 295122C)

The No. 1 engine exterior exhibited thermal damage from exposure to the postcrash fire. The starter remained attached to the forward frame of the engine and was thermally damaged. The starter was removed and its splines exhibited no evidence of anomalous wear. The engine oil tank was thermally damaged and separated from the inlet housing. The oil tank was later removed to better observe the 1st stage compressor blades. The inlet guide vanes (IGV) exhibited thermal damage. The variable guide vanes (VGV) could not be manually actuated due to resolidified molten aluminum within the forward portion of the VGV tracks. The stator vane actuator (SVA) piston was separated from its housing; the SVA piston housing exhibited fractures consistent with overload and thermal damage. The IGV and No. 3 VGV was separated from the actuator rod end linkages. Debris was observed on the lower half of the IGV and 1st stage compressor blades. The leading edges of the 1st stage compressor blades did not exhibit evidence of severe damage.

The fuel control and the centrifugal fuel purifier (CFP) remained attached, but the CFP housing was cracked and exhibited thermal damage. The throttle control positioning indicator was consistent with the “flight” position. Rotating the bolt for the throttle control gear rotated the throttle quadrant to the shut-off stop. The throttle control gear was removed and the splined connection did not exhibit evidence of anomalous wear. The worm gear and throttle control gear teeth did not exhibit evidence of anomalous wear. The position of the emergency (manual) throttle was measured to be about 1.7 inches in depth. The emergency throttle was moved to the fully open position and the position of the throttle was measured to be about 1.4 inches in depth. The power turbine blades were visible through the engine exhaust and all power turbine blades were present. The high speed shaft could not be manually rotated.

For additional details of the No. 1 engine findings, see Section 4.0 of this report.

2.5.2 NO. 2 ENGINE (S/N 296010)

The No. 2 engine case exhibited thermal damage from exposure to the postcrash fire. The starter remained attached to the forward frame of the engine and was thermally damaged. The starter was removed and its splines exhibited no evidence of anomalous wear. The engine oil tank was thermally damaged and remained attached to the engine. The tank was later separated from the engine to better observe the 1st stage compressor blades. The SVA attachment bracket was fractured and separated from the engine, but the SVA remained whole and thermally damaged. The IGV linkage was separated at its lower end (normally connected to the SVA). The IGV was manually actuated to better view the 1st stage compressor blades. Debris was observed on the lower half of the IGV and 1st stage compressor blades. The leading edges of the 1st stage compressor blades did not exhibit evidence of severe damage.

The fuel control and CFP remained attached, but the CFP housing was cracked and exhibited thermal damage. The throttle control positioning indicator was consistent with the “flight” position. The position of the emergency (manual) throttle was measured to be about 1.7 inches in depth. The position of the emergency throttle when moved to the fully open position was not measured. The power turbine blades were visible through the engine exhaust and all power turbine blades were present. The high speed shaft was able to be manually rotated but exhibited roughness with intermittent binding. A corresponding rotation of the power turbine was observed through the engine exhaust when the high speed shaft was rotated.

For additional details of the No. 2 engine findings, see Section 4.0 of this report.

2.6 COCKPIT INSTRUMENTS

The majority of cockpit instruments found at the accident site were unreadable due to impact and thermal damage. The percent torque gauge within the cockpit exhibited thermal damage and soot deposits, and its two needles were deformed in the forward direction. The two needles for the cockpit torque gauge were labeled “1” and “2”; needle “1” indicated about 0% and needle “2” indicated about 8% (**Figure 4**). The percent torque gauge mounted on the exterior of the helicopter for the left-seated pilot exhibited minor thermal distress. The two needles for the externally-mounted torque gauge were labeled “1” and “2”; needle “1” indicated about 34% and needle “2” indicated about 9% (**Figure 5**).

Figure 4. Cockpit engine torque gauge.

Figure 5. Exterior-mounted engine torque gauge.

3.0 MAIN GEARBOX AND INPUT FREEWHEELING UNITS (FWU)

The S-61N input FWU is a ramp-roller clutch that transmits drive when rotated in the normal drive direction, but freewheels when rotated in the direction opposite of normal drive. This functionality allows the main and tail rotor systems to mechanically disengage from the engine(s) in the event of a loss of engine power, preventing the affected engines from being backdriven by the rotor system.

3.1 INPUT FWU REMOVAL

On December 14, 2016, members of the Airworthiness Group convened at Florida Air Recovery in Fort Pierce, FL to remove and document the condition of the input FWUs. Oil drained from the input housing exhibited a tan color. There was no evidence of looseness of the spanner nut for the rotor brake when it was removed. Removal of the input housing cover revealed the main bevel gear and the main bevel input pinion (**Figures 6 and 7**). The gear teeth for the main bevel gear and the main bevel input pinion exhibited no evidence of anomalous damage. Separation of the front cover from the input housing revealed both FWU assemblies (**Figure 8**). Both input coupling retaining nuts were found to be hand tight, however both FWU assembly nuts did not exhibit evidence of looseness when removed. Manual rotation of the right FWU in the direction of normal drive resulted in engagement of the ramp-roller clutch; rotation in the freewheeling direction resulted in disengagement of the ramp-roller clutch. Manual rotation of the left FWU resulted in freewheeling motion in both directions of rotation. No anomalous damage was observed on the splines and gear teeth seen within the interior of the input housing during removal of the FWUs.

Figure 6. Main bevel input pinion.

Figure 7. Main bevel gear.

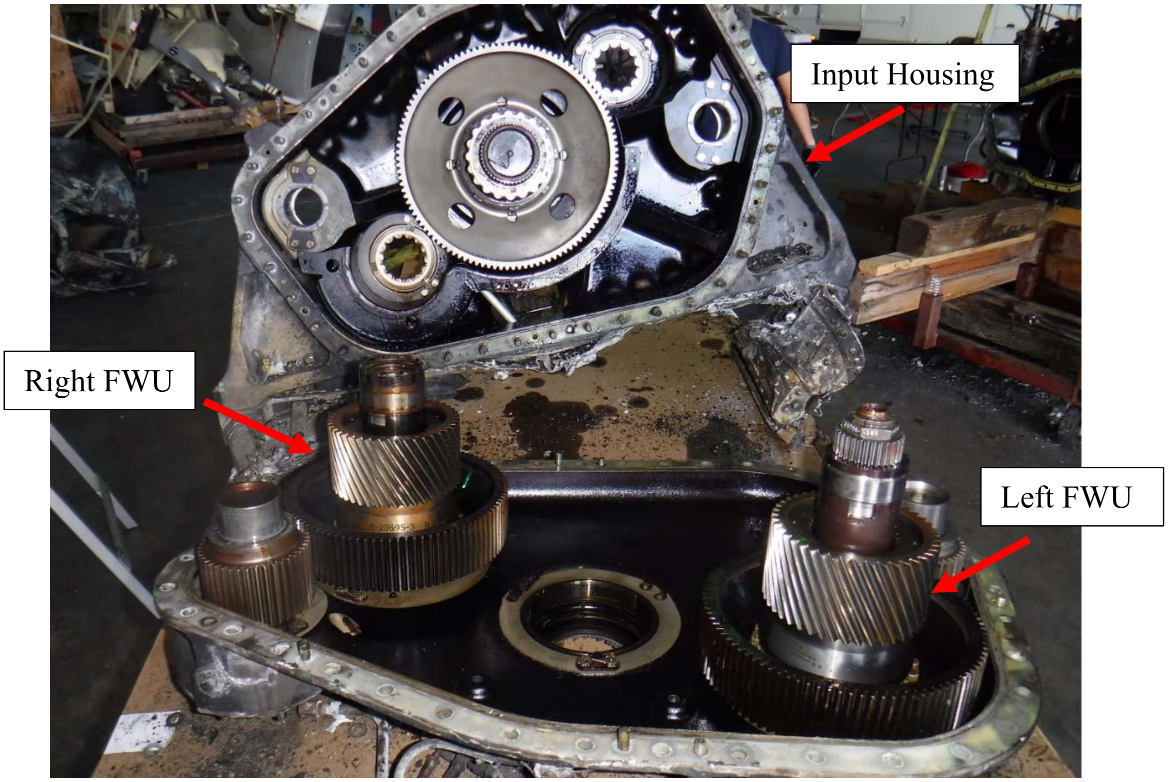

Figure 8. FWU exposed after removal of the front cover from the input housing. **(Photo courtesy of Sikorsky)**

The following markings were observed on one end of the left FWU:

78286-S6135-20695-004 L.H.
MFR21540 S/N F124-00228 SAC
C/L#118637 HT.IDENT#C8346

The following markings were observed on one end of the right FWU:

78286-S6135-20611-102
MFR S/N H120-00819

The following markings were observed on the opposite end of the right FWU:

S6135-20695-3 R.H.

Both left and right FWUs were retained and shipped to Sikorsky for further examination.

3.2 INPUT FWU EXAMINATION

On January 24-25, 2017, members of the Airworthiness Group convened at Sikorsky facilities in Trumbull, Connecticut to disassemble the left and right FWUs.

3.2.1 RIGHT FWU

After removal from the shipping crate the FWU was manually rotated: the ramp-roller clutch engaged when rotated in the drive direction, and disengaged when rotated in the freewheeling direction. A sludge-like substance was observed in the inner diameter of the spiral gear, adjacent to the outer race of the ramp-roller bearing. A sample of the substance was collected for lab analysis. The outer race of the ramp-roller bearing did not exhibit evidence of anomalous damage. The outer race of the ramp-roller bearing was measured twice along three longitudinal locations (labeled “top”, “middle”, and “bottom”), with the second measurement taken at a 90 degree offset from the first measurement. The results of the outer race are shown in **Appendix A** of this report.

The bearing cage inner diameter also contained a sludge-like substance similar to that of the inner diameter of the spiral gear. A sample of the substance was collected for lab analysis. No anomalous damage was observed on the bearing cage pockets. Shiny marks were observed on the cage pocket walls. Measurement of the cage pocket widths were taken, the results of which are shown in **Appendix A** of this report. All 12 roller elements were present and were generally in good condition. The ramps (bearing cam) had shiny wear marks exhibiting a polished appearance, but did not exhibit severe damage or gouges. The diameter between ramps was measured via coordinate-measuring machine (CMM); all diameters measured were within drawing requirements. The shiny wear marks on the ramps were measured, the results of which are shown in **Appendix A** of this report.

The bearing cage pins, which were released from their sleeves during removal of the spiral gear from the FWU shaft, were collected and retained for dimensional analysis. The results of these measurements are shown in **Appendix A**. The inner diameter of the bores which housed the bearing cage pin sleeves exhibited a smooth appearance. Light, circular contact marks were observed on the bearing retainer tangs, consistent with bearing cage pin contact with the tangs.

Both Oilite bushings were present on the bearing cage and exhibited no anomalous damage. The Oilite bushings were rotated about their seats with no evidence of binding. All splines and gears observed had no evidence of anomalous damage. Residual oil was observed on all bearing components throughout the FWU disassembly.

3.2.2 LEFT FWU

After removal from the shipping crate the FWU was manually rotated; the ramp-roller clutch remained disengaged and freewheeled when rotated in both directions of rotation. The splined nut was removed and exhibited no anomalous damage. A sludge-like substance was observed in the inner diameter of the spiral gear, adjacent to the ramp-roller bearing outer race. A sample of the substance was collected for lab. The outer race of the ramp-roller bearing did not exhibit evidence of anomalous damage. The outer race of the ramp-roller bearing was measured similar to the right FWU, the results of which are shown in **Appendix A** of this report.

The bearing cage inner diameter also contained a sludge-like substance similar to that of the inner diameter of the spiral gear. A sample of the substance was collected for lab analysis. Major constituents of the metallic particles were iron oxide, copper, and zinc. No anomalous damage was observed on the bearing cage pockets. Shiny marks were observed on the cage pocket walls. Measurement of the cage pocket widths were taken, the results of which are shown in **Appendix A** of this report. All 12 roller elements were present and were generally in good condition. The ramps had shiny wear marks exhibiting a polished appearance, but did not exhibit severe damage or gouges. The diameter between ramps were measured via CMM; all diameters measured were within drawing requirements. The shiny wear marks on the ramps were measured, the results of which are shown in **Appendix A** of this report.

Both bearing cage pins were observed to be in the retracted position. The bearing cage pin housings were labeled “A” and “B” for identification purposes. When both pin assemblies were removed from the bearing cage, the pins remained contained (and retracted) within its sleeve. Circumferential scoring was observed within the inner diameter of the bores which housed the bearing cage pin sleeves. Pin “A” was removed from the sleeve by pushing an allen key through the hole at the rear end of the sleeve. Resistance was felt when pushing the pin out of the sleeve. Once the pin was pushed out, the spring exited the sleeve. The pin and spring were reinstalled into the sleeve, and subsequent compression of the pin resulted in normal operation of the pin-and-spring mechanism. Pin “B” was not disassembled and remained in its compressed position for X-ray examination. (See Section 3.2.3 for additional details of the X-ray examination.) Circular contact marks were seen on the bearing cage tangs, consistent with bearing cage pin contact with the tangs. The circular contact marks were more pronounced compared to those observed on the right FWU.

Both Oilite bushings were present on the bearing cage and exhibited no anomalous damage. The Oilite bushings were rotated about their seats with no evidence of binding. All splines and gears observed had no evidence of anomalous damage. Residual oil was observed on all bearing components throughout the FWU disassembly.

3.2.3 MATERIALS LAB RESULTS

Lab analysis of the sludge-like samples taken from the inner diameter of the spiral gear and the bearing cage inner diameter determined them to be consistent with gearbox oil with fine metallic particles, the latter consistent with wear debris. Major constituents of the metallic particles were iron oxide, copper, and zinc.[5]

X-ray images of the Pin "B" assembly showed no evidence of visible foreign debris or contaminants. Additionally, the alignment of the spring and pin did not appear abnormal. Pin "B" was disassembled and dimensional measurements were taken of the pins, springs, and sleeves from both Pins "A" and "B" of the left and right FWUs. (See **Appendix A** for the dimensional measurements of Pins "A" and "B".) Examination of the inner diameter of all pin sleeves revealed no evidence of burrs or scoring.

3.3 MAIN GEARBOX BORESCOPE EXAMINATION

On February 28, 2018, representatives from Sikorsky, with oversight from the FAA, performed visual and borescope examinations of the main gearbox. No evidence of thermal damage was observed on the internal components of the main gearbox and the interior coatings appeared in good condition. The gear teeth exhibited normal wear pattern consistent with typical service wear. No anomalous damage was observed with the gears and bearings.

4.0 ENGINE DISASSEMBLY

Both engines were removed from the engine deck and shipped to Columbia Helicopters for further examination. On June 19-22, 2017, members of the Airworthiness Group convened at Columbia Helicopters facilities in Aurora, Oregon, to disassemble and examine the engines.

Figure 9. No. 1 engine prior to disassembly.
(Photo courtesy of GE Aviation)

Figure 10. No. 2 engine prior to disassembly.

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[5] The Oilite bushings contain sintered bronze containing copper and tin.

4.1 NO. 1 ENGINE DISASSEMBLY

The engine cases were index-marked at bolted interfaces along the length of the engine. No residual oil was observed when the oil supply line to the power turbine and the oil scavenge line were removed. The second stage turbine auxiliary sump air line was removed; pressurized air was applied through the line with no evidence of obstruction or debris. The power turbine section was removed from the second stage case and set aside. The fuel flow divider fuel selection was set to JP-5.

Application of 25 foot-pounds (ft-lbs) of torque on the starter dog (jaws) did not result in any movement of the engine core. Removal of the SVA pilot valve cover revealed the feedback cable remained connected to the pilot valve arm. The pilot valve exhibited no anomalous damage. The SVA pilot valve internal housing exhibited witness marks consistent with contact with the helical exterior of the feedback cable. The feedback cable could not be manually actuated and was found in a position consistent with the SVA in the closed position. The SVA housing was melted off from its piston, and remnants of the melted actuator housing was observed below its normally installed location. The SVA was set aside for later disassembly.

Removal of various lines from the accessory gearbox (AGB) revealed no evidence of residual liquids. The AGB radial drive shaft splines, and its mating internal splines, exhibited no anomalous damage. After removal of the AGB, application of 25 ft-lbs of torque on the starter dog did not result in any movement of the engine core. Attempting to manually rotate the AGB using the radial drive shaft was unsuccessful. The CFP was removed from the AGB and its external drive splines exhibited no anomalous damage. The CFP was set aside for later disassembly. After removal of the CFP, manual rotation of the AGB resulted in minimal rotation with evidence of binding. The lubrication pump was removed and both its internal and external splines exhibited no anomalous damage. The lubrication pump was not able to be manually rotated. The fuel control was removed and the splined connection between the fuel control and fuel pump exhibited no anomalous damage. Thermally degraded O-rings were observed when the fuel control was removed from the fuel pump. After removal of the fuel control, manual rotation of the AGB resulted in limited rotation and a corresponding rotation of the drive splines to the lubrication pump and the CFP, but not to the fuel pump-to-fuel control drive splines. During removal of the fuel pump from the AGB, one of the six studs separated and was retained in its mounting flange. The fuel pump could not be manually rotated. After fuel pump removal, manual rotation of the AGB was successful and resulted in a corresponding rotation of the drive splines for the fuel pump, lubrication pump, and CFP. The fuel pump external splines exhibited no anomalous damage. Debris, which had a hardened appearance and was black in color, was observed in the fuel pump inlet port. A sample of the debris was retained. The fuel pump was set aside for later disassembly. The front frame accessory drive gears did not exhibit anomalous damage. At this point in the engine disassembly, manual rotation of the starter dog was successful and resulted in corresponding rotation of the accessory drive internal spline (normally mating to the AGB radial drive shaft).

On the radiator (cooler), the inlet and outlet ports for both fuel and oil were unobstructed. The static fuel filter housing and bowl exhibited thermal damage. The static fuel filter bowl was removed, but its threads were stripped during the removal process. The filter element exhibited a blackened appearance but no debris was observed on the filter. Debris from the interface between the filter bowl and its housing was collected in a plastic bag. The start bleed valve was found in the closed position. All lines on the outside of the engine casing were removed and the engine casing did not exhibit crushing with the exception of the exhaust casing. The data plate information on the compressor case could not be read.

The third stage nozzle, between the second stage gas generator turbine and the power turbine, did not exhibit anomalous damage. The power turbine inlet temperature (T5) thermocouples were removed and did not exhibit evidence of melting. The second stage gas generator turbine case was disassembled, revealing the second stage gas generator turbine rotor, which exhibited no anomalous damage. Various blades exhibited a coating of soot on the aft-facing surfaces, but its forward-facing surfaces did not. The second stage gas generator shroud exhibited no evidence of rubbing or contact marks with its turbine rotor.

Removal of the power turbine rotor from its case revealed the power turbine blade dampers (located between the root end of the blades) were not flush to the forward surface of the rotor hub. The tip end of several blades exhibited slight curling near the leading edge. The second stage turbine rotor was removed and its blades exhibited no anomalous damage or erosion (**Figure 11**). All blades were present, and both sides of the blades exhibited evidence of soot deposits. The turbine disk exhibited thermal discoloration; the disassembly technicians stated that based on their experience the discoloration was typical of in-service use. The labyrinth seals, forward and aft cooling plates, and the coupling shaft between the first stage and second stage turbine rotors exhibited no anomalous damage. The honeycomb static seal on the inner diameter of the second stage turbine nozzle exhibited no anomalous damage. The second stage turbine nozzle and the first stage turbine shroud remained within the first stage turbine case when the case was removed. Four witness marks consistent with static (non-moving) first stage turbine blade contact with its shroud was observed on the 3 o'clock position of the shroud. A surface stain in the shape of static (non-moving) blades was observed on the 1 o'clock position of the shroud.

Figure 11. The second stage turbine rotor from the No. 1 engine.

The first stage turbine rotor was removed and its blades exhibited no anomalous damage or erosion (**Figure 12**). All blades were present, and both sides of the blades exhibited evidence of soot deposits, with heavier soot deposits observed on the blades around the 12 o'clock position. The curvic coupling teeth, the forward and aft cooling plates, and the first stage nozzle exhibited no anomalous damage. The turbine forward shaft, providing drive from the gas generator turbines to the compressor, exhibited no anomalous damage. The turbine shaft bolt was removed and its threads did not exhibit anomalous damage.

Figure 12. The first stage turbine rotor from the No. 1 engine.

The combustor case was disassembled into its respective halves. Heavy soot deposits were observed near the 6 o'clock position of the interior of the bottom combustor case. The top combustor case exhibited light soot deposits throughout its inner surface. The fuel nozzles exhibited no evidence of obstructions or blockages. Soot deposits were observed adjacent to the fuel nozzles; according to the disassembly technicians, soot deposits adjacent to the fuel nozzles were typical of in-service use. The combustor liner assembly and both fuel manifold lines exhibited no anomalous damage or melting.

The compressor rear frame exhibited heavy soot deposits on the interior of its top half. Separation of the compressor case halves revealed all 10 stages of the compressor rotors, after which the compressor spool (with the front frame and rear frame still attached) could be manually rotated. All compressor blade surfaces exhibited soot deposits (**Figure 13**). The compressor blades did not exhibit evidence of damage consistent with hard or soft body foreign object debris (FOD) ingestion[6] or severe erosion. The six compressor stator stages exhibited no

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[6] Hard body impact damage is characterized by a serrated appearance and deep cuts or tears to the blade leading and trailing edges. Hard body impact damage can result from impact with metal parts, concrete, asphalt, and rocks. Soft body impact damage is characterized by a large radius of curvature or curling deformation to the blade and can cause curling deformation

evidence of anomalous damage. Soot deposits were observed on the IGV, VGV, and the six stages of stators (**Figure 14**). From the 3 o'clock to the 6 o'clock region, the three stages of VGV tips were scored in the area between the second, third, and fourth stages. Impressions of the stator vanes were observed on the soot deposits on the compressor spool surfaces. Very light impressions of the last two stages of the VGV were observed on the soot deposits on top of the spool surfaces, but impressions of the first stage of VGV and the IGV were not observed on the soot deposits on the compressor spool surfaces.

Figure 13. Compressor rotors from the No. 1 engine.

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of the blades in the direction opposite of normal rotation. Soft body impact damage can result from impacts with pliable objects such as birds, ice, tire rubber, and plastic objects.

Figure 14. Compressor case halves from the No. 1 engine.

The torque tube was removed from the exhaust case, revealing the high speed shaft which remained attached to the power turbine flange via flexible disc coupling (also known as a Thomas coupling). The flexible disc coupling did not exhibit evidence of splaying or opening of the coupling laminates. The power turbine and the high speed shaft could not be rotated, precluding disassembly of the exhaust case. The No. 5 bearing housing was shifted, within the exhaust case, about 3/8 inches forward at the 9 o'clock position and 1/8 inches forward at the 3 o'clock position. The power turbine blades did not exhibit evidence of anomalous damage or severe erosion; the blades exhibited discoloration and the surfaces exhibited a rough appearance in areas that were not coated with soot (Figure 15). The power turbine accessory drive was stuck within the exhaust casing. The oil supply tube to the power turbine bearings exhibited deformation at the rotor hub-side.

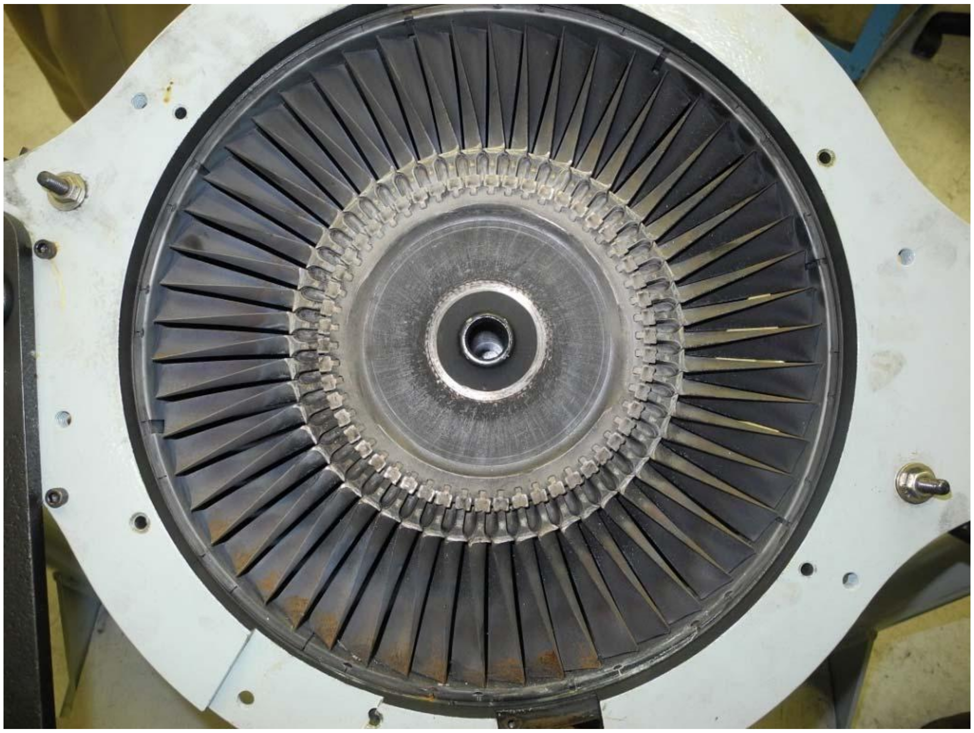

Figure 15. The power turbine rotor from the No. 1 engine.

4.2 NO. 1 ENGINE ACCESSORIES

4.2.1 FUEL PUMP

The fuel pump cover was removed, revealing a thermally degraded gasket underneath the cover. The front coupling external and internal splines exhibited no evidence of wear. The internal splines exhibited a rust-colored residue on a portion of its outer diameter. The front (muff) coupling adapter splines exhibited no anomalous damage. Removal of the front cover revealed white-colored deposits consistent with corrosion. A thermally degraded gasket was observed underneath the front cover. Two small, metallic globules were found underneath the front cover. A plug covering a port normally used for testing was removed and a thermally degraded O-ring was found underneath the head of the plug.

The rear cover was removed, revealing corrosion and thermal discoloration within the interior surfaces of the pump. Red-colored deposits were seen on the boost drive gear outer surfaces and about half of the gear web surfaces. The three shear posts were intact. The internal splines of the rear coupling, connected to the boost drive gear, exhibited no anomalous damage. The rear coupling was removed and the retaining ring was still in its installed position. The driveshaft splines mating to the rear coupling exhibited no anomalous damage. Red-colored deposits were observed on the contact surface of the boost driven gear teeth, but none were observed on the non-contact side of the gear teeth. The booster driven gear bearing support contained white-colored deposits consistent with corrosion. The pump drive gear and driven gear teeth contained red-colored deposits. Small, metallic globules were found throughout the inner surfaces of the drive and driven gear body and cover bearings (where the gear face contacts its bearings). Removal of the drive and driven gear resulted in axial scoring of the pump housing. The drive gear splines exhibited no anomalous damage.

The impeller, with the boost driven gear still attached, could not be removed from the pump housing. A borescope was inserted through the fuel inlet port to examine the impeller. The leading edge of an impeller blade was visible along with red-colored deposits adjacent to the visible impeller blade.

At no point in the disassembly could any of the aforementioned gears be rotated by hand.

4.2.2 STATOR VANE ACTUATOR

Examination of the SVA piston did not exhibit witness marks that could indicate the piston position at the time of ground impact.

4.2.3 CENTRIFUGAL FUEL PURIFIER

The CFP housing was split after removal of the band clamp. The shaft seal housing assembly was removed, and the splined connection on both ends of the shaft did not exhibit anomalous damage. The pilot shaft was removed from the impeller assembly, revealing its brass bushing. The brass bushing was intact with no evidence of damage to the rifling of the bushing. The centrifuge assembly was separated, revealing the filter screen, which exhibited no evidence of debris. The impeller could not be rotated by hand. Evidence of corrosion was seen throughout the internal aluminum components of the CFP.

4.2.4 ACCESSORY GEARBOX OIL FILTER

The oil filter housing was thermally damaged and breached. Remnant black-colored material, consistent with the material of a thermally degraded O-ring, was observed within the housing. Removal of the oil filter wafers revealed thermal damage to the filter wafers.

4.2.5 FUEL CONTROL FILTER

The fuel control filter was removed and exhibited evidence of corrosion. Disassembly of the filter screens revealed red-colored deposits. The filter assembly O-rings were observed to be intact during the filter screen disassembly.

4.3 NO. 2 ENGINE DISASSEMBLY

The engine cases were index-marked at bolted interfaces along the length of the engine. No residual oil was observed when the oil supply line to the power turbine and the oil scavenge line were removed. The power turbine section was separated from the second stage turbine case and set aside. The power turbine shaft and rotor were able to be rotated by hand. The static filter was not attached to the engine, but the filter mount was seen on the fuel control. Melted aluminum was observed in the area where the static filter would normally be installed. Hardened, black-colored deposits were observed near the oil scavenge line b-nut fittings, but no evidence of residual oil was observed. The pilot valve was found in the fully closed position. Residual oil was seen leaking from the oil cooler inlet line and had a medium-brown color. The fuel line from the CFP to the fuel pump contained hardened, black-colored deposits at both its inlet and outlet openings.

The internal and external drive splines from the AGB exhibited no anomalous damage. Additionally, the external splines of the AGB radial drive shaft and its mating internal splines exhibited no anomalous damage. The AGB could not be manually rotated. The oil cooler was removed and no residual oil was observed in the oil outlet line. The oil outlet port contained hardened, black-colored deposits. The SVA housing was thermally damaged and its piston remained within the housing. The SVA was set aside for later disassembly.

The fuel selection on the fuel flow divider was found set at JP-5. The T5 thermocouples were removed and none of its probes exhibited evidence of melting. After removal of the AGB, the application of 25 ft-lbs of torque on the starter dog did not result in movement of the engine core.

The lubrication pump was removed and pump drive splines, both internal and external splines, exhibited no anomalous damage. The lubrication pump was not able to be manually rotated. The fuel control was removed and the fuel pump-to-fuel control drive splines (both internal and external splines) did not exhibit anomalous damage. Thermally degraded O-rings were found when the fuel control was removed from the fuel pump. The fuel pump drive splines did not exhibit anomalous damage. A gasket on the fuel pump flange of the accessory gearbox exhibited impressions that mirrored the contact surface of the fuel pump. After removal of the fuel pump, neither the fuel pump nor the accessory gearbox were able to be manually rotated by hand. The front frame accessory drive gears did not exhibit anomalous damage. At this point, the starter dog was able to be manually rotated and exhibited continuity of drive to the accessory drive internal splines (which mates to the accessory gearbox radial drive shaft).

The second stage turbine case and third stage nozzle were removed from the core engine. The second stage turbine shroud showed no evidence of rubbing or blade contact marks. The second stage turbine blades exhibited no evidence of anomalous damage (**Figure 16**). Soot deposits were observed on the blades near the 6 o’clock position, but the remainder of the blades did not exhibit evidence of soot deposits. An orange-colored residue was observed near the 6 o’clock position of the labyrinth oil seal. The second stage turbine rotor was removed; two blades exhibited evidence of small curls at their tips, but no other anomalous damage was observed. All blades remained retained within the turbine wheel. The honeycomb static seal exhibited no anomalous damage.

Figure 16. The second stage turbine rotor from the No. 2 engine.

The curvic couplings on the rear turbine shaft, second stage coupling, the coupling shaft, and the first stage turbine did not exhibit anomalous damage. Corrosion was observed on the curvic couplings on the rear turbine shaft and the coupling shaft. Corrosion was also observed on the forward and aft surfaces of the second stage cooling plates. The first stage turbine case was removed and the shroud did not exhibit evidence of rubbing or blade contact marks. Staining of the shroud, in the shape of turbine blade airfoils, was observed around the circumference of the shroud. The second stage nozzle was removed and exhibited cracks near the leading edge root end of the nozzle vanes. The cracks were more extensive on three vanes centered about the 12 o’clock position. A crack was also observed on the trailing edge tip end of the nozzle vane. The cracks were measured to be about 3/8 inch in length.[7] The first stage turbine blades did not exhibit anomalous damage (**Figure 17**). Corrosion was observed on the first stage turbine wheel and its forward and aft cooling plates. The turbine forward shaft curvic coupling and the forward splines of the shaft exhibited no anomalous damage. The forward rotating labyrinth seal exhibited debris, overlaid on its surface, of a dull-gray color and crystallized appearance. On the surfaces of the forward stationary seal, which contacts the forward rotating labyrinth seal, debris of a jade-green color. The turbine shaft bolt shank exhibited corrosion. Additionally, the first stage turbine case exhibited corrosion on its internal walls. The first stage nozzle exhibited no anomalous damage. The turbine shaft bolt was removed and its threads exhibited no anomalous damage. The aft third of the length of the bolt exhibited corrosion.

Figure 17. The first stage turbine rotor from the No. 2 engine.

The combustor case halves were removed and were free of soot deposits. Additionally, the combustor liners were free of soot deposits. No evidence of blockages was seen on the fuel nozzles. The compressor rear stationary seal housing and labyrinth seal were removed and exhibited no anomalous damage. Oil residue was observed on both the labyrinth seal and the seal housing. Hardened deposits, black in color, were observed on the No. 2 bearing oil jet.

Separation of the compressor case halves revealed all 10 stages of the compressor rotors (**Figure 18**). Slight bending deformation in the direction opposite of normal rotation was observed on several compressor blades from various stages. Corrosion was observed on the vanes of the IGV and all three stages of the VGVs (**Figure 19**). The spool face for the third stage VGV, between compressor stages 3 and 4, exhibited evidence of rubbing; corresponding rub marks were observed on 7 of the vanes on the third stage VGV. The rubbing on the spool face was of negligible depth and could not be measured with calipers. Additionally, the spool face between compressor stages 5 and 6 exhibited evidence of rubbing of negligible depth. The remaining 6 stages of stators did not exhibit anomalous damage.

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[7] According to SEI-183, the rejection threshold for nozzle vanes is three cracks, no larger than 3/8 inch long, and with no danger to material breaking away.

Figure 18. Compressor rotors from the No. 2 engine.

Figure 19. Compressor case halves from the No. 2 engine.

On the bottom compressor case, there was evidence of rubbing between all stages of the stators, VGV, and IGV. The depth of the rub marks between stages 3 and 4 of the VGV was measured, using calipers, to be about 0.003 inches. On the bottom compressor case, rubbing was observed between the 6 o'clock to 7 o'clock position for the first 8 stages of compressor rotors; rubbing was observed between the 6 o'clock to 9 o'clock position for the 9th stage compressor rotor.

The torque tube was removed from the exhaust case, revealing the high speed shaft which remained attached to the power turbine flange via flexible disc coupling. The flexible disc coupling did not exhibit evidence of splaying or opening of the coupling laminates. All power turbine blades were present (**Figure 20**). At the leading edge tip ends of the power turbine blades exhibited impact damage with material curled both in the direction of normal rotation and opposite the direction of normal rotation (**Figure 21**). Power turbine accessory drive was manually rotated and continuity of drive was visually confirmed. The power turbine accessory drive's square-shaped driver did not exhibit anomalous damage and its shear point remained intact. The oil supply tube to the power turbine bearings exhibited slight bending deformation.

Figure 20. The power turbine rotor from the No. 2 engine.

Figure 21. Damage observed on the leading edge tip ends of the power turbine blades from the No. 2 engine.

4.4 NO. 2 ENGINE ACCESSORIES

4.4.1 FUEL PUMP

The front coupling splines and muff adapter did not exhibit anomalous damage. Remnants of a thermally degraded gasket and bellows was observed after removal of the front coupling from the pump housing. After the pump cover was removed, a thermally degraded O-ring as well as small metallic globules on the cover bearings were found. The O-rings around the pump cover bearings were thermally damaged and exhibited a tackiness when touched. The rear cover was removed from the pump housing. The booster drive and driven gears showed no anomalous damage. All three shear posts on the booster drive gear remained intact. The drive gear hub exhibited areas of red discoloration. The driveshaft exhibited no anomalous damage. No evidence of blockage was found on the pressurized fuel outlet. Small metallic globules were found on the pump gears and bearings. The pump gears and the impeller exhibited no anomalous damage but the gear teeth exhibited an iridescent coloration.

4.4.2 STATOR VANE ACTUATOR

The SVA piston was able to be manually actuated in both the extension and retraction directions. The piston did not exhibit witness marks that could indicate the piston position at the time of ground impact.

4.4.3 CENTRIFUGAL FUEL PURIFIER

The CFP band was removed but the housing halves remained assembled. Tools were used to pry the two housing halves apart, damaging the housing in the process. The shaft seal housing was removed and the splined connection did not exhibit anomalous damage on either end. The pilot shaft remained retained within the inner diameter of the impeller brass bushing. The pilot shaft was removed from the brass bushing. The brass bushing exhibited no evidence of damage to its rifling. The impeller was removed from the centrifuge. The impeller did not exhibit anomalous damage but could not be manually rotated. The centrifuge assembly was separated, revealing the filter screen. No debris was seen on the filter screen. The screen ring came apart when the screen was removed from its housing. Throughout the CFP disassembly, corrosion was observed throughout the internal aluminum components.

4.4.4 ACCESSORY GEARBOX OIL FILTER

Removal of the oil filter revealed small metallic globules within the oil filter housing. The oil filter wafers exhibited thermal damage. Remnant material, consistent with thermally degraded O-rings, was observed within the oil filter housing.

4.4.5 FUEL CONTROL FILTER

Removal of the fuel control filter revealed it exhibited a clean appearance. Disassembly of the filter screens showed no anomalous debris. The filter assembly O-rings were brittle and fragmented into smaller pieces during disassembly of the filter screen.

5.0 ENGINE FUEL CONTROL DISASSEMBLY

On August 28-29, 2018, members of the Airworthiness Group convened at Columbia Helicopters facilities in Aurora, Oregon to disassemble the fuel controls from the Nos. 1 and 2 engines.

5.1 NO. 1 FUEL CONTROL

Soot was present on the exterior of the fuel control housing (**Figure 22**). There was no evidence of cracks, fractures, or melting of the housing. The retaining clip for the pressure relief valve (PRV) housing was fractured at one of its ends, but lockwire remained attached to the fractured retaining clip end. Lockwire was present on the bolts securing the PRV housing to the fuel control. The fuel density adjustment dial tab was bent upward and the tab was offset from the dial hard stop by about 40 degrees. The PRV dial was at the JP-5 setting.

Figure 22. The No. 1 fuel control prior to disassembly.

The PRV housing was removed and black-colored material, similar to thermally degraded packing material, was observed within the bore of the fuel control.[8] The PRV diaphragm was not present, but thermally degraded debris was observed in the location where the diaphragm would normally reside. Both PRV springs and the spring seat remained within the PRV housing. Black-colored material was observed within the PRV housing. The shape of the PRV springs did not appear anomalous. The nut which holds the PRV diaphragm remained installed. The PRV piston would not move when pushed by hand. The PRV piston and sleeve were removed as an assembly and the piston position was consistent with the windows on the PRV sleeve being in the closed position. The piston was removed from its sleeve and rust was observed on the surfaces of the sleeve bore and on portions of the piston, but there was no evidence of debris within its balance grooves. The packing and backup ring for the PRV sleeve were present but appeared thermally distressed. Three rectangular discolorations were observed on the bottom

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[8] Throughout the fuel control disassembly, black-colored material similar to thermally degraded packings was observed on internal surfaces, bores, and components where packings were normally installed. In this section of the report, "black-colored material" will refer to material similar to thermally degraded packings unless otherwise specified.

land of the piston spool. The location of the discoloration was consistent with the piston position having closed the spool windows at the time the discoloration occurred. The adjacent spool lands exhibited a relatively shiny appearance compared to the discoloration on the bottom land. After the PRV piston was removed from its sleeve, the piston could be moved within the sleeve without restriction.

The spring between the PRV piston-sleeve assembly and the filter relief valve was removed. The shape of the spring did not appear anomalous. The filter relief valve was removed and exhibited corrosion on its surfaces. Black-colored material was observed at the bottom of the filter relief valve bore. The filter relief valve was in the closed position. When the filter relief valve was pushed by hand the valve moved to the open position; the valve returned to the closed position after manual force was released.

The gas generator speed (Ng) governor splines remained intact and the shaft exhibited axial and radial play when manipulated by hand. The disassembly technician noted that the shaft play was typical for the fuel control. When the power turbine speed (Nf) tachometer drive cable was manually rotated, the rotation was limited to twisting of the drive cable and the drive cable would not rotate freely.

The SVA rod protrusion from the housing was measured to be about 0.883 inches. The position of the emergency throttle was measured to be about 1.695 inches in depth. The flattened surface between the two emergency throttle rack gears was observed between the rack gear housings.[9] The rack gears remained pinned together. The rack and pinion gears exhibited corrosion on its surfaces but their gear teeth exhibited no other anomalous damage. Additionally, the cam did not exhibit anomalous damage.

The end cap was removed, revealing the minimum flow stop. The metering valve support was able to be rotated by hand; the metering valve support is normally torqued to 110 inch-pounds at overhaul. The metering valve support inner diameter surfaces exhibited corrosion. The metering valve support was removed, revealing the metering valve. The metering valve surfaces exhibited corrosion. The position of the metering valve relative to the housing was about 3.56 inches. An attempt was made to move the metering valve by hand, but the metering valve appeared seized. Removal of the metering valve revealed the flow window opening was consistent with the metering valve being at the minimum flow stop.[10] The spool and sleeve of the metering valve exhibited corrosion on its surfaces and the spool was seized within its sleeve.

The tachometer was removed from the fuel control. The square-drive to the Nf governor flyweights was rotated and there was no evidence of restriction to its rotation, but a squeaking noise was heard during rotation. The stop cock cover was removed and the plastic component that seals that stop cock valve was not present. Melted material, dark brown in color, was observed in the vicinity where the stop cock plastic component would normally reside.

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[9] The emergency throttle assembly comprises two rack gears that are pinned together and a pinion gear that rotates a cam within the fuel control. Each rack gear has its own housing, and the forward rack gear contains a flattened surface where it is pinned to the aft rack gear. When the flattened surface is visible between the two rack gear housings, the emergency throttle position is in the closed (disengaged) position. When the emergency throttle is opened (engaged), the flattened surface will migrate aft and reside underneath the aft rack gear housing.

[10] During the No. 1 fuel control disassembly, it was not documented if the metering valve had contacted the minimum flow stop during removal of the metering valve. During the No. 2 fuel control disassembly, its metering valve was observed to have contacted the minimum flow stop. The size of the opening of the metering valve was similar between the No. 1 and No. 2 fuel controls.

Thermally degraded packings, consistent in size to the packings installed on the plastic component, was observed in the same vicinity as the dark brown melted material. Movement of the throttle resulted in movement of the stop cock screw but not of the stop cock block. The Nf governor flyweights were removed and its surfaces exhibited light corrosion. The flyweights were free to move and exhibited no other anomalous damage. The Nf servo valve was able to be manually moved with no evidence of restriction to its movement. The Ng servo cap exterior had soot on its surfaces. The packing for the Ng servo cap was present but was brittle when touched.

The compressor inlet temperature (T2) bellows cover was removed, revealing the T2 bellows. The T2 bellows spring was observed protruding through its retainer. The retainer was found in two pieces: one piece had a diameter similar to that of the spring outer diameter and the second piece was the remainder of the retainer that remained installed on the T2 bellows. The T2 bellows exhibited corrosion and soot on its surfaces. The hydroformed sheet metal of the T2 bellows showed no evidence of ruptures but exhibited localized distortion.

The cover of the fuel control was removed, revealing the internal components of the fuel control (**Figure 23**). Generally, corrosion was visible throughout the surfaces of the internal components, but the visible components did not exhibit fractures or disconnection. All components exhibited freedom of movement except for the three-dimensional (3D) cam and the Ng governor gear. According to the disassembly technician, the internal configuration and condition of the fuel control appeared typical aside from the corrosion and thermal damage. The 3D cam was approximately at the ground idle position. The rack gear which rotates the 3D cam was found to be positioned to the end of the rack gear consistent with elevated temperatures.[11] The compressor discharge pressure (P3) bellows was vacuum tested and successfully held a vacuum for 1 minute.

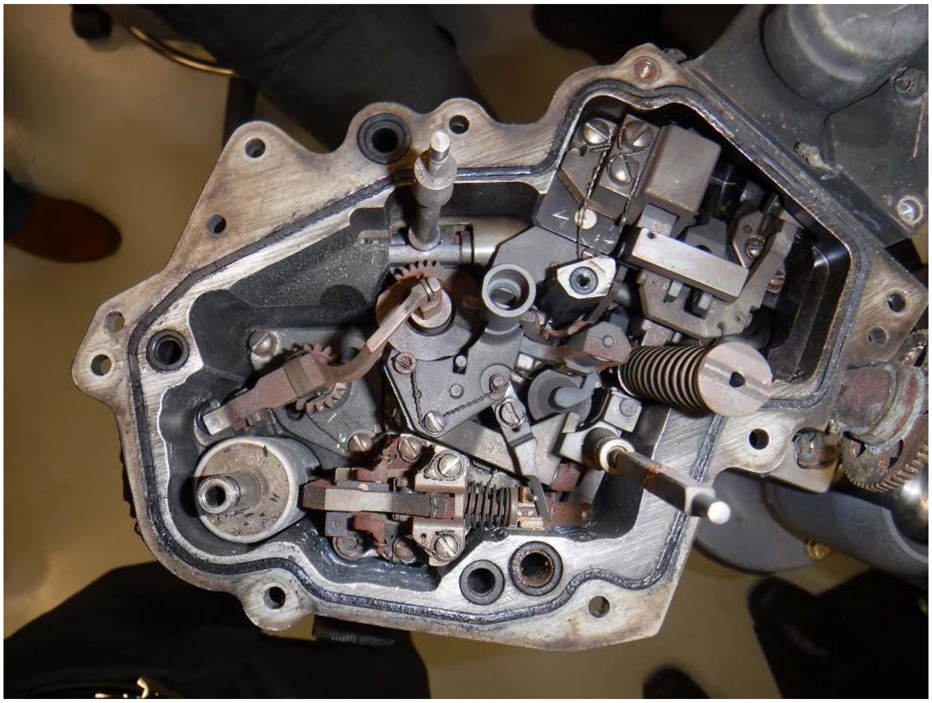

Figure 23. The internal components of the No. 1 fuel control after removal of the cover.

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[11] Depending on the ambient operational temperatures, the T2 bellows will move the 3D cam rack gear, which in turn will rotate the 3D cam. The two ends of the rack gear signify operation in elevated (hot) or low (cold) temperatures.

The 3D cam servo assembly was removed from the fuel control. Both packings for the 3D cam housing were not present. After removal of the 3D cam servo assembly, the disassembly technician had to break the 3D cam free from its housing by using tools to tap it out. The 3D cam exhibited corrosion but there was no evidence of cracks, fractures, or other anomalous damage. The 3D cam was freed from its housing, the 3D cam was reinstalled into its housing and could be moved rotationally and axially. The two teflon seals, normally white in color, exhibited a white-colored appearance and did not exhibit mechanical damage. Rust-colored byproducts were observed on the surfaces of the teflon seals and the housing interior surfaces.

5.2 NO. 2 FUEL CONTROL

Soot was present on the exterior of the fuel control housing (**Figure 24**). There was no evidence of cracks, fractures, or melting of the housing, but several of the external bosses exhibited small dents. The retaining clip for the PRV housing was intact and lockwire was present on the bolts securing the PRV housing to the fuel control. The fuel density adjustment dial tab was not bent and the tab was offset from the dial hard stop by about 40-45 degrees. The PRV dial was at the JP-5 setting.

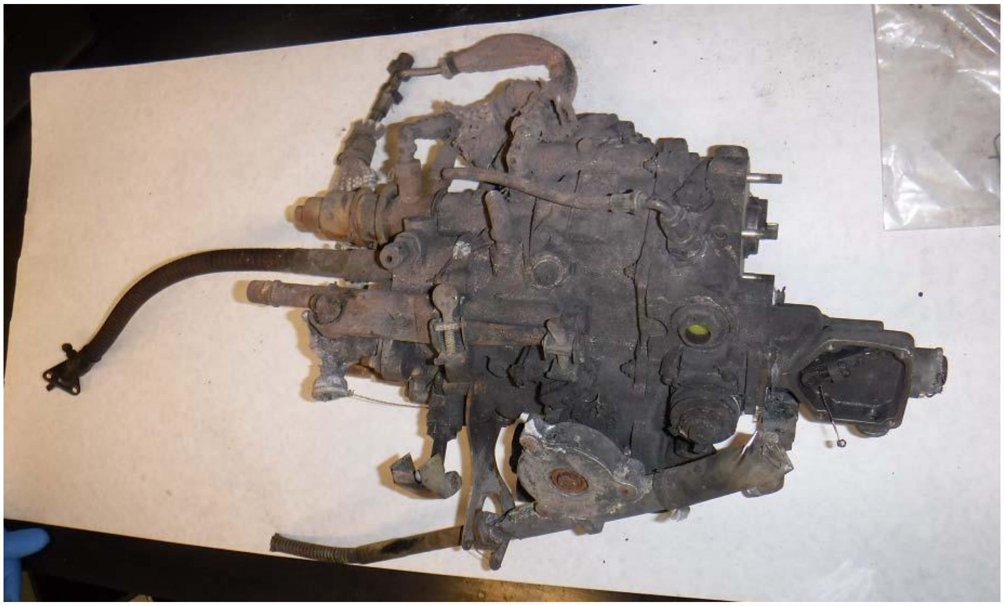

Figure 24. The No. 2 fuel control prior to disassembly.

The PRV housing was removed and its packing broke up during removal. Thermally degraded material, similar to the size and shape of the diaphragm, was found in the location where the diaphragm would normally reside. Both PRV springs and the spring seat remained within the PRV housing. The shape of the PRV springs did not appear anomalous. The nut which holds the PRV diaphragm remained installed. The PRV piston was found in the closed position. The PRV piston moved within its sleeve for the full stroke and there was no evidence of restriction to its movement. The PRV piston was removed and its surfaces were clean with no evidence of debris found in its balance grooves. Three rectangular discolorations were observed on the bottom land of the piston spool. The location of the discoloration was consistent with the piston position having closed the spool windows at the time the discoloration occurred. The adjacent spool lands exhibited a relatively shiny appearance compared to the discoloration on the bottom land. The PRV sleeve was removed from the fuel control housing and its packing broke apart during removal. The PRV backup ring was present but portions of it were deformed. The bore of the PRV sleeve exhibited relatively less corrosion compared to that of the No. 1 fuel control.

The spring between the PRV piston-sleeve assembly and the filter relief valve was removed. The shape of the spring did not appear anomalous. The filter relief valve was removed and exhibited corrosion on its surfaces. Black-colored material was observed at the bottom of the filter relief valve bore. The filter relief valve was in the closed position. When the filter relief valve was pushed by hand the valve moved to the open position; the valve returned to the closed position after manual force was released.

The Ng governor splines remained intact and the shaft exhibited axial and radial play when manipulated by hand. The disassembly technician noted that the shaft play was typical for the fuel control. When the Nf tachometer drive cable was manually rotated, the rotation was limited to twisting of the drive cable and the drive cable would not rotate freely.

The SVA rod protrusion from the housing was measured to be about 0.965 inches. The SVA rod could be manually pushed downward. The SVA feedback arm was free to move and exhibited continuity to the rocker within the pilot valve assembly. On the fuel control throttle, the gap between the throttle maximum stop and throttle pad surface was measured. That measurement was replicated on an exemplar fuel control on a test bench and the throttle position was found to be about 85 degrees.

The position of the emergency throttle was measured to be about 1.698 inches in depth. The flattened surface between the two emergency throttle rack gears was observed between the rack gear housings. The rack gears remained pinned together. The rack and pinion gears did not exhibit anomalous damage. Additionally, the cam did not exhibit anomalous damage. The pinion gear and cam rotated freely.

The end cap was removed, revealing the minimum flow stop. Based on the relative position of the pin to the minimum flow adjustment screw stop, the metering valve appeared to be at the minimum flow stop. The maximum flow stop was removed and exhibited thermal distress and corrosion on its surface. Remnants of thermally degraded packing and the backup ring were observed in the grooves in which they are normally installed. The sleeve and boss were removed and exhibited thermal distress and corrosion on its surfaces. The metering valve support was able to be rotated by hand; the metering valve support is normally torqued to 110 inch-pounds at overhaul. The metering valve support was removed, revealing the metering valve. The metering valve surfaces exhibited corrosion, but relatively less corrosion compared to the No. 1 fuel control metering valve. The position of the metering valve relative to the housing was about 3.615 inches. The spool and sleeve of the metering valve did not exhibit corrosion to the extent observed on the spool and sleeve of the No. 1 fuel control metering valve. The packing was present on the valve but was hard to the touch. The metering valve spool was seized within its sleeve.

One of the four nuts securing the Nf tachometer to the fuel control housing was not present. After the tachometer was removed from the fuel control, manual rotation of the Nf tachometer was attempted but it would not rotate. Manual rotation of the square-drive to the Nf governor flyweights was rotated and there was no evidence of restriction to its rotation, but a squeaking noise was heard during rotation. Corrosion and a white-colored substance was observed on the gears and surfaces from the Nf tachometer to the Nf governor flyweights. The stop cock cover was removed and the plastic component that seals that stop cock valve was not present. Black-colored material was observed in the location where the plastic component would normally reside. The small diameter packing for the plastic component was not present. The large diameter packing for the plastic component was present and brittle. The Nf governor flyweights were removed and its surfaces exhibited no anomalous damage. The flyweights were free to move. The Nf servo valve was able to be manually moved with no evidence of restriction to its movement. The Ng servo cap exterior had soot on its surfaces. The packing for the Ng servo cap was present but was brittle when touched.

The T2 bellows cover was removed, revealing the T2 bellows. The T2 bellows retainer was intact but appeared thermally distressed. The T2 bellows also appeared thermally distressed. A rupture was observed on one of the hydroformed sheet metal of the T2 bellows.

The cover of the fuel control was removed, revealing the internal components of the fuel control (**Figure 25**). Generally, the surface condition of the internal components did not exhibit corrosion to the extent observed on the No. 1 fuel control. The internal components did not exhibit fractures or disconnection. All components exhibited freedom of movement. According to the disassembly technician, the internal configuration and condition of the fuel control appeared typical to those seen at overhaul. The 3D cam was at a relatively higher axial position compared to the 3D cam of the No. 1 fuel control.[12] The 3D cam was also positioned about mid-travel on its rack gear. The P3 bellows was vacuum tested and successfully held a vacuum for 1 minute.

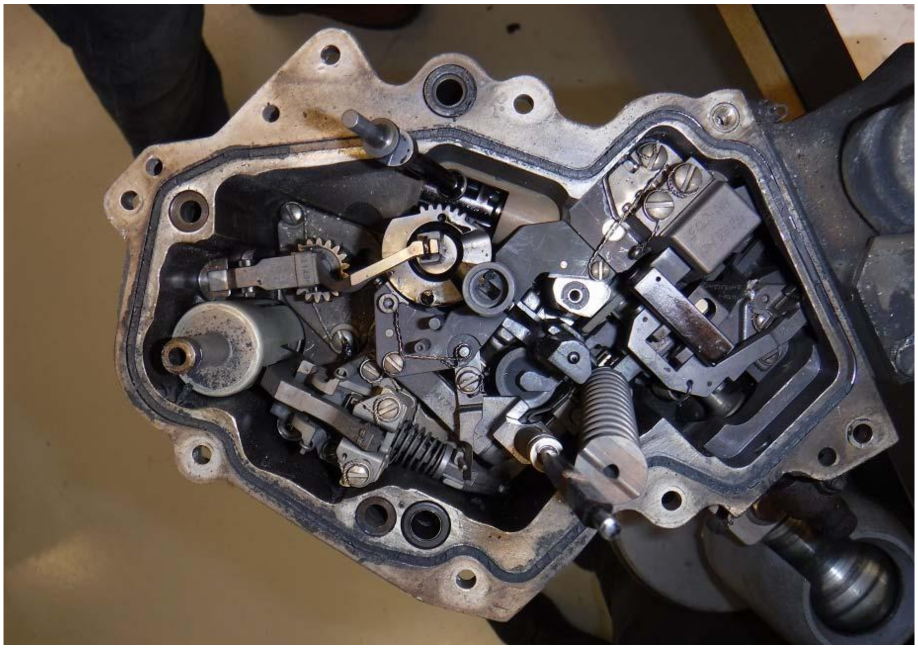

Figure 25. The internal components of the No. 2 fuel control after removal of the cover.

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[12] A "higher" or "up" axial position of the 3D cam denotes the direction when the fuel control main housing is placed on a table and the observer as a birds-eye-view of the internal components of the fuel control. The disassembly technician stated that in his experience when receiving the same model fuel controls for overhaul, he has previously observed the 3D cam axial position vary. Additionally, he stated the 3D cam can be received in a "down" axial position and would travel "up" axially while the fuel control was at rest. The negative feedback rod and follower spring contacts the underside lip of the 3D cam which provides a constant force upward on the 3D cam.

The 3D cam servo assembly was removed from the fuel control. On the 3D cam housing, one packing had a melted appearance while the other packing had a thermally hardened appearance. The 3D cam was able to be manually moved both axially and rotationally within its housing. The two teflon seals, normally white in color, exhibited a white-colored appearance and did not exhibit mechanical damage. There were no evidence of cracks, fractures, or other anomalous damage on the 3D cam assembly.

6.0 HELICOPTER FUEL SYSTEM

The accident helicopter was equipped with a 3-tank fuel system. The 3-tank fuel system comprises a forward, center, and aft tank with a capacity of 1470, 1708, and 1400 pounds, respectively. The fuel tanks are constructed of a rubberized fabric material with a fiberglass liner. The forward tank supplies fuel to the No. 1 engine and the aft tank supplies fuel to the No. 2 engine. The center tank only stores fuel which can be transferred to the forward and/or aft tanks, either individually or simultaneously, via electrically-actuated transfer valves. An electrically-actuated crossfeed valve between the forward and aft tanks allows for one engine to be supplied with fuel from both tanks. The fuel management panel, located to the left of the engine instruments in the cockpit, contains on/off toggle switches for each boost pump, the crossfeed valve, and the fuel shut-off valves, as well as annunciator lights for low fuel pressure and boost pump failure. Three dial indicators above the fuel management panel display fuel quantity within the forward, center, and aft tanks. Center tank fuel transfer to the forward and aft tanks is controlled via two on/off toggle switches (one for the forward tank and one for the aft tank) located to the left of the fuel quantity indicators.

The forward and aft tanks each contain a collector can at the forward end of the tank. The collector can contained the fuel collector assembly which included two boost pumps, a fuel suction line, and a manifold which combines the outputs from the boost pumps and the fuel suction line. The electrically-driven boost pumps provide fuel to its respective engine. Additionally, the boost pumps motivates fuel into the fuel transfer line to the center tank and to an ejector unit, within the same tank as the boost pumps, which motivate fuel from the parent tank into the boost pump collector can. Fuel transfer lines from the forward and aft tanks lead to the center tank where ejector units (one for the forward tank and one for the aft tank) motivates fuel from the center tank into the desired destination tank. For example, when the crew initiates a fuel transfer from the center tank to both the forward and aft tanks, fuel pressure from the boost pumps is used to feed the ejector units in the center tank. The center tank ejector units motivates fuel from the center tank into the forward and aft tanks.

6.1 FUEL SYSTEM EXAMINATION

The fuel management panel was not found in the wreckage. The fuel transfer valves were found loose in the airframe wreckage. Both fuel transfer valves exhibited soot deposits and thermal damage. Both fuel transfer valves were found in the open position.

A section of fuel line containing the forward fuel filter and the forward manual shut-off valve was found loose between the lower fuselage. The T-fitting connecting to the crossfeed valve was fractured consistent with overload. The manual shut-off valve was in the open position. The fuel filter bowl was partially fractured from the fuel filter housing, exposing the filter element. The filter element was coated in soot. Melted material, likely a plastic portion of the bypass relief mechanism, was observed on the inner surfaces of the fuel filter housing.

A section of fuel line containing the aft fuel filter, aft manual shut-off valve, and the crossfeed fuel line, including the crossfeed valve, was also found loose underneath the lower fuselage. The fuel filter bowl was partially crushed and punctured. Removal of the fuel filter bowl revealed the filter element. The filter element was partially crushed. Sand and dirt were found on the filter element, the fuel filter bowl, and the fuel filter housing. The bypass relief mechanism appeared intact. The crossfeed valve was found in the closed position. The crossfeed valve motor was fractured from the crossfeed valve but was found loose in the main wreckage. Resolidified molten aluminum was observed where the crossfeed valve motor would normally be installed. A fractured portion of the T-fitting remained attached to the crossfeed valve; its fracture surfaces matched the fractured T-fitting found on the fuel line section containing the forward fuel filter and forward manual shut-off valve.

The fuel collector assemblies for both the forward tank and the aft tank were found loose in the airframe wreckage and exhibited soot deposits and thermal damage. Each fuel collector assembly comprised two boost pumps and the suction line connected to the manifold. Most of the collector can for each collector assembly was missing. The boost pumps were identified as Nos. 1 through 4 for this investigation. Pump Nos. 1 and 2 were associated with one fuel collector assembly; pump Nos. 3 and 4 were associated with the other fuel collector assembly. The data plates for the pumps showed pump No. 1 was S/N C-3060; pump No. 2 was S/N C-3763; pump No. 3 was S/N C-2754; and pump No. 4 was S/N C-3493.

The exterior of pump No. 1 exhibited thermal damage and soot deposits. Removal of the impeller screen of pump No. 1 showed soot deposits and corrosion on the impeller, but no other anomalous damage to the impeller blades. Removal of the housing revealed the motor rotor, shaft, and two ball bearings. Continuity of drive was verified between the impeller, shaft, and rotor. Light corrosion was observed on the internal components of the pump. The two ball bearings exhibited a ratchet-like feel when rotated by hand but did not exhibit any binding that precluded full rotation. No anomalous damage was observed on the motor stator within the inner diameter of the housing.

Pump Nos. 2 and 4 exhibited similar findings to pump No. 1 except corrosion of the interior components of pumps No. 2 and 4 were more severe compared to pump No. 1.

The housing of pump No. 3 could not be removed, precluding visual observation of its interior components. Removal of the impeller screen showed corrosion and soot deposits on the impeller, but no other anomalous damage to the impeller blades. The four long bolts securing the housing (containing the motor stator) to the impeller housing were removed. Subsequent manual rotation of the housing, while keeping the impeller housing stationary, resulted in a corresponding rotation of the impeller.

6.2 ESTIMATED FUEL LEVEL DURING ACCIDENT FLIGHT

At the end of the second flight, the reported total fuel was 2,200 pounds with 850 pounds in the forward tank and 550 pounds in the center tank, resulting in 800 pounds in the aft tank.[13] Additionally, the crew stated fuel transfer was initiated while en route to the staging area where they were planning to perform the aft control rigging check. The crew was not specific as to which tanks (forward, aft, or both) fuel was being transferred. Estimating the fuel consumed

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[13] For additional information, see the Cockpit Voice Recorder transcript in the docket for this investigation.

during the accident flight[14] and assuming a scenario where no fuel was transferred from the center tank to the forward and aft tanks to produce the lowest estimated fuel levels, fuel quantities of 725 pounds and 675 pounds were estimated to be in the forward and aft tanks, respectively, at the time of the accident. With the helicopter at a 15 degree positive pitch (nose-up) attitude, the fuel level within the forward and aft tanks was estimated to partially cover the top-aft edge of the collector can (**Figure 26**).

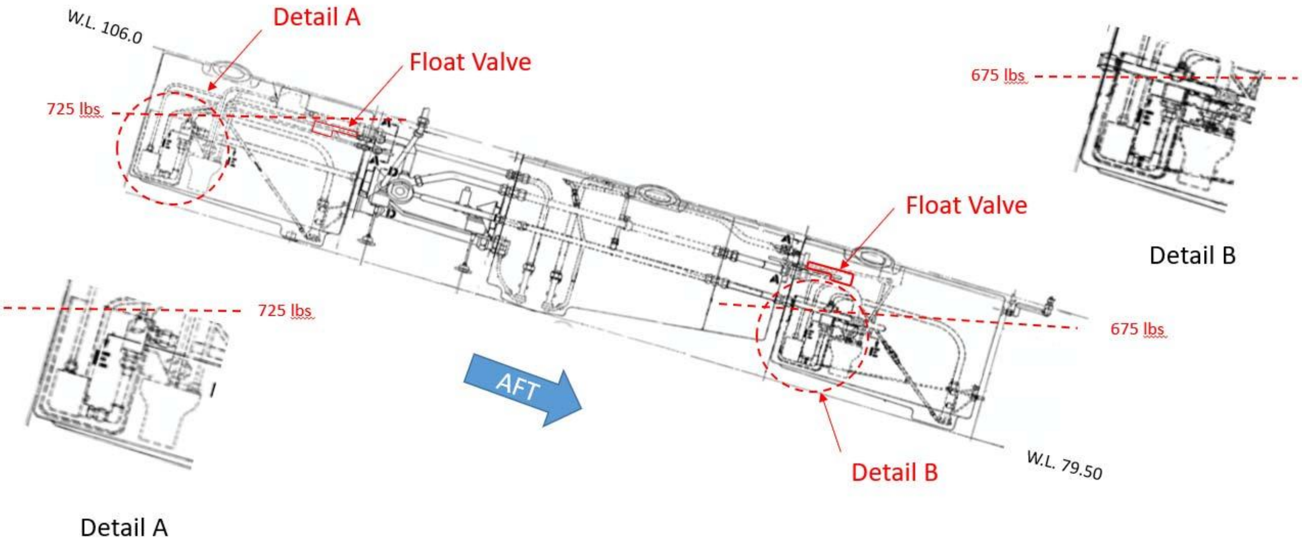

Figure 26. Estimated fuel level within the forward and aft tanks with a 15 degree positive pitch attitude.

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[14] A combined fuel burn rate [for the two engines] of about 1,000 pounds per hour was used for this estimation.

Appendix A

Input FWU Disassembly Measurements

Table 1. Right FWU ramp wear measurements.

Ramp number*	Top end measurement	Bottom end measurement
1	-0.0008”	-0.0005”
2	-0.0007”	-0.0005”
3	+0.0002”	-0.0005”
4	-0.0007”	-0.0007”
5	-0.0008”	-0.0005”
6	-0.0008”	-0.0004”
7	-0.0006”	-0.0005”
8	-0.0007”	-0.0006”
9	-0.0010”	-0.0006”
10	-0.0011”	-0.0004”
11	-0.0010”	-0.0008”
12	-0.0009”	-0.0005”
Note: Negative values equal depth into the zero-datum surface. Positive values equals protrusion from the zero-datum surface.		
*Ramp number does not coincide with the roller and cage pocket number.		

Table 2. Right FWU cage pocket width measurements.

Pocket number*	Bottom of the pocket	Middle of the pocket	Top of the pocket
1	0.420”	0.420”	0.420”
2	0.420”	0.420”	0.420”
3	0.420”	0.420”	0.420”
4	0.420”	0.420”	0.420”
5	0.420”	0.420”	0.420”
6	0.420”	0.420”	0.420”
7	0.420”	0.420”	0.420”
8	0.420”	0.420”	0.420”
9	0.420”	0.420”	0.420”
10	0.420”	0.420”	0.420”
11	0.420”	0.420”	0.420”
12	0.420”	0.420”	0.420”
Measurement of #1 pocket wear on LH side of pocket: About 0.0007” depth at bottom side of pocket, about 0.0001” depth at middle and top of the pocket.			
Measurement of the #6 pocket wear on LH side of pocket: About 0.0007” depth at bottom side of pocket, about 0.0001” depth at middle and top of the pocket.			
Note: Maximum allowable cage pocket width is .428”.			
*Pocket number coincides with the numbering of the rollers during disassembly.			

Table 3. Left FWU ramp wear measurements.

Ramp number*	Top end measurement	Bottom end measurement
1	-0.0006”	-0.0005”
2	-0.0007”	-0.0005”
3	-0.0006”	-0.0004”
4	-0.0007”	-0.0006”
5	-0.0005”	-0.0005”
6	-0.0006”	-0.0005”
7	-0.0006”	-0.0005”
8	-0.0007”	-0.0004”
9	-0.0006”	-0.0004”
10	-0.0006”	-0.0005”
11	-0.0006”	-0.0005”
12	-0.0006”	-0.0005”
Note: Negative values equal depth into the zero-datum surface. Positive values equals protrusion from the zero-datum surface.		
*Ramp number does not coincide with the roller and cage pocket number.		

Table 4. Left FWU cage pocket width measurements.

Pocket number*	Bottom of the pocket	Middle of the pocket	Top of the pocket
1	0.421”	0.421”	0.421”
2	0.421”	0.421”	0.421”
3	0.421”	0.421”	0.421”
4	0.421”	0.422”	0.421”
5	0.421”	0.422”	0.421”
6	0.421”	0.422”	0.422”
7	0.421”	0.421”	0.421”
8	0.421”	0.422”	0.421”
9	0.421”	0.422”	0.421”
10	0.421”	0.422”	0.421”
11	0.421”	0.421”	0.421”
12	0.421”	0.422”	0.421”
Measurement of #1 pocket wear on LH side of pocket: About 0.0002” depth all over. Measurement of #1 pocket wear on RH side of pocket: About 0.0002” depth all over.			
Measurement of #6 pocket wear on LH side of pocket: About 0.0002” depth all over. Measurement of #6 pocket wear on RH side of pocket: About 0.0003” depth all over.			
Note: Maximum allowable cage pocket width is .428”.			
*Pocket number coincides with the numbering of the rollers during disassembly.			

Table 5. FWU roller element diameters.

Roller number	Right FWU (all values are diameters)	Left FWU (all values are diameters)
1	0.4125”	0.4140”
2	0.4125”	0.4140”
3	0.4123”	0.4140”
4	0.4124”	0.4140”
5	---	0.4140”
6	0.4125”	0.4140”
7	0.4125”	0.4140”
8	---	0.4140”
9	---	0.4140”
10	0.4125”	0.4140”
11	---	0.4140”
12	0.4125”	0.4140”
Unknown*	0.4125”	---
Unknown*	0.4125”	---
Unknown*	0.4125”	---
Unknown*	0.4123”	---
Note: Average of two measurements were taken 90 degrees apart, about mid-length of the rotational axis of the roller element.		
Note: Roller element diameters must be between .4138-.4140”.		
*Unknown roller numbers are due to accidental removal of number identification (via permanent marker during disassembly) during handling of components.		

Table 6. FWU Oilite bushing measurements per dimensional evaluation worksheet found in Alert Service Bulletin No. 61B35-67B

	Right FWU		Left FWU	
Part Number	61350-20459-101	61350-20459-102	S6135-20748-1	S6135-20746-1
Dimension A	0.200”	---	0.068”	---
Dimension B	0.040” (Low) 0.064” (High)	---	2.445” *	---
Dimension C	2.540”	---	2.757” *	---
Dimension D	2.641”	---	---	2.761”
Dimension E	2.749”	---	---	2.555”
Dimension F	---	2.757”	---	2.439”
Dimension G	---	2.647”	---	0.057”
Dimension H	---	2.538”	---	0.151”
Dimension I	---	0.111”	---	---
Dimension J	---	0.240”	---	---
* The S6135-20748-1 Oilite bushing fractured into two pieces during cleaning prior to these measurements being taken. Dimension B and C were taken as a diametric measurement, but the bushing had possibly sprung due to fracture.				

Table 7. FWU pin, sleeve, and spring measurements.

		Outer Diameter	Length	Inner Diameter	Spring Load*
Left FWU	Pin A	.2795-.2797”	0.602”		
	Pin B	.2795-.2798”	0.603”		
	Sleeve A	0.359”	1.199”	.2810-.2815”	
	Sleeve B	0.359”	1.198”	.2806-.2810”	
	Spring A	0.264”	0.920”**		4.14 pounds
	Spring B	0.263”	0.920”**		4.23 pounds
Right FWU	Pin A	0.2795”	0.602”		
	Pin B	0.2790”	0.602”		
	Sleeve A	0.359”	1.200”	.2806-.2809”	
	Sleeve B	0.359”	1.198”	.2806-.2812”	
	Spring A	0.263”	0.928”**		4.53 pounds
	Spring B	0.262”	0.932”**		4.42 pounds
Dimensional requirements	Pin	.2795-.2800”	.590-.610”		
	Sleeve	.358-.359”	1.190-1.200”	.2806-.2813”	
	Spring	.260-.270”			3.6875-4.1875 pounds
* Spring load was measured when spring was compressed to a length of.670”.					
**The spring was unsprung when length measurement was taken.					

Table 8. Ramp-roller bearing outer race diameters.

	Right FWU	Left FWU
Top	3.7533”	3.7513”
Top (90 degree offset)	3.7533”	3.7514”
Middle	3.7534”	3.7513”
Middle (90 degree offset)	3.7538”	3.7513”
Bottom	3.7534”	3.7511”
Bottom (90 degree offset)	3.7537”	3.7512”
Note: Maximum allowable ramp-roller bearing outer race diameter is 3.7535”.		