CANADIAN FORCES
FLIGHT SAFETY INVESTIGATION REPORT (FSIR)

FINAL REPORT

FILE NUMBER:	1010-188732 (DFS 2-2-2)
DATE OF REPORT:	24 March 2006
AIRCRAFT TYPE:	CF188 - Hornet
DATE/TIME:	262009Z May 2003
LOCATION:	4 Wing Cold Lake, Alberta
CATEGORY:	A Category Accident

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

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

SYNOPSIS

The accident aircraft was number three of a four plane formation launched from 4 Wing, Cold Lake, Alberta, to participate in a Maple Flag mission. The four aircraft had completed their simulated weapons delivery and were flying relatively level at about 480 knots indicated airspeed (KIAS) and 3000 feet above ground level (AGL) in a "card" formation. Just prior to the accident, the number two aircraft had moved from a 6000 - 9000 foot line abreast position to tight formation on the lead aircraft to inspect it for a possible gear problem. This did put the leading element about 1.2 nautical miles (NM) directly in front and slightly above the accident aircraft. When number three reached the approximate point in space where the lead element of aircraft had rejoined, it began a very fast negative G “barrel” roll to the right, completing a full roll in about 3.5 seconds. Although the aircraft roll rate momentarily stopped at wings level, shortly thereafter the negative G continued and the roll to the right resumed. At about this time, with the aircraft in a negative G regime, the pilot ejected. The pilot sustained fatal injuries during the ejection process The aircraft continued to roll under negative G, nosed down and impacted the ground basically inverted at about 45 degrees of pitch and at a high velocity. The aircraft was destroyed on ground impact.

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1. FACTUAL INFORMATION

GENERAL

The CF188, is a single person, multi-role, twin-engine, tactical fighter. The accident aircraft, CF188732, was flown by 416 Squadron (Sqn) in 4 Wing, Cold Lake, Alberta. The flight was a sortie in the early stages of Exercise Maple Flag, a large multi-national air force exercise. The aircraft was configured with an Air Combat Manoeuvre Instrumented (ACMI) pod on the right wing and a Captive Air Training Missile (CATM) on the left wing. The ACMI pod feeds aircraft telemetry data to both its internal storage device as well as a ground station that stores the data for mission debrief. The CATM allows the aircraft weapon systems to operate as if it was armed with real weapons, but is a “fixed” aircraft store.

1.1 History of the Flight

The pilot was an element lead, and for this mission was number three in the second four plane formation of an eight plane attack sortie. The mission had proceeded as briefed and all four aircraft were headed for their egress point at about 5300 feet above mean sea level (MSL), which was about 3000 feet AGL. The formation, call sign “Red Dog” 35, 36, 37 (mishap aircraft) and 38, was in a “four ship card” with the lead element roughly 6000-9000 ft line abreast and the second element following about 2 miles behind with similar line abreast spacing.

On this last leg, lead had requested number 2 to move in to a close formation and inspect his aircraft in order to help him troubleshoot a persistent intermittent gear (unsafe) tone. Also, lead was calling on number three to take the lead of the formation since the gear problem would not likely allow the lead element to complete the mission. The close rejoin of the lead element occurred with the number two aircraft applying about 4G to decrease the closure rate on the lead aircraft. Also, the lead element had started to decrease speed and at that point were travelling at less than 400 KIAS. Because number 3 had remained at 480 KIAS, the trail spacing from the front element to the rear element had decreased to about 1.2 NM. Number 3 was directly behind and slightly below the lead element. About 9 seconds after the rejoin, as number 3 passed through the approximate point in space where the lead element had rejoined, the accident aircraft began a high negative G bunt and rapid barrel roll to the right at about 120 degrees of roll per second. The negative G spiked to more than –6.3 but remained at an average of about –2.5 for the entire roll, which only took about 3.5 seconds for the first 360 degrees of roll. As the wings approached level, the roll rate stopped for about 2 seconds, after which the right hand, negative G barrel roll resumed. The pilot initiated his ejection when the aircraft reached 76 degrees of roll (for the second time), with –30 degrees of pitch, 465 KIAS, about 1250 feet AGL and in a negative G flight regime (about –2.5 G).

The aircraft continued the slow roll and negative G until it impacted the ground with about 26 degrees of pitch and a steep bank angle (about 148 degrees of right roll), and an airspeed of 432 KIAS. The pilot was fatally injured during the ejection sequence. The aircraft crash position was N54 52.11, W110 24.43 (WGS84 datum).

1.2 Injuries to Personnel

	Crew
Fatalities	1
Major injury	N/A
Minor injury	N/A

1.3 Damage to Aircraft

The aircraft sustained “A” category damage when it impacted the ground. Ground impact forces completely fragmented the airframe with the resulting debris field measuring 1500 feet long and up to 500 feet wide. Within a few hours of ground impact a forest fire started in the debris field. This fire burned for the next four days, causing further damage to many aircraft components within the fire area. The ensuing fire fighting efforts caused some additional damage and may have removed some evidence. These latter events only affected debris in the fire area. See Figures 1 to 3 of Annex A.

1.4 Collateral Damage

The aircraft crashed into a remote area of the Cold Lake Air Weapons Range (CLAWR) about 3 kilometres (km) South of Loseman Lake and 400 meters west-north-west of an unnamed beaver pond. There are considerable oil and gas industrial activities throughout the CLAWR and the impact point was close to a gas pipeline such that aircraft debris was distributed around and onto the pipeline access trail. Oil and gas technicians isolated the line quickly to preclude any serious damage to their facilities. A large forest fire was already burning about 20 km to the North and West of the accident site, and Alberta forest services already had considerable resources available in the area. Several hours after the crash, a fire started in the debris field. Fire fighters from 4 Wing, the Alberta forest service and 4 Wing Recovery and Salvage (RAS) team spent four days extinguishing the ensuing fires. Helicopters from the Alberta Fire Fighters used slung “Bambi Buckets” to dump water into the crater and on the debris field to contain the fire within a manageable area. The fire danger precluded site investigation for the first 36 hours and limited the investigation efforts for the ensuing three days.

Eventually, the Oil and Gas technicians inspected the pipeline area and confirmed there was no damage to their facilities. Due to the remoteness of the crash site and the requirement to recover the aircraft to Cold Lake, 4 Wing’s RAS team had to improve 6 km of access trail to allow digging equipment access to the site. These improvements allowed the transport of the recovered aircraft debris to 4 Wing. After the debris was recovered much of the clean up work had been accomplished, and therefore the site became less difficult to make environmentally acceptable.

1.5 Personnel Information

	Pilot
Rank	Capt
Category/Expiry	Element Lead 14 Jan 04
IRT Category/Expiry	Cat 1/11 Sept 03
Medical Expiry	27 Aug 03
Total flying time	3138.7
Flying hours on type	661.9
Flying hours last 30 days	22.5
Duty hours last 24 hours	8
Flying hours last 24 hours	0.8
Flying hours on day of Occurrence	0.8

The pilot was the Sqn Scheduling Officer and had just upgraded to element lead in January 2003. His previous flying was mostly on the CC138 Twin Otter.

1.6 Aircraft Information

The aircraft was configured with 5 pylons and 2 external tanks. It carried a CATM and an ACMI pod, along with 1 chaff bucket. The ground proximity alert functionality was present.

An aircraft system-by-system analysis was conducted by the technical investigation group to determine if any of the background documents, physical evidence or archived Maintenance Signal Data Recording System (MSDRS) data indicated a connection to the accident. No linkages were discovered in this initial analysis but many parts, such as the flight control actuators, were sent to the Quality Engineering and Test Establishment (QETE) in Ottawa for in-depth investigation and analysis. There were no discrepancies noted in the Maintenance Record Set (MRS) check with all maintenance activities done in accordance with technical orders and by qualified technicians. Due to the level of destruction, it was not possible to take fluid samples from the aircraft. However, fluid samples were taken from servicing equipment and sent to the Alberta Research Council. Tests conducted revealed no anomalies.

The MSDRS was recovered a month after the accident from the debris field and sent to the National Research Council Flight Recorder Playback Centre (NRC FRPC) in Ottawa. Unfortunately, the cartridge had been exposed to sufficient heat that the tape was burned and no data could be extracted.

1.7 Meteorological Information

The 4 Wing weather office produced a synopsis of the crash site's weather shortly after being informed of the accident. Cold Lake has full meteorological services while Jimmy Lake Range (WHN) has automated reporting. The accident area had broken to overcast midlevel cloud layers with scattered cloud below. Frequent embedded alto cumulus castellanus / towering cumulus (ACC/TCU) caused light rain showers and reduced visibility to six statute miles. The forecast bird migration intensity was light.

METAR

CYOD 262000Z 36008KT 15SM –SHRA FEW025 SCT048 BKN100 OVC240 16/09 A2981

CYOD 262018Z 34005KT 15SM FEW025 FEW048 BKN080 OVC 240

CWHN 261800Z 34010G16 9SM FEW038 OVC060 OVC084 OVC099 14/09 A2979

TAF

CYOD 261806 33012KT P6SM SCT030 BKN090 BKN240
TEMPO 1824 P6SM -SHRA BKN025 OVC090
FM0000Z 30005KT P6SM SCT090 BKN 250

Freezing level:	12000 feet MSL.
Icing:	Moderate in convective cloud otherwise light to nil.
Turbulence:	Moderate in the vicinity of convective cloud otherwise light to nil.

1.8 Aid to Navigation

The entire mission was flown in the CLAWR at mid-level altitude in visual flying rules (VFR) weather due to the fire fighting activities restrictions in several sectors of the ranges. An altitude minimum of 5000 ft above sea level (ASL) was imposed to remain clear of fire fighting operations. Navigation was done using Inertial Navigation System (INS) guidance, which is an integral part of the CF188. All navigation aids and radars at Cold Lake were serviceable.

1.9 Communications

The crew was in contact with 42 Radar Sqn while flying the mission profile. Following the accident, all tapes from the 4 Wing Cold Lake air traffic control tower (Tower), 42 Radar Sqn, 22 NORAD Regional Operation Command Centre (ROCC), and the NATO Airborne Warning and Command System (AWACS) aircraft were quarantined. The "Red Dog" formation, 35, 36, 37 (mishap aircraft) and 38 was using two ultra high frequencies (UHF) for communication, one for communication within the formation and the other for talking to the AWACS aircraft, which was controlling the air battle.

Review of the Tower tapes indicated that the Tower was not monitoring the frequencies in use by the mishap aircraft at the time of the accident. 42 Radar Sqn advised the Tower of the accident at 2018Z hours and the “One Bell” response was initiated.

42 Radar Sqn tapes only show track information of the Red Dog formation because the “Word Safe Maxima” equipment, which records digital data (to include altitude) and voice, had been unserviceable for about 18 months. 22 NORAD ROCC radar information had only one identification friend or foe (IFF) contact with the mishap aircraft prior to the accident.

1.10 Crash/Alighting Area Information

The terrain at the impact location was densely treed, covered in thick moss over a layer of permafrost with underlying clay and rock. The accident site was relatively level with tree heights varying between 30 and 45 feet. Previously, multiple access trails had been cut throughout the CLAWR for oil and gas exploration. One of these trails and an associated gas line ran through the debris field. The accident did not damage the gas line and the trail complex was utilized in the recovery phase of the investigation to move gathered debris to a road access point. Total cooperation was forthcoming from the Gas and Oil industry representatives during all recovery and other investigation operations.

1.11 Fight Recorders

The CF188 does not have a Cockpit Voice Recorder (CVR) or a Flight Data Recorder (FDR). Various on board recording devices are fitted to the CF188 but none are designed to be crash survivable. Although a project is currently under way to provide a crash survivable CVR/FDR system, fleet implementation is currently not forecasted until the fall of 2006.

The CF188 has an MSDRS that is designed to record multiple aircraft parameters throughout flight and ground operations to be computer analysed after flight completion; mostly for maintenance purposes. Typically, the data is downloaded to a Magnetic Tape Cartridge (MTC) that can hold about 3 or 4 missions worth of data, after which the MTC is removed for data download and storage as part of the maintenance record process. Under the normal maintenance program, the data is systematically examined for trend analysis or used to aid in detailed fault analysis. Should events during the mission dictate a requirement for close examination of the aircraft parameters for any reason, the cartridge is removed and the data downloaded for detailed examination or analysis at the end of the mission. Although the system is not crashworthy, the data on MTCs has been very beneficial during previous accident investigations, even if the data was not completely intact due to the catastrophic events. Consequently, the recovery of the MTC was an objective in all phases of the RAS operation. Despite these efforts, the MTC for this aircraft was not located until a second specific search was initiated about one month after the accident. The MTC was then found in debris raised out of the crater during salvage operations by the digging machines.

Unfortunately, examination at the NRC FRPC facility showed the cartridge had been exposed to sustained heat in the crater and all the data was vaporized off the tape. Of note, the MSDRS was not designed as an FDR/CVR and the heavy metal case of the MTC actually works as a heat transfer device under circumstances such as post crash fires, which usually will destroy the data.

An examination of the archived MSDRS data for CF188732 was undertaken to see if any trends could be determined that would have implications in this accident sequence. This examination revealed no trends.

CF188732 was equipped with an ACMI pod on the right wing (station 9). The purpose of this pod is to record aircraft position data in three-dimensional space, on an accurate timeline, so that the flight path of the trip can be replayed for post mission debrief. The ACMI pods are supported by a range instrumentation and playback facility that were just recently installed in the CLAWR. With all aircraft fitted with ACMI pods, there is in-flight pod interaction with data transfer and on board recording occurring. With this system it is possible to show how all aircraft in the entire sortie interacted. This allows a complete battle replay so accurate results and learning points can be passed to participants in the post mission phase of the exercise. Pod data is downloaded to the range equipment at 1 hertz (once per second) but the pod has 10 hertz (ten times per second) data recorded on the Data Transfer Device (DTD), a removable cartridge installed on the pod itself.

The DTD from CF188732 was recovered in the debris field and was significantly damaged such that normal playback was not possible. However, the 10 Hertz data was stripped by the Original Equipment Manufacturer (OEM) and made a very accurate flight path reconstruction possible. In addition, certain aircraft parameters such as indicated airspeed (IAS); load factor (G), angle-of-attack (AOA) and height were made available for the investigation team analysis.

The CF188 has Mission Computers containing electronic cards that have non-volatile memory modules, some of which may have up to 3 seconds of data stored. These cards were again part of the objectives in all phases of the RAS operation. Unfortunately, none of these modules were recovered.

The RAS operation was successful in finding some long loose lengths of videotape in the trees of the debris field. These were also sent to the NRC FRPC where recovery of data on the tapes was accomplished. This revealed about 6 minutes of Head Up Display (HUD) data. Unfortunately the tape section stops about 1.5 minutes before the accident occurred.

1.12 Wreckage and Impact Information

The wreckage area was quite large, approximately 1500 feet long and 500 feet wide. Using inclinometers, ACMI data, the tree damage pattern and ground scars it is estimated the aircraft hit the ground roughly inverted at 432 KIAS, 26 degrees nose down, and 148 degrees right bank. A crater 20 feet wide, 30 feet long and 15 feet deep was created. Most of the upper half of the fuselage wreckage pieces, including the engines and gun, were buried in the crater.

The bottom half of the fuselage including flight control surfaces, landing gear, wings, internal electronic boxes, actuators and fuel tanks were spread down track in the remainder of the debris field.

There was a post impact fire along the debris field centreline about 300 feet wide. The Alberta Fire Fighting Services, using airborne resources, extinguished the fire. The aerial fire fighting involving helicopter water slinging resulted in the crater filling with water to a depth of 6 to 10 feet. After the fires were extinguished, a substantial amount of rain fell, which resulted in additional water infiltration at the crater. By the time salvage efforts commenced at the crater 10 days after the accident, the water depth was close to 12 feet.

1.13 Medical

The pilot suffered fatal injuries during this accident. He was found by a search and rescue (SAR) helicopter launched from 417 Combat Support Squadron (CSS), Cold Lake, approximately 40 minutes after the accident. His location was about 1400 feet up track from the impact point. A SAR Tech was dropped off in a swampy area near the pilot’s landing point and subsequently a Flight Surgeon and the Coroner were lowered to the site for confirmation of the fatal injury. The pilot was then transported to Cold Lake and subsequently transferred to Edmonton on the coroner’s orders where an autopsy was performed in the presence of a Canadian Forces (CF) Flight Surgeon. Medical samples were sent to the Armed Forces Institute of Pathology (AFIP) in Washington, USA for analysis. The toxicology test results were negative. The pilot was deemed both mentally and physically fit to fly on the day of the accident. The main injury was the result of a very large force being exerted to the left side of the pilot’s neck and head.

1.14 Fire, Explosives Devices, and Munitions

1.14.1 Fire

The crash caused a fire in the impact area. Alberta fire fighting resources were in the area due to a very large forest fire about 20 Km north and west of the accident site. These resources responded quickly to the fire in the debris field using helicopters slinging water to the crater and with personnel on the ground. These efforts kept the fire to a reasonable size but fires were present in the accident scene for at least the next four days. 4 Wing firefighters, more Alberta forest service resources and the 4 Wing RAS team battled these fires and allowed the accident team site access after about 36 hours.

1.14.2 Explosive Devices and Munitions

Beyond the fire danger, the aircraft carried dangerous equipment, munitions and explosive devices including:

a. 500 rounds of 20mm ammunition for the aircraft mounted gun.
b. 1 ejection seat, associated charges and rocket motor.
c. 1 set of canopy jettison charges.
d. Survival flares and pencil flares in the seat survival kit.
e. 2 nitrogen bottles (pressurized vessels).
f. 3 fire bottle cartridges.
g. Chaff dispenser and cartridges.
h. Pylon impulse cartridges (for external fuel tanks).
i. CATM gas grain generator.
j. ACMI pod.
k. Liquid Oxygen (LOX) converter.

Part of the early site recce included Explosive Ordinance Disposal (EOD) team members from 4 Wing. The EOD personnel established a Stores Awaiting Disposal (SAD) area well away from the main routes into the debris field and began gathering the dangerous materials or making them safe for transport to 4 Wing for further investigation. This extensive effort was largely successful but due to the high forces involved with the ground impact, which may have destroyed some materials without leaving traces, the extensive post crash fire and the challenging terrain and ground cover some components were not located. These components include:

a. 282 rounds of 20mm ammunition casings.
b. 1 fire bottle cartridge.
c. SMDC set for the canopy jettison (likely destroyed).

All other materials, not made safe and transported to 4 Wing, were destroyed using a 35-pound explosive charge in a safe site near the accident scene.

1.15 Survival Aspects

The pilot initiated ejection quickly considering the negative G flight regime and the roll rate on the stricken aircraft. However, somewhere in the ejection sequence, the pilot sustained a fatal injury.

Several pieces of Aircrew Life Support Equipment (ALSE) were badly damaged in the ejection sequence or did not function in an optimal manner. Specifically, both bladders on the life preserver survival vest (LPSV) were destroyed and would not have been functional if a water entry had occurred. Also, the majority of contents in the LPSV were forced out of the pockets and some made contact with the pilot causing injury. Finally, the helmet was removed from the pilot's head during the escape sequence but remained attached to his ALSE through oxygen hose connections. In addition, the visors separated from the helmet. They were most likely torn from the pilot's helmet due to exposure to the 465 kts windblast.

1.16 Test and Research Activities

1.16.1 Wreckage Analysis

A wreckage analysis was performed at 1 Air Maintenance Squadron (1 AMS) by the technical investigation team. Parts of various aircraft systems were recovered and analysed in order to establish, to the extent possible, the "state of health" of these systems and their potential involvement in the accident. There were no aircraft fluid samples available from the wreckage.

1.16.2 ACMI Playback

The NRC FRPC analysed the recovered MSDRS, which was unfortunately unusable due to heat damage. However, the flight data from the ACMI pod, both internal and transmitted to the ground station, was recovered and proved pivotal in establishing a plausible scenario. Based on this data, the NRC FRPC also provided composite video animations of the accident profile, which were extensively used during the investigation.

1.16.3 ALSE Analysis

An ALSE analysis was performed by personnel from Defence Research and Development Center (DRDC) Toronto. This inspection was centered on the personal equipment worn by the pilot on the accident flight, and revealed some anomalies.

1.16.4 Simulator Trials

Boeing, the aircraft Original Equipment Manufacturer (OEM), provided two safety investigators to the team. Through this contact, the investigation team became aware of several Boeing tools in St Louis to help analyse the data that was gathered from the ACMI pod and specifically the recovered 10 hertz data from the DTD on CF188732. The investigation team used these tools to explore possible modes of failure that could reproduce the accident flight profile. This analysis revealed that a malfunction of the left stabilator, trailing edge down, could reproduce the accident profile.

As well, the US Navy's In-Flight Escape Systems Branch of the Naval Air Warfare Center Aircraft Division, using all available parameters from this accident, conducted ejection simulations.

1.16.5 QETE Tests

QETE did a number of tests and analysis for this investigation. Remains from flight controls, including parts of left and right stabilators, were analysed to find indications on flight control behaviour, failures and modes of operation during the accident sequence. Components from the hydraulic systems and some of the aircraft's gauges were also analysed.

Another set of tests that were undertaken relates to the ejection system. Various paint chips were found in a damaged area of the front left parachute riser. This equipment, and a control sample of paint from a helmet, were sent to QETE for analysis. This showed that the two samples matched, indicating helmet contact at the damaged point on the riser. Similar tests for other contact points with the ejection equipment showed contact between the outside of the right calf guard and the pilots G suit fabric.

1.16.6 Harness Suspension Tests

Parachute harness suspension tests were conducted at the Aerospace and Engineering Test Establishment (AETE), located in Cold Lake, in order to gain a better understanding of the dynamics involved between the pilot's body and the various parts of the parachute and harness, as it related to this accident.

1.16.7 Flight Test

A flight test was conducted by AETE on June 6, 2003, in an attempt to reproduce the possible wake turbulence caused by the lead CF188 ahead of the accident aircraft, with its possible effect on flight controls and flight path.

1.16.8 Escape System Risk Assessment

A risk assessment (RA) of the CF188 escape system was conducted in June 2003 by the Directorate of Aerospace Engineering Project Management, Fighters and Trainers (DAEPM (FT)). The object of this RA was to assess the risks associated with ejections at various speeds and altitudes, and to forward recommendations for the CF188 Escape System Modernization (ESM) program. This RA resulted in the revitalizing of the ESM, which was at the time in a somewhat stagnant state.

1.16.9 Vortex Study

NRC conducted a wake vortex study in an attempt to determine the likelihood and effects of wake turbulence imparted by the two CF188s ahead of the accident aircraft .

1.16.10 FCS Reset Study

A fleet wide study was conducted which specifically targeted the use of the flight control system (FCS) reset button by pilots, as well as the number and frequency of certain flight control malfunctions. This study used Aircraft Data Files (ADF) contained within the MSDRS for missions during the period of January 2002 to April 2004.

1.17 Additional Information

1.17.1 On Scene Search for MSDRS and MTC

Considerable efforts were made to locate the MSDRS and MTC because of the possible data this component may have contained. The recovery of the MTC was an objective of the RAS operation. All phases of the RAS operation were carried out under the direction of DFS staff by the 4 Wing RAS Team that was comprised of qualified (QL5 and above) MOC 500 technicians, the majority of which were current on the CF188.

The RAS operation included establishment of a grid on the accident scene about 1500 feet long and varying between 250 to 500 feet to either side of the extended flight path. The team completely searched, identified and tagged all of the aircraft parts and fragments in this grid. Subsequently, a backhoe was brought to the crater to remove all of the parts in the hole, dig an additional 4-5 feet on the sides and 6-8 feet to the rear of the hole so RAS personnel could sift through the materials removed in that operation. As well, a detailed sweep was conducted in the area where other electronic boxes and cards from the compartments adjacent to the MSDRS were found on the scene. Finally, a mine detector sweep was conducted in the area of highest probability using a single mine detector and a qualified operator in an attempt to locate the MTC. About 70 containers of debris were gathered on the accident scene by the RAS operation and transferred to 4 Wing Cold Lake for further examination. This debris was separated and individually examined by qualified experienced technicians to identify parts for further investigation. This final debris examination was also designed to find any pieces of the MSDRS electronic box or the MTC. None of these efforts were successful at recovering or identifying any of the MSDRS.

Approximately one month after the accident and following the general crash sequence analysis, another attempt was made to recover the MSDRS and the MTC. The search area was expanded and better metal detectors were procured for searching the debris field. These efforts proved successful and the MTC was located in debris removed from the crater during the original crater expansion, when the second effort team used shovels and sifting techniques to search the crater mud a second time.

1.17.2 Search for Aircraft Parts Down Track of Crash Site

Witness testimony, ACMI flight path data and the ACMI generated aircraft behaviour indicated that Things Falling Off Aircraft (TFOA) might have been a factor in the accident. Therefore the investigation team searched the area under the last 17 km of the accident aircraft's track for TFOA. The very thorough search of an area 17 km long by 1 km wide was conducted over multiple days from both the air (using CH146 helicopters) and the ground (using the 4 Wing GSAR team). No aircraft parts were found in this effort. Eventually, the flight control re-build on the accident scene revealed that parts of all flight controls were found in the impact area. In addition, other evidence and analysis showed that TFOA was unlikely to have been a factor, so the search for TFOA was terminated.

1.17.3 Useful or Effective Investigation Techniques

The impact point was extremely hazardous for multiple reasons. A daily hazard assessment was conducted to determine the level of Personal Protective Equipment (PPE) for each area in the debris field. Essentially, after the fire was extinguished, the debris field was divided into two areas which dictated separate PPE requirements for each site. The burnt area required full PPE (mask, suit, goggles and gloves), whereas elsewhere just mask and gloves were required.

Beyond the fire, carbon fibre, hazardous materials, ammunition and biohazard considerations, there was a wild life hazard (multiple bear sightings and wolf/coyote signs) that required constant attention and qualified armed guards.

All personnel were logged onto and off the site and these records should become part of each individual person’s service record.

Although the use of PPE was appropriate and well coordinated at the accident site, such was not the case during the wreckage analysis at the 1 AMS hangar. Some confusion existed with regards to the appropriate level of protection to be adopted when sifting through and handling wreckage parts. In general, the level of PPE to be adopted should be dictated by the investigator-in-charge (IIC), in consultation with the on-scene controller emergency response (OSCER) and the Wing/Base/Unit Recovery and Salvage Officer (RASO).

2 ANALYSIS

2.1 Wreckage and Documents Analysis

2.1.1 Aircraft Systems

As described in section 1.12, the investigation team encountered a delay of several days before they could begin to retrieve the wreckage parts. During that timeframe, some of the key pieces, such as stabilator actuators, were submerged in the water-filled crater or otherwise exposed to the subsequent wet weather, resulting in the degradation of evidence to various degrees.

Nonetheless, the technical investigation team was able to retrieve a large number of parts associated with many of the aircraft systems. From initial witness accounts as well as ACMI data, it became readily apparent that particular attention would focus on the aircraft’s flight controls. Retrieval, gathering, and initial analysis were performed on site. The recovered parts were then shipped by ground transport to 4 Wing Cold Lake for further analysis at 1 AMS facilities.

Components of the following aircraft systems were analysed, with no evidence of malfunction or contribution to the accident sequence:

a. Air Data system;
b. Avionics system;
c. Environmental Control system (ECS);
d. Engines (ground idle at time of impact);
e. Fuel system;
f. Hydraulic system;
g. Instruments;
h. Landing gear (retracted at time of impact);
i. Secondary Power systems;
j. Main aircraft structures;
k. Weapons (none missing); and
l. Wingfold system (wings were unfolded at time of impact).

Parts of all flight control surfaces were recovered (see Fig 4). The following deflections were estimated from measurements taken on the available parts of the flight controls and their actuators (see also Fig 5):

a. Right hand control surfaces:
  1) Inboard leading edge flap (LEF): 4.5 deg down;
  2) Outboard leading edge flap: 7.5 deg down;
  3) Trailing edge flap (TEF): 2 to 4 deg up;
  4) Aileron: 1 deg down;
  5) Horizontal stabilator: 0.6 deg leading edge up;
  6) Rudder: no data

b. Left hand control surfaces:
    1) Inboard LEF: neutral;
    2) Outboard LEF: neutral;
    3) TEF: 2 deg up;
    4) Aileron: 4 deg up;
    5) Horizontal stabilator: 4.6 deg Leading edge up;
    6) Rudder: no data

c. Speed brake:
    1) Closed

Due to the level of destruction involved with this accident, neither the two flight control computers, nor their electronic components were found. Several other electronic cards from various systems were located, in various states. None of these cards were useable in terms of data retrieval.

The behaviour of the horizontal stabilators became the subject of extensive analysis and research as soon as the flight profile playback from ACMI was compared to both Boeing simulator trials and past occurrences from Canada and the United States. This analysis is described further in section 2.2.

2.1.2 Maintenance records review

Records showed the accident aircraft had flown an above-average number of flight hours since May 2003, which indicates a high rate of serviceability. This was correlated by information collected during interviews. All aircraft maintenance documentation was completed as required.

As well, no overflown inspections were noted, or any lifed items expired. All of the squadron’s tools and aircraft maintenance support equipment (AMSE) were accounted for.

The MSDRS archive analysis did not reveal any out-of-the-ordinary or repeated maintenance activities carried out on the aircraft since its last supplementary inspection, which was carried out on October 24, 2002.

Lastly, personnel who carried out maintenance activities on CF188732 since the same supplementary inspection were qualified and authorized to do so.

2.1.3 Fluid Samples

As mentioned in section 1.16.1, no fluid samples were recovered from the accident aircraft due to the degree of destruction and post-crash fires. Samples of fuel, hydraulic fluid, oxygen, and engine oil were taken from servicing sources in Cold Lake, and were sent to the Alberta Research Council for analysis.

Normally, fluid sampling analysis is required to be performed by QETE in Gatineau, Quebec (Ottawa area). However, a decision was made to expedite the analysis in order to avoid undue delays to the Maple Flag exercise. Although tests conducted showed no anomalies, a review of test reports conducted later by QETE revealed that not all required tests were done. However, based on tests conducted, fluids were not assessed as contributors to the accident.

2.2 Flight Profile Analysis

2.2.1 Flight Profile Description

As far as flight controls and abnormal aircraft behaviour are concerned, the accident profile is essentially composed of two distinct events.

a. The first event. The first event began after a steady period of straight and level flight, at approximately 3000 feet above ground level (AGL) and 480 KIAS. It was characterized by a rapid roll to the right, approximately 45 degrees, and accompanied by a peak negative G of –2.5. The aircraft then slowly recovered to a level attitude, still experiencing minor pitch oscillations.

b. The second event. After 3-4 seconds of relatively level flight, the second event occurred when the aircraft began a very abrupt negative G barrel roll to the right, completing a complete roll in about 3.5 seconds. The peak negative G value recorded during the initial portion of this first roll was –6.3, with subsequent values varying between –2 and –5. As the aircraft reached level flight again, a sudden stop in roll occurred, and the aircraft remained relatively level for approximately 2 seconds, after which the right roll resumed, with an average of about –3 G, and a roll rate which progressively decreased until the end of transmitted data, where the aircraft was basically inverted.

It is estimated the pilot initiated ejection shortly after the sudden stop in roll during the second event. The estimated flight parameters at ejection were the following:

a. 76 deg right bank;
b. -30 deg pitch;
c. -2.5 G;
d. 465 KIAS; and
e. 1250 feet AGL.

2.2.2 CF188 Flight Controls Summary

The CF188 Hornet flight controls system is of the fly-by-wire type (or digital flight controls). In other conventional, older style systems, the pilot's controls (stick and rudder pedals) are directly or indirectly mechanically linked to the control surfaces of the aircraft by an assembly of cables, pulleys and push rods.

In a fly-by-wire system, the pilot's inputs are sent to a set of computers, which then send command signals to actuators, which in turn move the various control surfaces. Only in a seriously degraded mode of operation does the pilot have any direct link to the control surfaces themselves.

The normal mode of operation of the CF188 flight control system is called Control Augmentation System (CAS). In this mode, the two Flight Control Computers (FCCs) continuously process a large number of inputs from various sensors, as well as pilot control inputs. This enables the FCCs to have a continuous "awareness" of the environment, such as altitude, temperature and air density, as well as the aerodynamic status of the aircraft, with variables such as airspeed, attitude, accelerations and angle-of-attack.

CAS mode maximizes aircraft performance and manoeuvrability in response to the pilot's inputs. Refer to Fig 6 for an overview of CF188 flight control components.

The FCCs also have two degraded modes of operation. The first, and most benign, is Direct Electrical Link, or DEL. In this mode, command inputs from the pilot are still processed through the FCCs, but with a reduced number of computed variables, and a somewhat reduced effectiveness.

The second, which is of prime interest in this investigation, is Direct Mechanical, or MECH mode, and is only applicable to the horizontal stabilators. In this mode of operation, the FCCs are now completely bypassed and provide no control outputs. Instead, a set of direct mechanical linkages from the pilot's control stick provide inputs to the hydraulic Main Control Valve (MCV) of both horizontal stabilators. Pitch control is significantly degraded in MECH mode, and this instability often results in pilot induced oscillations (PIO). A degree of roll control is provided by differential deflections of the horizontal stabilators. In essence, MECH mode is incorporated to provide a last resort, emergency flight control mode in case of multiple failures in the system.

For instance, should the aircraft suffer a major electrical failure, such as loss of both engine-driven generators, or an unlikely series of multiple failures in both FCCs, the only flight control surfaces left to fly the aircraft would be the stabilators, through MECH mode.

It is important to note that a combination of modes can occur simultaneously, depending on the nature of the failure. The FCCs basically control the three main aircraft motion axis independently; pitch, roll and yaw, and will move all available aircraft control surfaces as required to affect the desired motion in each axis. It is therefore possible to have the pitch axis in MECH and the roll and yaw axis in CAS or DEL.

After some analysis, the investigation team became very interested in the following combination of modes: roll and yaw axis in normal CAS mode, and pitch axis in MECH, further referred to as MECH-ON-ON (see sections 2.2.2 to 2.2.6).

The CF188 pilot's checklist includes procedures to deal with various flight control anomalies. The pilot can reset the FCCs in an attempt to restore CAS mode via the FCS reset button, located on the left side console of the cockpit, behind the throttles.

In dealing with FCS malfunctions, the recommended procedure is to stop any on-going manoeuvring, climb to a safe altitude, and decelerate the aircraft, so as to establish a safer and more predictable flight profile from which to conduct checklist items. Pilots would therefore be expected to make a "Terminate" or "Knock-it-off" radio call to alert other formation members of their situation as they leave the tactical scenario of the mission to address the FCS problem.

More specifically, the "red page" MECH ON emergency checklist dictates the following 2 items:

1. Speedbrake…………..CHECK IN
2. Airspeed………………Decelerate slowly to below 400 Kts/Mach 0.8

The pilot is then directed to further items included in the "yellow page" checklist. In short, these items call for the pilot to identify the failure type, then, should an FCS reset be warranted, to climb to a safe altitude and establish an airspeed between 160 to 180 kts if the flaps are in the HALF position, or 200 to 300 kts if the flaps are in the AUTO position (the latter being the case for the accident aircraft). The next step is to press the FCS reset button in an attempt to restore CAS mode.

The FCS will revert to MECH mode for several reasons including a flight control hardware problem, hydraulic contamination within the stabilator actuator, position sensing or feedback mechanism problems, or multiple failures of the FCC's themselves. If the cause of the initial reversion to MECH is still present when the FCCs attempt to restore CAS mode, the FCC's will quickly (within approximately 30 milliseconds) return the stabilators back to MECH mode.

For instance, should a failure occur which creates a sudden uncommanded deflection of one stabilator, the FCCs will shut down all 4 hydraulic shutoff valves (SOVs) related to CAS functioning within each stabilator, thus reverting both stabs to MECH mode. It is important to understand that, although still hydraulically moved, each stabilator main ram actuator now follows a different command path which bypasses most of the normal features and components (both physical and electronic) used by CAS mode. Upon pressing the FCS reset button, the FCC's will re-engage and return the stabs to CAS very quickly (less than 1 second), powering-up the SOVs and therefore re-enabling all the normal CAS components. Should the failure which created the first sudden deflection still be active or re-occur, the uncommanded deflection is likely to be repeated, the FCCs will detect the anomaly, and revert the stabs to MECH mode again.

In essence, by design, CAS mode cannot function with uncommanded or erratic behaviour of the control surfaces. By way of constant monitoring, should tolerances be exceeded, the FCCs will disengage CAS and, in the case of the horizontal stabilators, engage MECH mode.

Lastly, MECH mode has its own stabilator scheduling, based on two basic parameters: control stick position, and flap position (auto, or half/full). When MECH is first engaged, the stabilators' position is grabbed as is, and then slowly driven at an average rate of ¾ deg/sec to the position it should be at based on the MECH schedule. This notion will also be of interest in the next sections.

2.2.3 Boeing Simulator Profiles

The investigation team sent members to Boeing, St Louis, USA, to explore the flight path data using the six-degree of freedom (6DOF) simulators available in that location. The 6DOF is a computer-based emulator with the capability to predict aircraft behaviour (flight path) given failed systems or failures of parts of systems using aircraft flight parameters, configuration and flight conditions.

Based upon the 10 Hertz ACMI data, a number of possible flight scenarios that could have caused the observed aircraft flight path leading to the crash were suggested. In order to validate the plausibility of each of these scenarios, 6DOF computer modelling for an F-18 A model, in the same stores configuration and at the same flight conditions, was conducted by Boeing specialists for each scenario.

With the 6DOF data obtained from this process, a number of profiles were developed and attempted in the flight simulator. Of note, the flight simulator in St Louis is aircraft accurate. This means the simulator will behave like a real aircraft given the data input from the emulator.

During the simulator sessions, various aspects of the simulated event were changed in an attempt to bring the simulator flight characteristics into close agreement with observed ACMI data. Perfect agreement between simulation and the actual flight conditions was not the objective, only developing reasonable and plausible mechanisms to explain the event. When this was achieved, simulator testing was ceased. It must be acknowledged that the ACMI was not designed as an accident re-creation tool (see section 1.11). Under extreme flight conditions, the ACMI recorded data may be in error (possibly grossly). Nevertheless, these simulator trials resulted in the following high level of confidence conclusions:

1. A pilot in a normally functioning F-18 could not induce the aircraft to react according to the incident flight profile;

2. Single failure of the LEF, Ailerons or Rudders (all flight control surfaces) could not induce the aircraft to react according to the incident profile; and

3. A single failure of the left horizontal stabilator, with a full (10.5 degrees) trailing edge down deflection, caused by an as yet undetermined mechanism, could induce the accident profile.

Several trials were conducted in order to simulate a failure of the left stabilator as described above, using both CAS and MECH modes of flight control operations.

Although it was technically improbable that the stabilators would remain in CAS mode after a large uncommanded deflection (and thus a large split between command and output), the profile was executed using the exact flight parameters of the accident, with the left stabilator driven fully to 10.5 deg trailing edge down and held there, and the right stabilator remaining in CAS. The initial resulting G excursion was only to –3.8 G, slowly reducing over the next 5 seconds to +1G. The roll rate climbed rapidly to 60 deg/sec and remained there all the way to impact. In effect, the right stabilator reduced the pitch rate by being driven as a result of CAS command opposite to the left stabilator, resulting in a reduction in negative G.

Trials conducted with the same inputs, but with both stabs reverting to MECH after driving the left one to 10.5 deg trailing edge down, consistently produced a flight path very similar to the accident profile. The maximum G excursions obtained were –7.2, with sustained values of –5.

Using what became the most likely failure mode, investigators then ran a simulation of the entire accident flight profile, as described in section 2.2.1. The simulation result was extremely close to the accident profile, even when run repeatedly.

The first event was likely caused by a left stabilator hardover failure to approximately 6 deg trailing edge down (TED), with the right stabilator remaining in its normal 1 deg TED, and the FCS reverting both stabs to MECH almost simultaneously. The pilot was then able to recover to a level attitude, with some pitch and roll oscillations as the MECH schedule drove the faulty stabilator back to neutral at the standard rate of ¾ deg/sec.

The second event was induced with a second hardover failure of the left stabilator, this time to full TED deflection (10.5 deg) and MECH mode engaged. The left stabilator was then allowed to schedule itself back to normal MECH position at a rate of ¾ deg/sec while the right stabilator remained at its normal position throughout. The simulator pitched down to -6.5 G and rapidly rolled to the right at a rate very similar to the accident profile. The negative G and roll began to reduce almost linearly as the stabilator asymmetry was being corrected, again matching the accident data.

It quickly became obvious that the sudden pause in the rapid roll of the second event, after the first 360 deg, was likely caused by pilot input. By pulling approximately ½ aft stick, the simulator's roll rate reduced dramatically, and the G reversed to +2 momentarily. It is believed that the pilot then took advantage of this pause to initiate his ejection, which was duplicated by the simulator test pilot. Upon releasing the controls to eject, the G returned to approximately –4 and the roll rate increased to 40 deg/sec, again very close to the accident profile.

The simulation runs consistently ended with an impact with the following parameters, which are very close to the data collected from the accident aircraft ACMI.

1. -2 to –3 G;
2. 20 deg/sec roll rate;
3. 25 to 40 deg dive inverted;
4. 420 to 440 KIAS airspeed.

In all, the Boeing simulator trials were extremely helpful in understanding the mechanisms involved with the accident profile and provided investigators with a high degree of confidence in the results.

2.2.4 Stabilators Analysis

From the information gathered during both initial wreckage analysis as well as Boeing simulator trials, great importance was placed on the horizontal stabilator actuators to try to resolve their mode of operation at impact (CAS or MECH). To this end, the collected wreckage parts associated with both stabilators were sent to QETE for detailed analysis. The recovered actuators, which are very complex mechanical assemblies, were both heavily damaged.

Photographs, radiographs and tomography (CT) scans of both stabilator actuators were taken prior to disassembly. An area of primary interest within the actuators was the Mode Selector Valve (MSV), the position of which could indicate whether CAS or MECH mode was prevalent at the time of initial impact.

Fig 7 shows a radiograph of the right hand stabilator actuator. The MSV is the long, narrow horizontal shaft at the top of the actuator, the middle of which is highlighted by a red circle. In CAS mode, hydraulic pressure pushes the MSV spool to the right, compressing the spring. Initial indications seemed to show the possibility of MECH mode since there appears to be some translation of components of the MSV, towards the left, even though the spring is compressed.

Disassembly showed that the MSV sleeve had fractured which allowed a portion of the sleeve to move to the left. It is most probable that impact forces resulted in the fracture. Examination of the spool showed an impact mark on its surface, created by the sharp edge of the fractured sleeve.

The position of this mark defines the relationship of the MSV spool and the sleeve at the moment of impact, and is the position corresponding to CAS mode. The sleeve is held in position within the valve body by a shoulder on the right hand end, thus after the fracture, the right piece of the sleeve was still in its correct position. The broken-off left piece of the sleeve was free to move in its bore in the valve body, and as was evident in the post crash radiograph, had moved to the left (i.e. forward with respect to the aircraft's longitudinal axis) under the impact forces.

From this evidence, the investigation team has a strong indication that the right hand stabilator actuator was in CAS mode at the time of initial impact.

Similar analysis was performed on the remains of the left stabilator actuator. Unfortunately, it was found in a considerably worse condition than the right stabilator, due to exposure to the intense post-crash fire, and subsequent immersion in water, in the impact crater, for several days. The level of corrosion precluded any conclusive position indications. Therefore, it is unknown whether the left stabilator actuator was in CAS or MECH at the time of initial impact. The functional philosophy of the flight controls precludes a split mode of operation between both stabilators. Should one of them cause a MECH reversion, then both stabilators will automatically be reverted to MECH.

Another area of the left stabilator, which was analysed by QETE, was the Linear Variable Differential Transducer (LVDT) of the main actuator ram. The LVDT in this case acts as a feedback loop to the flight control computers to monitor the proper movement of the ram in conjunction with computer commands. The failure of such feedback mechanisms was another area examined for possible contribution to the accident scenario. However, no abnormalities were found, and it was determined that the left stabilator LVDTs were in the correct position at the time of impact.

In summary, none of the analysis performed on the stabilator actuators revealed any evidence of malfunction which could have contributed to the accident. Furthermore, the investigation team has obtained no hard evidence of any other flight control malfunctions from the wreckage analysis.

Nonetheless, based on the ACMI flight information available, it is believed a problem of unknown origin did occur with the flight controls pitch axis of the accident aircraft. Historically, there can be multiple causes of a MECH reversion and sometimes the problem is only transient in nature.

Investigators were then left with conflicting conclusions between the Boeing simulator trials and the stabilator analysis form QETE. The first clearly demonstrated that the most likely scenario involved a hardover failure of the left stabilator, with an associated MECH reversion of both stabs all the way to impact. The second brings physical evidence of CAS mode at impact.

Further analysis conducted at the 1 AMS flight control lab in Cold Lake, using serviceable stabilator actuators, revealed the possibility of the actuators being forced from MECH to CAS mode during the initial ground impact phase of the accident.

Although it is generally thought that a high speed impact is instantaneous, the impact can be broken down into a continuous chain of events (much like the automotive industry does during its crash certifications). The initial deceleration of the aircraft (in this case) begins when the nose first makes contact with the ground. The rest of the aircraft then crumples and passes on the deceleration forces to the other components further behind.

Assuming a relatively linear deceleration throughout the impact, it then took approximately 60 milliseconds from the moment the nose first made contact to the time the stabilator actuators came to a stop.

As mentioned in section 2.2.2, when the FCCs revert the stabilators to MECH mode, power is removed from the hydraulic SOVs, which are spring loaded to the closed position. The analysis conducted at 1 AMS demonstrated the possibility that the deceleration forces may have overpowered the springs keeping the SOVs closed, allowing hydraulic pressure to flow to the stabilator MSV (although for a very short period of time), thus causing its translation to the CAS position just before the actuators themselves made ground contact, subsequently causing the MSV spool fracture as described above.

Although this latest description will only remain a possibility due to the complex nature of the post crash damage, the investigation team believes the only way the aircraft could have sustained the accident flight profile is under MECH mode, yet the stabilator actuator analysis performed by QETE is deemed both accurate and valid.

Whether the aircraft impacted in MECH or CAS does not change any of the preventive measures derived from this accident. The investigation has not yielded any specific cause for the hardover failure of the left stabilator, and thus the investigation team cannot offer any recommendations on how to prevent a reoccurrence of this type of failure. This investigation has however brought forth many other recommendations as described in section 4 of the report.

2.2.5 Wake Turbulence

As described in the report synopsis, the accident aircraft was number 3 of a 4 ship flying in card formation. The lead element was in the process of rejoining in a closer formation approximately 1.4 miles in front of aircraft CF188732 when the accident flight profile began.

A study of the possible effects of wake turbulence on the accident aircraft was conducted by NRC using available ACMI flight profile data of all formation aircraft, as well as geographical and meteorological information at the time of accident.

Based on mathematical modelling of aircraft vortices, there is a high probability that the accident aircraft was affected by the wake of the preceding aircraft at least once during the two events described in section 2.2.1. At the time of the onset of the first event, aircraft CF188732 was 7600 feet behind, 150 feet below and slightly right of the track of the lead aircraft, with winds coming from the left at 20 knots. This places aircraft CF188732 within the predicted cone of vortex. Furthermore, the rejoin manoeuvre of the number 2 aircraft on the lead involved a 4 G turn. An aircraft pulling G creates a lot more lift, therefore much stronger vortices. A few seconds later, at the time the second event (violent barrel roll) occurred, the accident aircraft had flown to approximately the same point in space where the strongest vortex would be encountered. The lead element was then 6200 feet ahead, 700 feet above and slightly to the left of the accident aircraft.

An independent report from Boeing predicted the maximum vertical acceleration deviation due to the wake turbulence would be in the order of -0.5 G, and that roll excursions such as the one encountered during the first event (approximately 45 degrees) could be expected. This was supported by a flight test conducted by AETE on June 6, 2003, during which a CF188 following a single lead aircraft of the same type at roughly the same distance experienced roll excursions of approximately 45 deg and minor pitch oscillations.

Based on this data, it is not believed the wake turbulence of either the lead aircraft, or the combination of the rejoining element would be the sole reason to induce the negative rolling G regimes encountered in either event. However, it is conceivable these wake encounters had an exacerbating effect if combined with the suspected flight control malfunction, or a transition between modes of operation of FCCs.

2.2.6 Past Occurrence Correlations

Flight control malfunctions do occur in fly-by-wire aircraft. A search for correlations between this accident and past occurrences was conducted, using data from the Canadian Forces Flight Safety Information System (FSIS), as well as data provided by the Safety Centres of other CF188 users.

This research revealed that the most severe flight path deviations associated with flight control malfunctions usually involve the horizontal stabilators. In many instances when the stabs reverted to MECH mode, pitch excursions occurred. As well, some documented attempts to reset the FCS from MECH to CAS resulted in uncommanded deflections of the stabs, creating violent, negative G flight profiles.

Two occurrences of particular interest involved F18s of other nations. In the first occurrence, the aircraft sustained a failure of both stabilators into MECH mode. The pilot stabilised the aircraft at 16,000 feet above sea level (ASL), and decelerated and configured the aircraft flaps as per the checklist before attempting an FCS reset. Upon pressing the reset button, the aircraft began a violent, right hand, sustained negative G barrel roll, resulting in the rapid loss of 8000 feet before the pilot could recover to a straight and level attitude. The investigation showed this flight path was caused by a sudden, uncommanded deflection of the left stabilator, trailing edge down. In effect, the reset from MECH to CAS had failed with the reintroduction of the failure mode resulting in a stabilator hardover and a return to MECH. This occurrence has very significant similarities to the profile of aircraft CF188732, and supports the investigation team's Boeing simulator trials.

The second occurrence also highlights the possibility of pitch and roll excursions. In this event, the aircraft had sustained a left stabilator failure immediately following take-off, creating a MECH ON condition. Following an uneventful reset at altitude, a second failure occurred later while the aircraft was flying in a straight and level attitude, at an altitude of 10,000 ASL and 410 KIAS. During this second failure, the aircraft pitched over abruptly and rolled to the right, sustaining –1.8 G and 450 degrees of roll before the pilot regained control. An associated MECH ON caution was observed. After the recovery, the aircraft remained in MECH with heavy aft stick force required to maintain level flight. Two subsequent reset attempts failed, the second of which was accompanied by a right and forward sudden stick slap, along with further nose down and right roll attitude changes. The aircraft was successfully recovered in a MECH-ON-ON condition, half flap configuration to an arrested landing. The maintenance troubleshooting was unable to reveal the exact cause of the failure.

2.2.7 FCS Reset Study

As mentioned in section 2.2.2, CF188 pilots can attempt to reset the flight control computers via the FCS reset button on the left side console. Since transient uncommanded deflections of flight controls are a possibility during FCS resets, the checklist procedures requires a “climb to a safe altitude”. However, neither a specific altitude, nor range of altitudes were present in the checklist at the time of the accident. It is however common knowledge amongst CF188 pilots that such resets should not be attempted in the low-level arena.

Although the aircraft was not in the type of flight profile dictated by the pilot's checklist, investigators attempted to establish the relative likelihood of a CF188 pilot resetting the FCS in such a situation.

An exhaustive study of Air Data Files from MSDRS downloads was initially conducted by the GasTops company, already involved with MSDRS data software. Data from over 29,000 missions flown from January 2002 to April 2004 was analysed to specifically pinpoint instances where pilots pressed the FCS reset button, along with the associated conditions at the time (airspeed, altitude, configuration, etc). Only airborne resets were to be counted, since it is common for pilots to have to reset the FCS during the aircraft start sequence on the ground.

An initial report was published in the summer of 2004 which presented initial correlations supporting the possibility of an FCS reset initiated outside of checklist parameters. In light of these initial findings, a Flight Safety Investigation Situation Report (Sitrep) was disseminated In October 2004 (Sitrep #12) which highlighted concerns, as well as proposing some recommendations to amend pilot checklist and procedures.

Initially, the study showed a relatively high number of FCS resets conducted outside the checklist envelope. Subsequently, the data files containing only MECH ON cautions were further analysed by the NRC FRPC, where inconsistencies with the original algorithm were found. A comprehensive review of the data determined that only one actual, confirmed airborne MECH ON FCS reset occurred between January 2002 and April 2004. Due to the large amount of data, the investigation team decided that it would not be worthwhile to examine all of the other types of potential FCS resets. However, the initial study did reveal some valid data points which demonstrated that actual resets had been initiated outside the checklist envelope.

Complementary to the ADF files analysis, investigators contacted several members of the CF188 flying community in order to determine the operators' point of view on this issue. From these informal interviews, it became apparent that some pilots may have pressed the FCS reset button while airborne, and outside of checklist parameters.

A review of the CF188 Data Management System (DMS) and FSIS showed that some airborne flight control malfunctions were not entered in DMS, nor within the Flight Safety system. When reviewing the fleet's history from 1982 to the fall of 2004 for airborne MECH ON reversions, the following discrepancies were revealed :

a. A total of 12 airborne MECH ON reversions were reported in FSIS, 2 of which were absent from DMS;
b. A total of 11 airborne MECH ON reversions were reported in DMS, 3 of which were not reflected in FSIS;
c. 15 total confirmed MECH ON's could be derived from both databases from 1982 to the fall of 2004.

In summary, although the confirmed numbers of cases were significantly reduced by using a much tighter analysis provided by the FRPC, the recommendations distributed in Sitrep 12 still apply to the current situation in the CF188 community. Accordingly, the checklist amendments proposed were implemented in February 2005.

2.2.8 Plausible Accident Scenario

Due to the lack of hard data, the investigation team was unable to definitively determine the cause of the flight profile of the accident aircraft. However, based on the research and analysis conducted during this investigation, investigators are confident the following scenario represents the most plausible explanation for this accident:

a. The initial event began with a failure of the flight control system pitch axis, which created an uncommanded deflection of the left horizontal stabilator, trailing edge down. This created the first of two negative G, rolling manoeuvres to the right, with peak values of 45 deg right bank and –2.5G's. Sensing a discrepancy in the left stabilator, the FCCs commanded both left and right stabilators in MECH mode. The pilot was able to recover the aircraft to a level attitude and maintain aircraft control, still with the stabilators in MECH. It is conceivable the wake turbulence of the lead aircraft may have contributed to either the onset, or the rolling motion, or both.

b. The pilot realised the pitch axis was now in MECH mode, through the aircraft automated voice alert *"Flight Controls, Flight Controls"*, and the associated MECH ON annunciation on the left Digital Display Indicator (DDI). At about this point in time, aircraft #2 was rejoining with the lead.

c. It is then conceivable that the accident pilot might have elected to press the FCS reset button in an attempt to clear the malfunction.

d. Immediately following the reset, the FCCs attempted to return the aircraft's pitch axis to CAS mode, and the left horizontal stabilator sustained another deflection in the same direction as the first event, but at an even greater angle, sending the aircraft in a violent, negative G barrel roll to the right. It is most probable that, at this point, the stabilators returned to MECH mode. The sudden and very high amount of negative G (over –6 initially), coupled with the rapid roll rate, was physically overwhelming, and the pilot was most likely seriously disoriented initially. It is also possible that the encounter of the combined wake turbulence of both lead aircraft at this time might have contributed in some way to the event.

e. Towards the end of the first 360 deg of roll of the second event, the pilot was able to apply sufficient flight control inputs to effectively stop the rolling motion and negative G. It is reasonable to believe the pilot took advantage of that pause to locate the ejection handle and initiate the ejection sequence. As his hands left the controls, the aircraft resumed the negative G right hand barrel roll. By the time the ejection was initiated, the aircraft was already in a steep bank angle to the right with about –2.5G, as described in section 2.2.1.

f. At some point between the time the ejection sequence was initiated and the parachute descent was stabilized, the pilot sustained a fatal injury. See details in section 2.3 of this report.

g. Although the aircraft continued to roll and sustain negative G all the way to impact, a very notable, progressive decrease in roll rate occurred between the time the pilot levelled the wings after the first complete roll and the end of ACMI data. It is believed that the stabilator asymmetry was being corrected by the MECH mode schedule, at the standard rate of ¾ deg/sec. This is supported by the estimated position of the stabilators at impact (as described in section 2.1.1), as well as the Boeing simulator trials. Taking into account the estimated deflection of the left stabilator required to produce the main event and the theoretical time required by the MECH schedule during a reset to cancel-out this deflection, there is indeed a close match with the actual 8 to 10 seconds duration for the full second event, as derived from the ACMI data.

Based on available evidence, analysis and research, the investigation team believes the most likely scenario for the accident of aircraft 188732 involved a voluntary reset of the FCS by the pilot. It is important to note that no hard evidence could be found to support this hypothesis. Rather, this investigation rests with the most plausible scenario.

In summary, this scenario is supported by the following analysis:

a. The comparison of the ACMI derived flight profile with the Boeing 6DOF simulator trials;

b. Significant similarities with other documented occurrences of MECH reversions and FCS resets, along with associated pitch, roll, negative G regimes and loss of altitude;

c. The FCS reset study, which supports the possibility of an FCS reset performed outside of the checklist envelope; and

d. The effect of impact deceleration on the stabilator MSV, substantiating QETE’s analysis of the right stabilator actuator.

2.3 Ejection & Aircrew Life Support System Analysis

2.3.1 Ejection Envelope

The CF188's ejection seat incorporates an altitude sensing component which will vary the timing of the sequence of events once the seat leaves the aircraft.

In all cases, a drogue chute will be deployed from the seat's headbox, behind the pilot's head, approximately 0.5 second after the seat catapult is fired (i.e. very shortly after the seat leaves the aircraft). The purpose of this drogue is to help stabilize the seat and to decelerate it prior to the main parachute deployment. As well, the drogue acts as a "tractor" to pull the main parachute out of the headbox.

Should the pilot eject at a high altitude, the drogue chute will stay attached to the seat and the main parachute will be inhibited to ensure excessively high opening shock loads are not permitted to injure the pilot or damage the parachute. Once the seat reaches an altitude of approximately 13,000 feet MSL, the drogue pulls the main parachute out of the headbox for deployment, and the seat separates from the pilot and parachute.

If the ejection is initiated at an altitude between approximately 13,000 feet and 7500 feet MSL, a G sensing component will come into play, and main parachute deployment will be inhibited until either the seat reaches 7500 feet, or it has decelerated to less than 3 G, whichever comes first. The purpose of this is again to protect the pilot from a violent opening shock of the main parachute at high speeds.

Lastly, the low altitude envelope of the ejection seat is defined as 7500 feet MSL and below. Should the pilot eject at or below 7500 feet MSL, the altitude and G limitations are removed, and the drogue chute will only have approximately 1 second to slow and stabilize the seat prior to main parachute deployment. This feature is in support of the seat's so called "zero-zero" capability, which means it is certified for ejections down to zero airspeed, zero altitude. In the low level arena, the speed of the aircraft at the time of ejection becomes a critical parameter. The higher the airspeed, the more violent the opening shock imposed on the pilot from both the drogue and main parachute deployment.

At high speeds, the pilot is subjected to large windblast forces upon exiting the cockpit. These forces can damage his ALSE and cause injuries.

The investigation of the escape system performance in this accident involved a frame-by-frame review of the lead aircraft's HUD tape to determine that the bailout tone (i.e. emergency IFF on UHF Guard), which began as soon as the ejection handle was pulled and continued until ground impact, was 3.2 seconds. Using this time and flight path data from the ACMI pod, a detailed analysis was undertaken to determine the probable ejection initiation point. Initial calculations, subsequently supported by Martin-Baker and Navair calculations, determined that the pilot initiated ejection from the aircraft within the envelope of the ejection system. However, the aircraft was in a –2.5 G, rolling flight regime, with a steep bank angle, at high velocity (about 465 KIAS - maximum certified velocity of the escape system is 600 KIAS) and below the 7500 feet MSL threshold described above.

Analysis of the escape system components, including the ejection seat, harnesses and parachutes (drogue and main), was conducted by both Canadian Forces and Martin-Baker experts. The Canopy jettison system functioned in a normal manner, as did the ejection gun and rocket motor. Both drogue and main chutes were assessed as having deployed and inflated normally, and showed normal signs of wear and tear post-ejection. The ejection piston, on which the seat rides as it is propelled out of the cockpit, revealed evidence of the seat being thrown forward, which is consistent with a substantial amount of negative G, or large bunting motion of the aircraft. The harness retraction and leg restraint were activated normally; however some anomalies were noted.

2.3.2 Harness and Posture

Ejection seat pilots are aware of the importance of adopting a proper body posture before initiating the escape sequence. The very high amount of G's imposed on the pilot during the catapult and rocket motor phase of the ejection can create injuries even with a good posture. Given the –2.5 G condition at the time of this ejection, it is likely the pilot had difficulty adopting the ideal position. In addition, any strap-in deficiencies, such as an improperly tightened harness, would have created a lifting of the pilot's body from the seat, which in itself is a very precarious position from which to initiate ejection.

In addition, a rolling negative G regime may create a situation where the pilot's limbs, particularly the legs, are not in the ideal position, i.e. lifted above their normal positions. This condition may have contributed to the pilot's injuries and the seat's aerodynamic instability. For example, the ALSE analysis revealed evidence of contact between the pilot's right leg and the outside portion of the thigh guard of the seat bucket.

The investigation revealed that the full strap-in procedure was not being conducted as per the manufacturer's specifications. It quickly became obvious that this was not limited to the pilot of this investigation, but was common practice fleet-wide, and resulted in the shoulder harness not being fully and properly adjusted. An ill-adjusted harness will result in a degraded pilot restraint during ejection, as well as an excessive "triangular void" above the pilot's shoulders once the pilot is suspended in the harness.

Parachute suspension tests, using a person of relatively similar size and weight and wearing the same type of harness and flight gear as the accident pilot, were carried out at AETE. These tests demonstrated that this triangular void, or space, could be in the order of 7 inches, when using the deficient strap-in procedure mentioned above. This phenomenon is not readily apparent to the pilot when strapped in the cockpit. As measured during the tests, this space can be minimized, but not completely eliminated, by following the full strap-in procedure.

Other than the strap-in procedure, three main deficiencies were noted with respect to the physical installation of straps and harnesses:

1. The leg restraint right side snubber line was 3 inches longer than the left side line. Trials conducted at AETE highlighted the possibility that loose lengths of snubber line resulting from improper tightening could float up in negative G flight and subsequently end-up migrating outside of the seat enclosure. It is believed that such was the case with the right hand snubber line, which may have relocated itself beyond the thigh guard to the right. Subsequently, as the seat traveled up the rail during ejection, it is believed the snubber line forcefully pulled the pilot's right leg outside the seat bucket, which created an obstruction to the full retraction of the snubber line. This is consistent with physical evidence of contact found on the pilot's right leg portion of the G suit and right hand boot, as well as evidence found on the right hand, outside portion of the ejection seat.

2. The left side lower harness lock stitching was broken, allowing the harness to open by approximately 4 inches at some point during the ejection sequence (refer to Fig. 9 and 10).

3. The rigid seat survival kit (RSSK) attachment strap was incorrectly routed <u>through</u> the lower lock harness webbing instead of outside the webbing, which showed signs of damage.

It is believed that the combination of degradation to the left side lower harness lock stitching due to the position of the oxygen pipe attachment nut from the RSSK, as well as the improper routing of the RSSK attachment strap, created a weakness which resulted in the failure of the stitching during the onset of the opening load from the main parachute. This resulted in a loosening of the left side of the harness and a significant increase in the triangular void on the same side.

2.3.3 Injury Mechanism

The In-Flight Escape Systems Branch of the US Navy's Naval Air Warfare Center Aircraft Division performed ejection simulations using all available parameters for this accident. These parameters included the pilot's anthropometrics, weight, ALSE worn at the time, winds and flight parameters at the time of ejection. These simulations offered investigators an approximation of the altitude, speed and load factor (G's) at various stages of the pilot escape sequence.

It must be noted that these simulations are limited by some variables which are unique to the Canadian version of the ejection seat, and thus not part of the normal model validation criteria. In particular, the use of the simplified combined harness (SCH) versus the US Navy's Torso Harness, and the significant amount of negative G at ejection, do induce variances in terms of center of gravity shifts and aerodynamic stability during ejection. Nonetheless, these simulations offered investigators with decent approximations which were useful in determining the main mechanism of fatal injury.

The results were in line with well-established knowledge of ejection systems, and showed three separate events during which a significant "spike" of load factor was applied on the pilot.

The first is the peak acceleration during the catapult and rocket motor phase of the ejection, which resulted in an approximate vertical load factor of 17 G's. This phase can produce spinal injuries even in more benign ejection scenarios. The potential for harm in this case may have been exacerbated by the fact that, as explained previously in section 2.3.2, the negative G regime likely created either a lifting of the body out of the seat, or otherwise a less than ideal body posture during the ejection.

The second major G loading event is related to the opening of the drogue chute. Although its action was of relatively short duration (in the order of 1 second), it still created an overall deceleration of approximately 15 G's. Unlike the catapult and rocket motor phase, this loading was likely applied in a direction other than pure vertical. The yawing and pitching motions of the seat (referred to as instability) made it likely for this deceleration to be applied backwards, sideways, or any combination thereof in relation to the pilots' spinal axis, therefore inducing an increased potential for injury. Basically, the faster the seat travels through the air, the higher the deceleration will be.

The third and most significant event is the opening of the main parachute. The GQ 1000 parachute currently used in the CF188 is designed to inflate quickly to aid in the zero feet, zero altitude capability. This feature can generate large decelerations, which translate to large parachute riser forces. The US Navy simulations indicated that this loading was in the order of 24 to 26 G's. As per the drogue chute, the opening shock is in direct proportion to the speed of the ejection seat at the time of deployment. It is generally accepted that a shock of this magnitude, if applied sideways to the human body, will be fatal.

In general, all calculations for the ejection system analysis indicate that there should have been at least 5 seconds of fully inflated parachute before ground contact in this ejection. Notably, the pilot was found on the ground with both shoulder straps of the harness to his right side but evidence showed that the shoulder harness retraction in the seat as the Ballistic Inertial Reel (BIR) fired was equal and even on both shoulders. This indicates that at some time between harness retraction in the seat and ground contact, the pilot was forced through the shoulder harness towards the left.

Given that a fatal blow was dealt to the pilot, a detailed forensic analysis of the escape system and ALSE was undertaken to determine what occurred. Part of this effort included matching medical evidence to damage observed on the ejection system and ALSE with subsequent analysis for possible injury mechanisms.

This analysis involved linking facts and assumptions about the injury mechanism that raised concerns about the ejection system combination of equipment and possible re-production of the injury should similar ejection parameters be encountered. In particular, the aircraft flight regime, the inherent instability of the ejection seat, the drogue chute mode selection below 7500 feet MSL, the fast opening main parachute and the SCH generation 1 all appear to be factors in the generation of a fatal event during the parachute-opening phase of the ejection sequence. This scenario is well supported through the evidence of helmet to parachute riser contact, which damaged the riser and was confirmed by the QETE paint chip examination of the front left riser which matched helmet paint debris embedded in the riser.

Recent ejection tests conducted by the US Navy in early 2005 also confirmed the possibility of fatal forces applied to the upper body, head and neck due to large seat pitch and yaw angles relative to the opening direction of both the drogue and main parachutes. These recent tests involved the SJU-5/6 seat, which is essentially the same as the CF188 seat with the exception of the torso harness currently in use with the US Navy, versus the CF SCH generation 1. These tests also revealed probabilities of up to 80% for the occurrence of at least serious neck injuries at ejection speeds above approximately 270 KIAS with the use of the Joint Helmet Mounted Cueing System (JHMCS), which adds mass to the helmet, and possibly also changes its aerodynamic properties. Although currently not in use in Canada, the JHMCS is predicted to enter service in 2007.

Martin-Baker specialists created an ejection animation during the course of this investigation in order to re-create as closely as possible the dynamic interaction of the flight profile and ejection seat component performance. Fig 12 and 13 are taken from this video. When the seat leaves the aircraft and enters the airflow, it is accelerated by the rocket motors, but not yet actively stabilized by the drogue chute. It can therefore be subjected to aerodynamic and propulsive forces which generate large pitch, yaw and roll angles. In this case, the position of the pilot's body and limbs may have also contributed to these motions. When the drogue chute opens, it helps to decelerate the seat and align it with the airflow, in preparation for the release and opening of the main parachute. However, in the case of a low altitude ejection, the priority is placed on a quick main chute deployment, in support of the seat's zero-zero capability (zero altitude, zero airspeed). The drogue therefore only has about one second to stabilize the seat before releasing to extract the main parachute. If the seat is not stabilized, it's angular momentum can allow adverse pitch and yaw angles to be developed prior to application of the main parachute loads.

As was the case during the recent US Navy ejection tests, it is believed the seat's motions created a less than optimal alignment with the main parachute during the opening phase. This imposed a very large lateral force on the risers and on the pilot's upper body. Fig 12 depicts the point at which the drogue chute was released from the seat as it pulled the main chute from the headbox. Fig 13 shows a probable angle between the pilot and the main parachute opening axis. The estimated instantaneous acceleration sustained at the point of the fatal injury on the pilot was in the order of 200 to 250 G's. It is important to note that this does not mean the overall seat and pilot mass sustained this deceleration. As stated above, the overall man/seat G loading was in the order of 24 – 26 G's. However, the impact forces on the pilot's head from the parachute riser were very high. It is also most likely the opening shock of the parachute that forced the pilot through the left hand portion of the harness.

In summary, the chronological description of the accident ejection sequence was:

1. The pilot initiated ejection in a rolling, -2.5 G, 465 KIAS, 30 deg nose down, 76 deg right bank condition at approximately 1250 feet AGL.

2. Due to the negative G, the pilot's position at the time of ejection was likely not ideal, with possible lifting from the seat.

3. The aircraft canopy successfully jettisoned.

4. The ballistic inertial reel pulled the pilot back for restraint, possibly not to the full extent due to incorrect strap in procedures. As the seat began to travel up the catapult, the leg restraint pulled the legs back towards the seat. However, the extra snubber line on the right side had likely floated up and gone beyond the right calf guard, over and beyond the emergency override handle, and forcefully pulled the pilot's right leg outside the seat to the right.

5. The seat continued to travel up the ejection piston and was thrown forward due to the aircraft's negative G barrel roll motion.

6. The pilot's leg remained outside the seat to the right, and made contact with the outside of the seat bucket, which may have contributed to the seat's aerodynamic instability. As the pilot entered the high-speed windblast, the helmet visors were torn off.

7. The drogue chute opened normally after rocket motor burnout. Due to the low altitude of the ejection, it only stabilized and slowed the seat for about 1 second, after which the main parachute was extracted.

8. The main parachute deployed and inflated as designed. The seat was still at high velocity in the airflow, and not aligned with the parachute's opening axis, due to additional yaw and pitch of the seat that developed between release of the drogue parachute and main parachute line stretch.

9. As the main parachute inflated, it imposed a large deceleration force to the seat and pilot, to the rear and right. Likely, under this load, the weakened stitching of the left harness lower lock failed, opening the

left side of the harness by about 4 inches, therefore increasing the space between the top of the pilot's left shoulder and the parachute riser attachment point.

10. This sudden and large sideways force created the pilot's fatal injury. Additionally, the pilot's head was pushed through the shoulder harness to the left via the increased space described above. It is believed this is when the pilot's helmet was forcefully removed, as indicated by contact evidence between the helmet and parachute riser.

Another nation operating a fleet of F18's experienced similar injury patterns due to similar accident mechanisms. This nation conducted a detailed and extensive analysis of their existing escape system independently of the CF investigation and arrived at virtually the same conclusions. In order to reduce the risk of injuries similar to those that were seen in this accident, a new escape system that incorporates a multipoint drogue system to improve seat stability was developed. The drogue chute of this ejection seat deploys directly behind the seat as soon as it leaves the aircraft, providing an improved alignment with the airflow and an improved deceleration prior to main parachute opening. It stays until main parachute deployment, therefore increasing the opportunity for the seat and pilot to be in proper alignment with the parachute when it opens. This is one example in addressing seat stability, although other solutions may be available as well.

2.3.4 Other Concerns

Other ALSE and seat problems were apparent. Most notably the Life Preserver Survival Vest (LPSV) had inflated from windblast, destroying the floatation bladder, the LPSV contents had been dumped out of the pockets and some seat harness straps were quite worn. It is believed that when the LPSV was exposed to the 465 kts windblast, the beaded manual activation handle was torn free from its Velcro attachment point and that the CO2 inflation cylinder was activated. The LPSV bladder was at the time positioned beneath the SCH shoulder strap, pinching it during inflation. The bladder was torn apart, and would have been useless in the case of a water landing. In addition, the visors separated from the helmet. They were most likely torn from the pilot's helmet due to exposure to the 465 kts windblast. The very purpose of these visors is to protect the pilot's eyes during ejection, and therefore their performance was judged unacceptable.

2.3.5 Ejection System Risk Assessment

When the problems encountered during this ejection became apparent, the investigation team recommended expeditious examination of the ejection system for possible changes. The Chain of Command responded by convening an independent risk assessment (RA) team with experts from the TAA, the Operational Airworthiness Authority (OAA) and AETE escape system specialists to examine the ejection system for possible deficiencies and to recommend changes if required. Experts from the escape system OEM also provided input. This initiative determined that many CF-18 aircrew had been using incorrect strap in procedures including incorrect routing of the RSSK strap. The RA also identified strap wear problems and emergency oxygen bypass hose deficiencies.

Finally, the RA also confirmed that the damage patterns to the LPSV required an equipment change. Their recommendations resulted in new equipment being issued (LPSV – MSV 975), strap-in procedural changes (in particular leg garter (snubber line) adjustments) and LPSV bladder placement (overtop the shoulder harness).

As well, a Special Inspection for strap wear and general inspection of the SCH throughout the fleet was issued (SI NS-015) which included the need to ensure correct RSSK strap routing. The results of this SI revealed that of 155 harnesses inspected, 52 were unserviceable.

A local survey of emergency oxygen bypass hose fittings on Cold Lake CF188's revealed a deficiency which goes back to a modification instruction issued in 1987. This modification included instructions to drill a hole on top of the RSSK to relocate the emergency oxygen hose through it. A drilling jig was supposed to be used by technicians performing the task in order to precisely identify the location of the hole to be drilled. However, the jig was not provided with the mod instructions, and had to be ordered through the CF supply chain. The survey found that the location of the drill holes varied from aircraft to aircraft. It is therefore likely the drill jig was not used, or used improperly, for some aircraft. In all, 25 locally inspected aircraft in Cold Lake showed improper placement of the drilled hole in the RSSK.

Subsequent to this accident, another modification instruction was issued to place a leather shroud around the emergency oxygen hose attachment fitting on the RSSK, and to ensure proper emergency oxygen bypass hose placement.

These changes all reduced the risk associated with ejection injuries or post-ejection survival but did not substantially reduce the risk of the main fatal injury mechanism in a subsequent similar ejection scenario. To reduce this risk, the RA team recommended that the CF188 Escape System Modernization (ESM) program be expedited. This program involves changing the SCH generation 1 to a newer harness and other seat enhancements.

Another aspect associated with the CF188 Escape System dealt with the training received by technicians. The investigation team found that the Aircraft Operating Instruction (AOI) and the Canadian Forces Technical Orders (CFTO) have conflicting expectations about the technicians' knowledge when assisting the aircrew during strap-in . Further, there was inconsistency noted in the expected level of knowledge and responsibility of technicians for annual or qualification pilot strap-in checks. Specifically:

1. No training standard was found to qualify technicians responsible for seat checks (which includes strap-in checks).

2. No training standard specifically outlines pilot strap-in procedures (other than the AOI) and the flight line technician’s role in the strap-in.

3. There are no procedures for pilot strap-in when no technicians are present (cross-countries, remote operations) in the AOI.

3 CONCLUSIONS

3.1 Findings

3.1.1 The accident aircraft was serviceable at the time of departure for the mission, and was not the subject of repetitive or recent unresolved snags.

3.1.2 The aircraft technical documentation and maintenance work were completed in accordance with orders and accomplished by qualified personnel.

3.1.3 The lack of a crash worthy CVR/FDR was a major limiting factor for this investigation.

3.1.4 Although fluid samples from servicing sources did not reveal any significant contamination, not all required tests were performed.

3.1.5 There was an apparent lack of coordination on the use of personnel protective equipment while handling wreckage parts at the 1 AMS hangar.

3.1.6 The aircraft was flying in an approved configuration for the type of mission flown, and the formation was flying in an approved regime and formation.

3.1.7 The pilot was mentally and physically fit to fly the mission.

3.1.8 The accident aircraft likely sustained a MECH reversion caused by an uncommanded deflection of the left horizontal stabilator due to an undetermined FCS problem, which created the first aircraft upset event.

3.1.9 It is probable the accident aircraft encountered the wake turbulence of the lead aircraft at the time of the first upset.

3.1.10 It is believed the pilot was able to recover to a relatively level attitude after the first upset, still in a MECH-ON-ON mode.

3.1.11 It is probable that some CF-18 pilots were conducting FCS resets outside of the approved envelope.

3.1.12 It is possible that the pilot voluntarily pressed the FCS reset button shortly thereafter, in a low altitude, high speed flight regime.

3.1.13 At the time, no specific altitude was included in the checklist for the pilot to climb to in order to conduct an FCS reset.

3.1.14 It was assessed that, while the FCCs initiated a reset to CAS mode, the left stabilator sustained a near full deflection, trailing edge down, creating an abrupt, negative G barrel roll to the right and reverting the stabilators back to MECH mode.

3.1.15 It is likely the accident aircraft encountered more wake turbulence from the lead element of CF188s around the time of the second upset.

3.1.16 Pilot inputs on the flight controls are most likely responsible for the sudden and short pause near wings level following the first 360 degrees of roll.

3.1.17 The pilot initiated ejection in a low altitude, high airspeed, rolling negative G regime shortly after the aircraft resumed its barrel roll to the right.

3.1.18 As a result of a training deficiency, the strap in procedures employed by many aircrew (including the accident pilot) at the time of the accident were incorrect.

3.1.19 The pilot's posture during the ejection was likely not ideal due to negative G's sustained at the time of ejection.

3.1.20 The right hand leg restraint snubber line had likely not been tightened properly, and the extra line likely floated up and to the outside of the right hand calf guard due to the negative G prior to the ejection. Subsequently, the pilot's right leg was pulled outside the seat, as indicated by evidence of contact on the outside of the seat.

3.1.21 The pilot's helmet visors were most likely torn off when they entered the high-speed windblast.

3.1.22 The pilot sustained a fatal injury during the escape sequence, due to the opening force of the main parachute against his upper body. This force was likely caused by a misalignment of the pilot and seat in relation to the opening axis of the parachute.

3.1.23 The position of the oxygen pipe attachment nut from the RSSK, as well as the improper routing of the RSSK attachment strap, created a weakness of the left lower harness lock.

3.1.24 The left lower harness lock stitching failed under the main parachute opening load, creating a reduced restraint of the pilot and an increase in the space between the top of the pilot's left shoulder and the parachute riser attachment point. The pilot was forced out of his harness through this space due to the parachute opening shock.

3.1.25 Several ALSE components did not function as intended during the escape sequence.

3.1.26 No evidence was found that any other aircraft system, excluding flight controls and the escape system, were causal in this accident.

3.1.27 Inconsistencies were noted in both FSIS and DMS with regards to MECH reversion reporting.

3.2 Cause

The cause of this accident could not be determined with certainty because of the lack of sufficient data due to the absence of a crash worthy CVR/FDR and the amount of destruction sustained by the aircraft upon impact. The investigation team believes the accident flight profile was initiated by a flight control malfunction of the left horizontal stabilator which prompted a MECH-ON-ON condition. This was followed by an event which resulted in the full deflection (TED) of the left stabilator. The deflection of the stabilator, which was consistent with an FCS reset, took place in a low altitude, high speed, flight regime. This therefore created a situation from which the aircraft could not be recovered successfully. The ejection seat aerodynamic instability, in conjunction with the main parachute's high opening load, were most likely responsible for the pilot's fatal injury.

3.3 Contributing Factors

3.3.1 The low level, high speed regime of the accident aircraft created a very challenging situation for the pilot. The high amount of negative G, fast roll rate, and proximity to the ground left little time to analyse and attempt to recover the aircraft before a decision to eject had to be made.

3.3.2 The wake turbulence of the lead element may have contributed to the onset of the FCS malfunction and/or the accident flight profile.

3.3.3 The negative G condition at the time of ejection, as well as the strap in procedures employed at the time of the accident, would have made it difficult for the pilot to adopt a proper ejection posture. In addition, these factors may have contributed to the seat's aerodynamic instability and the pilot's injuries.

3.3.4 The improper routing of the RSSK attachment strap through the left lower harness lock, as well as the position of the emergency oxygen bypass fitting retaining nut created a weakness in the left lower harness lock, causing its failure under main parachute opening load.

4. SAFETY MEASURES

4.1 Safety Measures Taken

4.1.1 Ejection System Risk Assessment

The Chain of Command convened an independent RA team in June 2003 to examine the CF188 Ejection System deficiencies and to recommend changes if required. This initiative was successful at determining strap-in deficiencies, RSSK strap routing anomalies, strap wear problems, emergency oxygen bypass hose routing deficiencies and strap-in procedural problems.

A project to improve the escape performance of the CF188 SJU-9/10 ejection system is underway. However, the current scope of the ESM cannot improve the stability of the seat during the critical drogue chute and main parachute opening sequences. As briefed at the November 2005 Airworthiness Review Board, a Risk Assessment Working Group (RAWG) was convened in October 2005 to review the overall risk for every configuration of the SJU-9/10 escape system and identify potential mitigating actions, including ejection seat replacement. A first revision of the new Escape System RA was drafted and submitted for senior staff review in December 2005.

This RA will identify the risk associated with all scenarios. A detailed briefing will then be presented to the Airworthiness Advisory Board (AAB) members to determine what level of risk the fighter force is prepared to accept and further define the risk mitigation strategy to be implemented.

4.1.2 Strap-in Procedures

1 Cdn Air Div HQ issued an immediate change to CF188 AOI strap-in procedures (AOC 051 – 141649Z Jun 03) to correct noted deficiencies to include: leg restraint adjustments (snubber line), LPSV bladder placement, proper strap-in sequence and a caution about excessive seat height for proper harness tightening.

4.1.3 Special Inspection

The CF188 Weapons System Manager (WSM) issued a Special Inspection (SI NS-015) for harness strap wear and general condition of the SCH, and the need to ensure proper RSSK strap routing. This SI identified 52 unserviceable harness or ejection seat straps. These deficiencies were rectified.

4.1.4 Emergency Oxygen hose fitting modification

A modification instruction was issued in August 2003 to prevent the further rubbing and chaffing of SCH harnesses against the emergency oxygen hose RSSK fitting. The modification consisted of a leather sleeve to be placed around the hose fitting.

4.1.5 LPSV Change

The damage patterns on the LPSV indicated an equipment change requirement. 1 Cdn Air Div authorized the use of a replacement LPSV – the MSV975 (14240-1 (A3 OA3) 5 June 2003). Further, the list of authorized items for pockets on the LPSV was standardized via a new packing procedure published in September 2004.

4.1.6 Briefings

Briefings were conducted at 4 Wing Cold Lake to the CF188 community (made available to 3 Wing Bagotville) on preliminary findings on the accident sequence (by WFSO) and the ejection system Risk Analysis (by RA Team lead) on 12 June 03.

4.1.7 Airworthiness Advisory Board

A meeting of the AAB was held on 13 June 03 to consider the RA and to make recommendations for long term solution to the deficiencies noted in the RA associated with the SCH. This meeting concluded with a decision to examine options to replace SCH, accelerate current ESM, or acquire a new escape system.

4.1.8 Checklist Amendments

An investigation SITREP was published in October 2004, which contained a description of the hazards associated with FCS resets, as well as recommended checklist changes. Also, the SITREP acted as a reminder to operators to follow established procedures, including when dealing with flight control anomalies, and to duly report all of these anomalies to both maintenance and their Flight Safety officers.

The CF188 pilot checklist amendments proposed were incorporated in Feb 2005 to include a minimum safe altitude of 15,000 feet AGL before attempting an FCS reset from MECH to CAS, a warning about a possible loss of altitude of up to 7000 feet following a reset, and additional steps instructing pilots to not reset in the case where both roll and yaw axis are still functioning normally in CAS.

4.1.9 CT155/CF188 Commonality

The CT155 Hawk, currently used as a training aircraft in Moose Jaw and Cold Lake, has an Ejection System similar to that of the CF188. Consequently, the results of the escape system findings related to this accident were passed along to the CT155 community for consideration, and a separate RA for the Hawk SCH has been developed to evaluate the associated risk.

4.2 Safety Measures Required

4.2.1 Escape System Modernization

The multiple safety actions already implemented on the CF188 ejection system, while reducing overall risk of ejection injury, will not substantially reduce the risk of the fatal injury mechanism observed in this accident. To reduce this risk, the revised CF188 ESM program must be completed as expeditiously as possible.

As discussed in section 2.3.2, the root cause of the fatal acceleration imposed on the pilot's upper body was the opening load (or shock) of the main parachute, in combination with the ejection seat not being aligned with the main parachute opening axis.

The way to prevent this is to ensure some form of aerodynamic stability of the seat itself from the moment it leaves the aircraft until main parachute opening, (i.e. preventing it from tumbling through the air) and to help decelerate the seat prior to the main parachute opening.

It is therefore strongly recommended that the ESM include ejection seat aerodynamic stability improvement measures for the CF188 fleet. The need to stabilize the pilot and seat will become even more critical with the implementation of the Night Vision Imaging System (NVIS) and the JHMCS, each of which will add weight and aerodynamic drag to the pilot's helmet.

4.2.2 Flight Data Recorder

The CF188 should be fitted with a crash survivable CVR/FDR system. This equipment would likely have yielded sufficient data to understand the technical fault with CF188732, as well as pilot actions, and allow timely preventive measures to be actioned. The current lack of such a device has rendered this investigation extremely complex and time consuming. Had the accident aircraft not been equipped with, and using, an ACMI pod, investigators would have been left with virtually no information whatsoever on the accident flight profile.

The CF188 WSM has directed, in December 2004, the start up of a new project to develop, prove, procure and install a new CF188 recording system with a crash survivable memory unit (CSMU). A first initiative, called the Flight Data

Recording System (FDRS), is being developed in-house by the Canadian Forces (CF) at DRDC Ottawa.

Other options to gather the required flight data have also been proposed in the fall of 2005. Under the direction of DAEPM(FT), a working group (WG) will review all requirements and evaluate the best option to implement this capability in the CF188 fleet. It is recommended that the results of this WG be submitted to the DFS led CVR/FDR WG for consideration prior to being submitted to the Airworthiness Authority for approval. Once selected, fleet implementation of the chosen system should be accomplished as soon as possible.

In addition to fulfilling its mandate as a crash worthy FDR/CVR, it is recommended that the FDRS be fitted with a Flight Operations Quality Assurance (FOQA) capability, in order to also serve as an effective prevention tool. Various database management software is available today to process information downloaded from the aircraft on a routine basis, and enable advanced analysis and trending in order to prevent potential safety issues from becoming accidents.

4.2.3 Ejection Training

Several deficiencies were noted with the training that technicians and pilots receive with respect to duties associated with the CF188 Ejection System. A training standard for technicians involved with annual ejection seat checks should be developed; a more specific discussion of pilot strap-in procedures and duties should be added for line personnel; and, the AOI should be clarified to define strap-in procedures in situations where pilots do not have MOC 500 technician's assistance available, such as during cross-country flights or deployed operations.

4.2.4 Warning, Leg Restraint Lines

It is recommended that a warning be added to the CF188 AOI, page 2-1-10, at the bottom of paragraph b in order to highlight the possibility of loose restraint lines floating up in negative G conditions and creating a hazardous condition as described in section 2.3.2.

4.2.5 CT155/CF188 commonality

Based on section 4.1.8, it is recommended that a systematic means of passing escape system information between both fleets on a routine basis be developed and maintained.

4.2.6 MSDRS Visibility

The MSDRS and its MTC were very difficult to locate despite specific searches for the equipment. A unique paint scheme, perhaps employing a unique colour (and /or other means of identification) should be used on this equipment to allow easier identification at crash sites.

4.2.7 Use of ACMI Pods

The data from the ACMI pod was crucial in proceeding with the investigation and keeping the confidence of the CF188 community in the aircraft. The operational authority should consider the feasibility of carrying and using the ACMI pod, to the maximum extent possible, as a default configuration on all CF188's until the fleet is equipped with a proper FDR.

4.2.8 Reporting Culture

CF-18 operators must be reminded, on a recurrent basis, to report all FCS related occurrences to their Unit Flight Safety Officer or NCM in order to create FSIS entries. These occurrence reports should contain all relevant information in order to enable tracking, trending, and derive appropriate lessons learned and safety recommendations.

This on-going investigation has identified that some of the FCS related emergencies are not reported in the Flight Safety Information System. It is important to note that, as a guideline, all occurrences requiring the use of red or yellow pages of the CF-18 pilot's checklist should be followed by an FSIS occurrence report. In doing so, the narrative portion of the report should contain all necessary information, such as circumstances, manoeuvring at time of occurrence, relevant aircraft flight parameters (airspeed, altitude, attitude, etc.), actions taken by the pilot and subsequent aircraft response, etc.
The proper reporting of FCS malfunctions (and other significant occurrences) in FSIS is of great importance in order to enable the Flight Safety system to track and address CF188 safety issues and help operators mitigate the risks involved. This can only be achieved via honest and thorough reporting.

4.2.9 Checklist Reinforcement

CF-18 pilots should be reminded of the importance of following established procedures when dealing with flight control emergencies. Although multiple FCS manipulations may be accomplished on the ground without grave consequences, such is not the case for airborne problems. Of crucial importance is climbing to a safe altitude and establishing the proper speed and configuration prior to attempting an FCS reset. Amendments published in February 2005 also highlight the option not to reset FCS in the event of a MECH-ON-ON situation, i.e. stabilators in MECH mode, roll and yaw axis in normal CAS mode. The stabilators will not reset themselves from a MECH ON condition without the pilot pressing the FCS reset button, thus keeping aircraft control more predictable and avoiding the chance of pitch excursions during reset, or further reversion back to

MECH at an untimely phase of flight (low altitude environment, approach and landing).

4.2.10 Visor Retention

During the ejection sequence, both visors were torn from the pilot's helmet. A visor retention system that will retain the pilot's visors throughout the CF188's ejection envelope should be investigated.

4.2.11 Fluid Sampling

As mentioned in section 2.1.3, not all required fluid sample tests were performed as per QETE's requirements. Ideally, all fluid sample analysis should be done at QETE. However, the need to alleviate operational delays may dictate that a preliminary analysis be conducted locally. It is therefore recommended that the possibility of publishing the test requirements and procedures to both accredited labs and relevant wing authorities be considered. As well, local tests should be done under QETE's supervision or direct delegation. In cases where a local analysis is needed, a second set of fluid samples should be sent to QETE as well.

4.3 Other Safety Concerns

4.3.1 Harness Wear, Other Fleets

This is not the first aircraft fleet on which seat harness inspection for wear seems to have been less than rigorous. Results of SI NS015 should be passed to all CF WSMs for consideration of conducting a similar harness and strap inspection on all other CF fleets.

4.3.2 Personnel Hazards Exposure

Exposure to hazardous conditions on an accident site should be added to the personnel files for all personnel exposed to such hazardous sites. While precautions were taken on this accident scene, such was not the case during the wreckage analysis phase at 1 AMS. DFS will be developing a process to ensure protection to exposed hazardous materials is considered during all phases of the investigation, along with historical archiving (on personnel files and medical documents) of all the exposures.

4.3.3 Personnel Protective Equipment

It is recommended that all wings review their occurrence procedures and checklists to ensure sufficient guidance is included on the use of personnel protective equipment, including references to such manuals the AGA 135 and the Post Crash Environmental Guidelines from 1 Canadian Air Division (1 Cdn Air Div).

4.4 DFS Remarks

The investigation into this tragic accident was very thorough. Unfortunately, due to the complexity of the factors that appeared to cause this accident, this investigation took a great deal of time and effort to complete. As the report indicates, this investigation was severely hampered and lengthened by a lack of appropriate data that could have been provided by a crash survivable CVR/FDR. Fortunately DGAEPM staff are actively working this issue and hopefully a solution to this serious problem will be implemented in the near future for the CF188 fleet.

The investigation into this accident had to resolve two main issues: what caused the aircraft to go out of control and what caused the fatal injuries to the pilot. The investigation team did an excellent job in determining the most likely scenario outlining what occurred during the flight control malfunction. However, the team was unable to definitively determine the basic cause of the actual flight control malfunction itself due to the lack of data. While this shortfall is of some concern, the proposed preventive measures (many of which have already been accepted and implemented) should reduce the risk of a similar re-occurrence.

The answer to the second question facing the investigation team has resulted in serious concerns with the current CF188 escape system. This concern must be tempered with the fact that, aside from this accident, the CF188 escape system has provided 10 successful ejections in 10 attempts over almost 500,000 CF188 flying hours. In addition, this was the first low altitude high speed ejection attempt in the CF188. This factor coupled with the unusual flight regime at the time of ejection (a high negative G rolling manoeuvre) placed extraordinary demands on the escape system. The investigation team concluded that, in this particular case, it was highly unlikely that the current CF188 escape system was capable of providing a successful ejection. Moreover, the CF will be placing additional demands on the CF188 escape system with the incorporation of new helmet mounted systems in the near future.

It was interesting to note that other nations who operate the F-18 have experienced difficulties with the escape system and that, through analysis totally independent to the analysis contained in this FSIR, have reached virtually identical conclusions. As a result, other operators of this aircraft are actively working on developing solutions to the problems identified by the CF accident investigation team. DGAEPM and Director Air Requirements staffs are monitoring these developments closely with a view to incorporating appropriate initiatives into the CF188 ESM. Suffice it to say, this latter program needs to proceed as a matter of priority.

Finally, the identification of a number of deficiencies with respect to escape system training, operating procedures and adherence to checklists are of serious concern. It appears that a number of unauthorized changes have gradually crept in to CF188 procedures over the years. What is most disturbing is that some of these changes seem to have gained wide acceptance. These findings reinforce yet again the requirement for a strong, effective airworthiness program that ensures that activities are completed in accordance with an accepted and approved standard.

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A.D. Hunter
Colonel
Director of Flight Safety

ANNEX A: Figures

Fig 1. Impact crater

Fig 2. Impact area

Fig 3. Impact crater close-up

Fig 4. Some of the flight control parts recovered

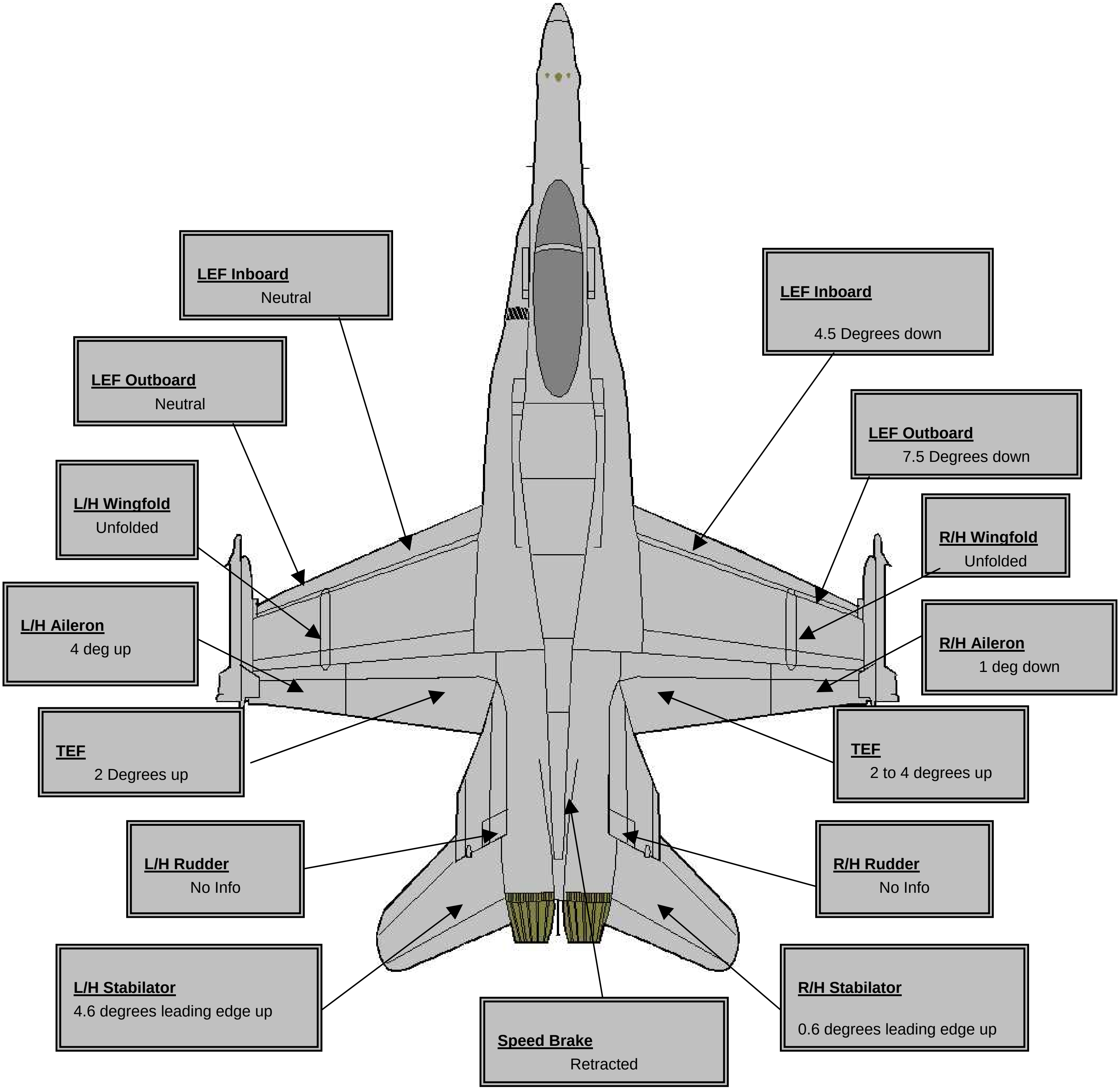


Fig 5. Flight control deflections at time of impact

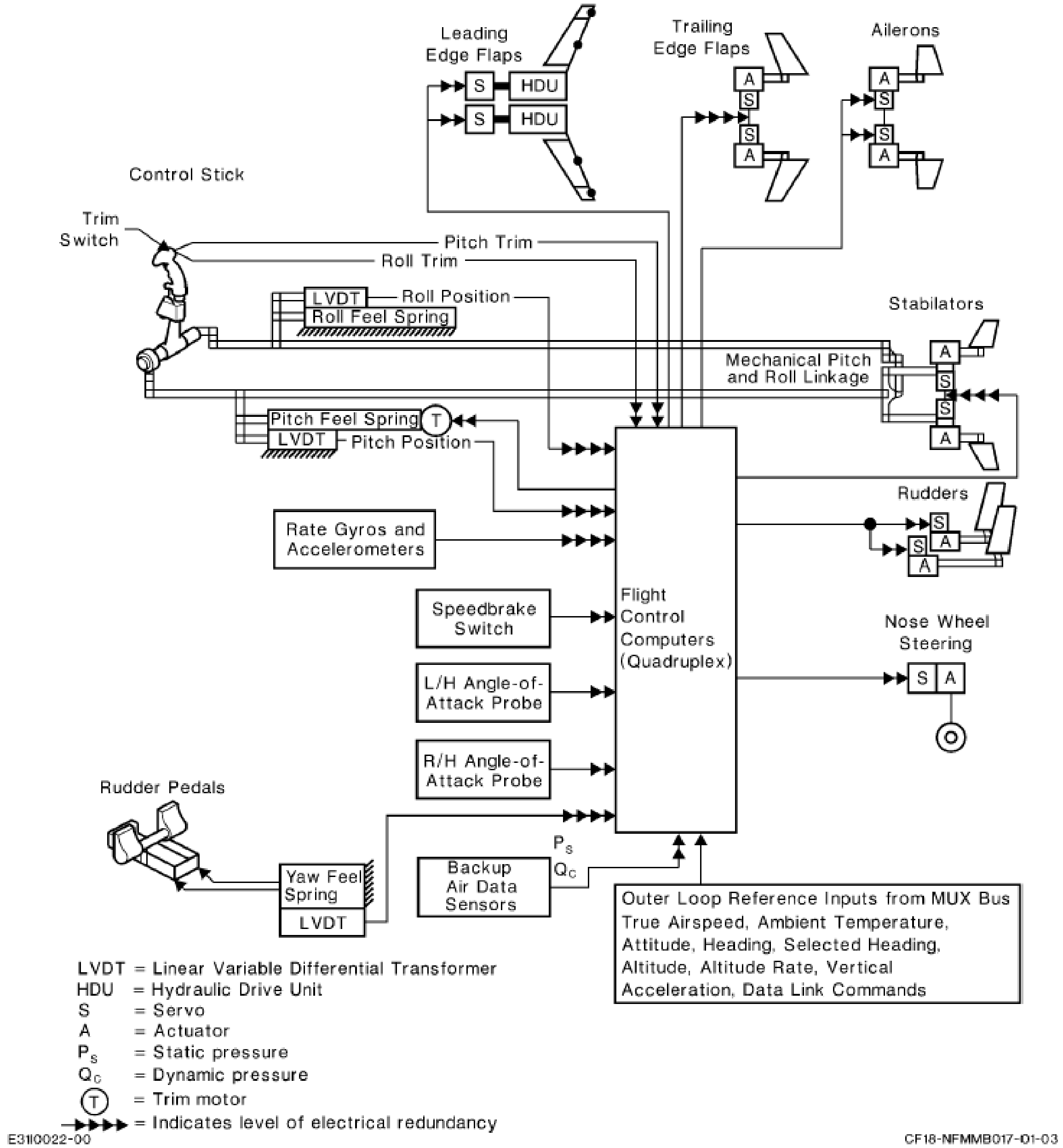
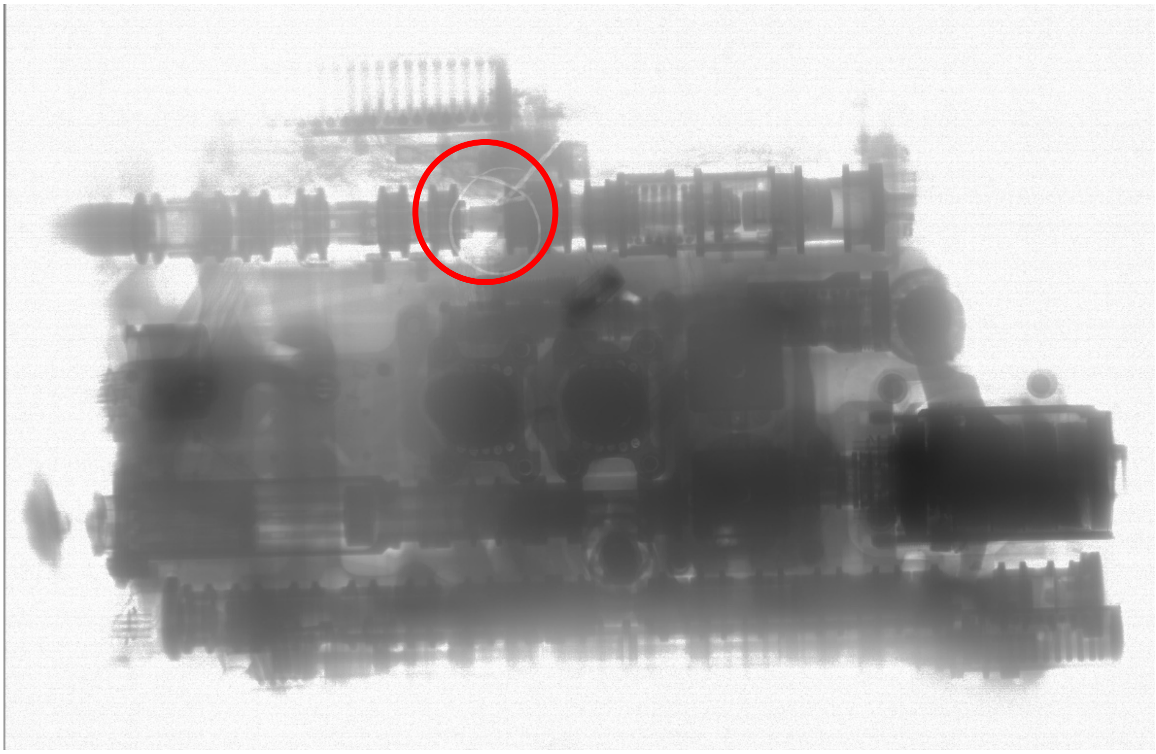


Fig 6. Functional schematic of CF188 flight controls

Fig 7. Radiograph of right stabilator actuator. Mode select valve spool fracture is highlighted in red circle.

Fig 8. Disassembled MSV with close-up of spool fracture.



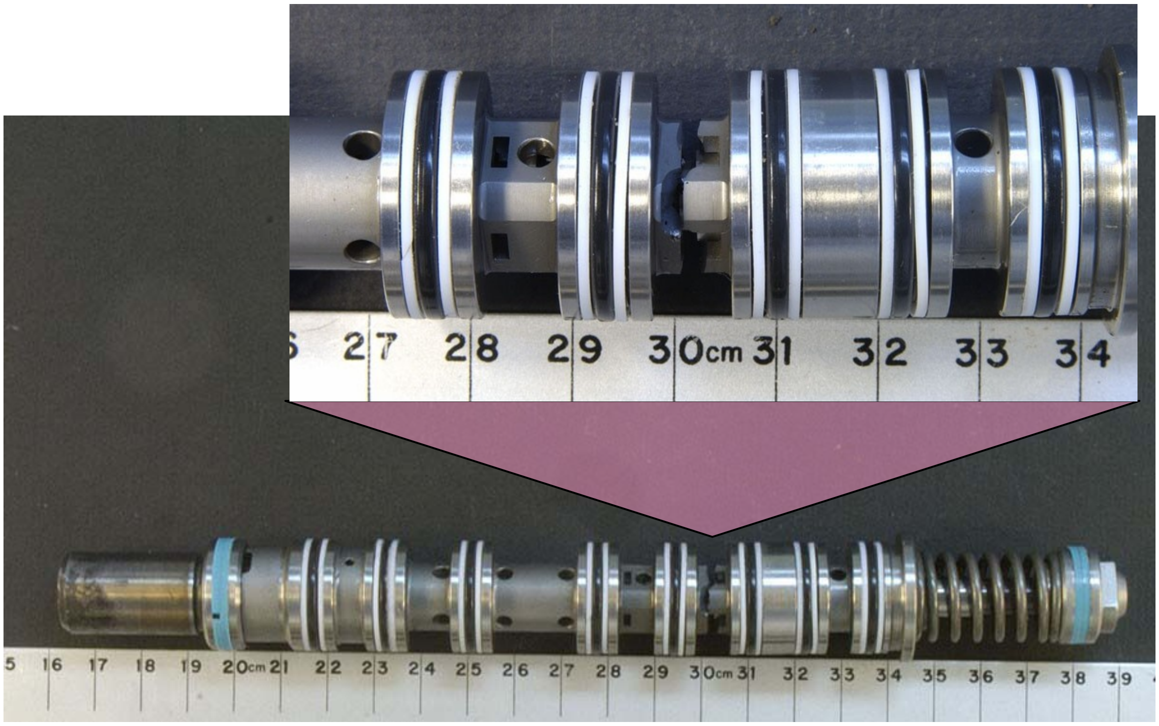


Fig 9, 10. Broken stitching, left lower harness lock; comparison with serviceable lock.

Fig 11. Oxygen attachment pipe nut location vs. lower harness lock stitching.

Fig 12,13. Extraction of main parachute by drogue chute; approximation of misalignment of seat/pilot with main chute axis on inflation.

ANNEX B : ABBREVIATIONS

AAB	Airworthiness Advisory Board
ACC	Altocumulus Castellanus
ACMI	Air Combat Manœuvre Instrumentation
AETE	Aerospace Engineering Test Establishment
AFIP	Air Force Institute of Pathology
AGL	Above Ground Level
ALSE	Aircrew Life Support Equipment
AMAD	Aircraft Mounted Accessory Drive
AMSE	Aircraft Maintenance Support Equipment
AOA	Angle-of-Attack
AOI	Aircraft Operating Instructions
ASL	Above Sea Level
AWACS	Airborne Warning And Command System
BIR	Ballistic Inertial Reel
CAS	Control Augmentation System
CATM	Captive Air Training Missile
CF	Canadian Forces
CFTO	Canadian Forces Technical Orders
CLAWR	Cold Lake Air Weapons Range
CSMU	Crash Survivable Memory Unit
CSS	Combat Support Squadron
CVR	Cockpit Voice Recorder
DDI	Digital Display Indicator
DEL	Direct Electrical Link
DAEPM(FT)	Director Aerospace Engineering Project Management, Fighters&Trainers
DGAEPM	Director General Aerospace Engineering Project Management
DMS	Data Management System
DRDC	Defence Research and Development Center
DTD	Data Transfer Device
ECS	Environmental Control System
EOD	Explosive Ordinance Disposal
ESM	Escape System Modernization
FCC	Flight Control Computer
FCS	Flight Control System
FDR	Flight Data Recorder
FDRS	Flight Data Recording System
FOQA	Flight Operations Quality Assurance
FRPC	Flight Recorder Playback Center
FSIS	Flight Safety Information System
G	Load Factor
GCU	Generator Control Unit
HUD	Heads-Up Display
IAS	Indicated Air Speed
IFF	Identification Friend or Foe

INS	Inertial Navigation System
JHMCS	Joint Helmet Mounted Cueing System
KIAS	Knots, Indicated Airspeed
KM	Kilometre
LEF	Leading-Edge Flap
LOX	Liquid Oxygen
LPSV	Life Preserver Survival Vest
LVDT	Linear Variable Differential Transducer
MCV	Mode Control Valve
MECH	Direct Mechanical
MRS	Maintenance Records Set
MSDRS	Maintenance Signal Data Recording System
MSL	Mean Sea Level
MSV	Mode Select Valve
MTC	Magnetic Tape Cartridge
NATO	North Atlantic Treaty Organisation
NM	Nautical Mile
NORAD	North American Defence
NRC	National Research Council
NVIS	Night Vision Imaging System
OAA	Operational Airworthiness Authority
OEM	Original Equipment Manufacturer
OSCER	On-Scene Controller Emergency Response
PIO	Pilot Induced Oscillations
PPE	Personnel Protective Equipment
QETE	Quality Engineering and Test Establishment
RA	Risk Assessment
RAS	Recovery And Salvage
RASO	Recovery And Salvage Officer
RAWG	Risk Assessment Working Group
ROCC	Regional Operations Control Center
RSSK	Rigid Seat Survival Kit
SAR	Search And Rescue
SCH	Simplified Combined Harness
SITREP	Situation Report
SMDC	Shielded Miniature Detonation Cord
SOV	Shut-Off Valve
SQN	Squadron
TAA	Technical Airworthiness Authority
TCU	Towering Cumulus
TED	Trailing Edge Down
TEF	Trailing Edge Flap
TFOA	Things Falling Off Aircraft
TRU	Transformer Rectifier Unit
UHF	Ultra-High Frequency
VFR	Visual Flight Rules
WG	Working Group
WSM	Weapon System Manager
1 AMS	1 Air Maintenance Squadron

1 Cdn Air Div	1 Canadian Air Division
6DOF	6 Degrees Of Freedom