Report on the accident to Aerospatiale AS332L Super Puma, G-TIGK, in North Sea 6 nm South West of Brae Alpha Oil Production Platform on 19 January 1995

Micro-summary: This Super Puma successfully ditched in the North Sea following a rotor failure.

Event Date: 1995-01-19 at 1240

Investigative Body: Aircraft Accident Investigation Board (AAIB), Great Britain

Investigative Body's Web Site: http://www.aaib.dft.gov/uk/

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Aerospatiale AS332L Super Puma, G-TIGK: Main document

Aircraft Accident Report No: 2/97 (EW/C95/1/1)

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Contents

Figures 3 to 14 showing photographs of sample TRB, recovered tail rotor assembly, damaged "White 'TRB, main rotor blades and damaged structure and components.

Appendix B: Diagrams showing cabin seating layout and general design features of life raft; photographs of right main door and broken spring-loaded attachment arms, ADELT housing; Enclosures 1 to 3 containing occupant evacuation actions, heliraft examination findings and a copy of SAR Memorandum of Understanding of 3 March 1997.

Appendix C: Enclosures 1 and 2 showing extracts from AC20-53A and LTT Report AEA-TSD-0562; Figures 1A to 12D showing photographs of TRB lightning tests at LTT, Culham; Figures 13A to 13C showing diagrams of modified TRB P/N 332A.12.0020.

Registered Owner and Operator:	Bristow Helicopters Limited (BHL)
Aircraft Type:	Aerospatiale AS332L Super Puma (Tiger) helicopter
Nationality:	British
Registration:	G-TIGK
Place of Accident:	6 nm south-west of the Brae 'A' oil production platform
Latitude:	58° 36' North

Longitude:	01° 10' East
Date and Time:	19 January 1995 at about 1240 hrs
	All times in this report are UTC

Synopsis

The accident was notified to the Air Accidents Investigation Branch (AAIB) on 19 January 1995 at 1315 hrs and the investigation was initiated that day. The AAIB team comprised Dr E J Trimble (Investigator in Charge), Mr R G Matthew (Operations), Mr R W Shimmons (Operations - Rescue and Survival), Mr P R Coombs (Engineering), Mr C G Pollard (Engineering - Salvage), Mr R Parkinson (Engineering - Salvage) and Mr R J Vance (Flight Recorders).

The helicopter was conducting a charter flight, ferrying 16 maintenance engineers from Aberdeen to the Brae oilfield. Having just passed a position 120 nm on the 062° radial from the Aberdeen VHF omnirange (VOR) radio beacon, and whilst beginning its descent from 3,000 feet above mean sea level (amsl), the helicopter was struck by lightning. This resulted in severe vibration which, a few minutes later, developed into a loss of tail rotor control, necessitating an immediate ditching in heavy seas. The ditching was executed successfully and the helicopter remained upright enabling the passengers and crew to board a heliraft,from which they were subsequently rescued. There were no injuries sustained and the passengers and crew were later returned to Aberdeen by helicopter and ship.

Despite six to seven metre waves and a 30 kt southerly wind, the helicopter remained afloat for some three hours and thirty minutes before it was brought alongside a safety vessel. However, whilst secured to this vessel the helicopter's flotation bags punctured and it sank some two hours later, at 1803 hours.

The investigation identified the following causal factors:

1. One of the carbon composite tail rotor blades suffered a lightning strike which exceeded its lightning protection provisions, causing significant damage and mass loss.
2. The dynamic response of the gearbox/pylon boom assembly to the tail rotor system imbalance induced rapid cyclic overstressing of the gearbox attachments which was accelerated by the early failure of the upper mounting bolt locking wire, allowing consequent loosening and fatigue failure of this bolt.
3. Complete loss of the yaw control system and a momentary pitch-down as a result of detachment of the tail rotor, gearbox and pitch servo assembly.
4. The lightning strike protection provisions on this design of carbon composite tail rotor blade were inadequate due to it having been developed from an earlier fibreglass blade which had been certificated to lightning test criteria which have since become obsolete.

Eight Safety Recommendations have been made as a result of this investigation.

1 Factual Information

Showing G-TIGK drifting in heavy seas after ditching and evacuation of occupants, with tail rotor/gearbox missing and damaged main rotor blade.

1.1 History of the flight

The helicopter, G-TIGK, was operating under charter to one of the North Sea oil companies and the purpose of the flight was to ferry 16 maintenance engineers from Aberdeen to the Brae 'A' oil production platform. Prior to landing at Brae 'A', the flight was to land at the East Brae platform to uplift two more engineers.

The crew had reported for duty at 0730 hrs that morning and, before the accident flight, had completed a return flight in G-TIGK to the Forties oil field. The helicopter had remained serviceable and there were no 'Carried Forward Defects' recorded in the Technical Log.

The forecast weather for the flight to Brae was: Scattered or broken cloud between 2,000 and 6,000 feet amsl, with isolated towering cumulus or cumulonimbus, giving occasional showers of rain, hail, sleet or snow, and some isolated thunderstorms.

G-TIGK, callsign '56C', was scheduled to depart at 1130 hrs and, following a small administrative delay, took off at 1138 hrs with the first officer as handling pilot. Leaving the Aberdeen VOR on the 062° radial, the helicopter climbed to, and levelled at, Flight Level (FL) 70 where the crew thought that they might be out of icing conditions, and from where they were able to see a number of clouds building up on, and around, their planned route. Although there were several comments on the cockpit voice recorder (CVR) about the cumuloform clouds, the crew later stated that they did not see anything particularly significant on the radar and therefore decided to descend to warmer air at 3,000 feet amsl. However, one comment was heard on the CVR concerning the large size of a cloud build-up to the north of the Brae oilfield and another about a build-up of soft ice pellets on the ice detector.

The flight continued along the planned route, leaving Aberdeen Radar coverage at a range of 80 nm at 1217 hrs when the crew changed frequency to the Aberdeen Flight Information Service (FIS). Whilst remaining in radio telephony (RT) contact with the FIS, the crew then established initial contact, on their second radio, with Brae Traffic Watch ('Brae'). At 1233 hrs, the crew informed Aberdeen that they were at the reporting point 'Gatein', 120 nm on the 062° radial from the Aberdeen VOR, and changed frequency to Brae. At about 1236 hrs, whilst initiating the normal let down to the East Brae platform and as they passed through a patch of cloud at about 3,000 feet amsl, there was a 'bang' accompanied by a 'flash' and the helicopter began to vibrate severely.

The first officer later stated that he briefed the passengers at this time, and continued to do so as the flight progressed; some of these messages were heard on RT. Some of the passengers heard a bang, whilst some just heard a noise and a few said that they saw a flash, but did not know whether it was inside or outside the fuselage. One passenger reported a 'sort of pulsing vibration in the air' and all felt the physical vibration, but thought that the helicopter was under control. None, however, heard any passenger address (PA) announcements.

Assuming an imminent need to ditch, the first officer initiated an autorotative descent and transmitted a Mayday call on the Brae frequency, stating that they had been struck by lightning, had severe vibration and were going to ditch. As the helicopter descended through 1,500 feet amsl both pilots realised that, although the helicopter was still vibrating severely, it was responding normally to the controls. They therefore decided to level off and to try to reach the Brae 'A' platform, the nearest diversion. The commander informed Brae of this decision and, in order to complete the necessary checks expeditiously, began the Approach Checks by selecting the landing gear

DOWN. The decision as to whether to land on Brae 'A', or to ditch beside it, had not been made at this time.

The crew of another company helicopter call sign '56B', which was loading passengers on the Brae 'B' platform, also heard the initial Mayday message. They then unloaded their passengers and, by 1239 hrs, had taken off in order to assist 56C if necessary.

Meanwhile the first officer of 56C, as the handling pilot, was unsure as to whether the apparent directional stability of the helicopter was being maintained by the tail rotor or by the 'weathercock' effect of the airspeed, so he gently deflected the yaw pedals to see if there was a response. He had just commented to the commander that everything seemed to be in order when there was a 'crack' and the helicopter gave a violent lurch to the left, rolled right and pitched-down steeply. Realising that a ditching was now imminent, the first officer transmitted another Mayday informing Brae of his decision to ditch and carried out the TAILROTOR DRIVE FAILURE checks, which included shutting down the engines in order to contain the yaw, and then arming and inflating the floats. 56B relayed this Mayday message to Aberdeen FIS at 1241 hrs, and set course towards the assumed position of 56C.

The passengers of 56C now realised that a ditching was inevitable and prepared themselves for it in the manner detailed by the video briefing given to all passengers prior to boarding. Another PA announcement was given at this time but, although it was heard on the RT by Brae, it was not heard by the passengers.

The first officer accomplished a gentle touchdown on the sea, despite six to seven metre waves and a 30 kt southerly wind; the helicopter alighted with the wind in its one o'clock position. The commander applied the rotor brake and both pilots activated the emergency release of their doors. At about 1242 hrs, the commander made an RT transmission to say that they had alighted safely. Leaving the commander to complete the cockpit drills, the first officer then went aft to help the passengers evacuate into the helirafts. Two of the passengers who had deployed the left heliraft later stated that it had been blown over such that it lay edgeways on its rim, with its floor against the side of the fuselage, and that the combination of the wind and the swell was going to make it very difficult to utilise. The first officer, on entering the cabin, decided that all occupants should board the already deployed right heliraft in order to keep everyone together. All the passengers and, lastly, the two crew boarded this heliraft without difficulty and awaited rescue. Despite overloading of the '14 man' heliraft and puncturing of a buoyancy chamber below its boarding ramp, it remained afloat satisfactorily. (The evacuation, survival aspects and subsequent rescue are detailed in section 1.15).

At 1243 hrs, 56B had relayed to Aberdeen the final message from 56C and continued with its attempt to locate the ditched helicopter,which it eventually succeeded in doing at 1306 hrs. 56B then remained in the hover by the heliraft and assumed the duties of 'On Scene Commander' (OSC), assisting with the co-ordination of the other helicopters and guiding the surface vessels to the scene. The total assets alerted were: one Norwegian Dauphin helicopter, one RAF Sea King and the Sumburgh Coastguard S61, all equipped with winches; three Tiger helicopters and one Dauphin, which were not winch equipped; two oil platform Safety Vessels and one RAF Nimrod aircraft. 56B continued as OSC until command was assumed by the RAF Nimrod at 1430 hrs.

The crew and passengers were recovered from the heliraft by the Fast Rescue Craft (FRC) of two oil platform Safety Vessels, 'Grampian Freedom' and 'St Patrick', at about 1340 hrs, and taken aboard the Grampian Freedom to await transfer back to the mainland. Of the 18 survivors, 15 were winched aboard helicopters and put onto the Brae 'A' platform, before being flown back to

Aberdeen that evening. However, three passengers did not wish to be winched and remained aboard the Grampian Freedom, which sailed into Aberdeen the following morning.

By 1355 hrs the 'Highland Pride', another Safety Vessel, had arrived on the scene and, having recovered one of the helirafts, began an attempt to salvage the helicopter, which was brought alongside at 1609 hrs. Whilst secured to the Highland Pride, the helicopter's flotation bags punctured and the helicopter later sank at 1803 hrs after being released. Prior to the helicopter sinking, three of the four main rotor blades had been cut off and lost, although one was subsequently recovered.

1.2 Injuries to persons

Injuries	Crew	Passengers	Others
Fatal	-	-	-
Serious	-	-	-
Minor/none	2	16	-

1.3 Damage to aircraft

The helicopter sank to the sealed and was damaged beyond economic repair.

1.4 Other damage

None.

1.5 Personnel Information

1.5.1	Commander:	Male, aged 44 years
	Status:	Captain. North Sea Commander
	Licence:	Airline Transport Pilot's Licence (Helicopters) issued 9 January 1988. Validated 16 November 1994. Valid until 16 May 1995
	Aircraft ratings:	AS332L;S76A;S61N;WS55;Bell 212, 206 and 47
	Medical Certificate:	Valid to 30 June 1995
	Instrument Rating	Valid to 11 December 1995
	Base check:	VMC: Dated 16 November 1994. Valid
		IMC: Dated 19 December 1994. Valid
	Line check:	Dated 28 December 1994. Valid

Emergency drills:	Dated 7 April 1994. Valid to 7 May 1995
Wet dinghy drill:	Dated 6 July 1993. Valid to 6 July 1995
Crew Resource Management:	Dated 29 September 1994. Valid
	Total flying - 9,610 hours
	On type L - 4,965 hours
Flying experience:	Last 90 days - 142 hours
	Last 28 days - 41 hours
	Last 24 hours - 3 hours 20 minutes
Previous rest period:	2 days

The commander joined BHL in July 1974, then converted from fixed to rotary wing operations and flew the Sikorsky S61N on the North Sea for two years. He then spent a summer flying the WS55 and the Bell 206 in the Middle East, before becoming a captain in September 1976 and returning to the North Sea in the summer of 1977. In January 1978, he attained his Airline Transport Pilot's Licence (Helicopters) and, having qualified for his captaincy on the Bell 212 in 1978 and the Sikorsky S76A in 1982, converted to the AS332L Tiger in 1987. He flew both the Tiger and the S76A for six months, after which he flew only the Tiger. He was promoted to 'North Sea Commander' in July 1989, when BHL introduced this new status for suitably qualified captains.

1.5.2	First Officer:	Male, aged 39 years
	Status:	Senior First Officer
	Licence:	Airline Transport Pilot's Licence (Helicopters) issued 11 February 1993
	Aircraft ratings:	AS332L, Bell 206 and Bell 47
	Medical Certificate:	Valid to 31 October 1995
	Instrument Rating:	Valid to 28 October 1995
	Base check:	VMC: Dated 26 October 1994. Valid
		IMC: Dated 28 October 1994. Valid
	Line check:	Dated 23 November 1994. Valid
	Emergency drills:	Dated 20 March 1994. Valid to 20 April 1995
	Wet dinghy drill:	Dated 10 May 1994. Valid to 10 May 1996

Crew Resource Management:	Dated 23 April 1993. Valid
Flying experience:	Total flying - 3,158 hours
	On type - 2,593 hours
	Last 90 days - 167 hours
	Last 28 days - 57 hours
	Last 24 hours - 6 hours
Previous rest period:	16 hours 20 minutes

Having served in various capacities as a Merchant Marine officer since 1974, the first officer qualified on the Bell 47 and the Bell 206 at Trent Aviation, Cranfield, and then joined the BHL fleet in 1990, converting to the AS332L Tiger.

1.6 Aircraft information

1.6.1 General Information

Manufacturer:	Aerospatiale (now Eurocopter)
Type:	Aerospatiale AS332L
Aircraft serial no:	2044
Year of manufacture:	1982
Certificate of Registration:	Issued on 15 April 1982 in the ownership of Bristow Helicopters Ltd.
Certificate of Airworthiness:	Issued on 28 September 1994 in the Transport Category (passenger) and valid until 27 September 1995.
Engines:	2 Turbomeca Makila 1a Turboshaft engines
Total airframe hours:	13,665

1.6.2 Weight, balance and fuel

Regulated Take-off Weight:	18,960 lb	Zero Fuel Weight:	12,242 lb
Total fuel at take-off:	3,350 lb	All Up Weight at take-off:	18,957 lb
Total fuel at ditching:	2,450 lb	Estimated weight at ditching:	18,057 lb

The helicopter's centre of gravity was about 186 inches aft of datum, which was within the limits of 177.99 inches to 190.9 inches aft.

1.6.3 Maintenance checks on tail rotor gearbox attachments

During a Check 1 inspection the tail rotor gearbox had been removed to facilitate scheduled inspection of the tail pylon of this aircraft and was refitted on 12 December 1994, at which time the aircraft had completed 13,568.04 airframe hours. On 21 December 1994 a check of the torque of the tail rotor gearbox attachment bolts was carried out at 13,571.58 airframe hours, as was required between 5 and 10 hours after any gearbox installation. The technical records showed that the recorded torque figures were found to be satisfactory. A further required 100 hour post-installation torque check was carried out on the attachment bolts on the 18 January 1995 (ie the night before the accident) at 13,665.00 airframe hours. The technical records again recorded that the torques were found to be satisfactory.

1.6.4 Significant aircraft design features

The AS332L type is a helicopter of conventional layout (Appendix A, Figure 1A) having articulated main and tail rotor heads equipped respectively with four composite main and five composite tail rotor blades. The bulk of the main aircraft structure is of conventional riveted aluminium alloy construction.

The composite elements of the tail rotor blade design in use on G-TIGK at the time of the accident, and on other AS332L helicopters in use at the time on the North Sea, differed from the original design, part number 332A.12.0010, first used on the AS332L. This modified blade design, part number 332A.12.0020, was introduced by all UK based North Sea operators of the type after a ground incident in May 1987 had revealed that the original design had unsatisfactory foreign object damage (FOD)/impact resistance characteristics.

The tail rotor blades had an outer skin layer of fibreglass (FG) of 0.13 mm thickness, overlying two skin layers of carbon HR cloth, each of 0.39 mm thickness, with an innermost layer of 0.25 mm thick FG on each side of the leading edge, and a foam core. The spar was of linear glass-fibre, positioned within the leading edge, and in addition two spanwise 'ribs', one of carbon fibre reinforced plastic (CFRP) and one of woven glass reinforced plastic (GRP), were positioned aft of the main spar in each blade, the CFRP rib being at approximately mid-chord with the GRP rib further aft (Appendix A, Figure 2). As can be seen in Figure 2, two (steel) tip weight bolts were secured within the blade tip area, the forward bolt attached to the aft side of the spar and the aft bolt in a FG 'block' bonded to the forward side of the CFRP mid-rib. The tail rotor blades had one piece titanium leading edge anti-erosion shields bonded over a recess in the leading edge profiles.

The main rotor blades had skins of CFRP and a core predominantly of a nomex type honeycomb. They were fitted with overlapping stainless steel leading edge anti-erosion shield sections bonded to the CFRP skins, with overlapping 'joggles' at their junctions.

1.6.5 Lightning protection

In the case of both the main and tail rotor blades, the anti-erosion shields formed the main element of the lightning protection conduction system. In addition, on each blade a brass strip linked the inboard end of the anti-erosion shield with a bolt positioned within the blade root area which was attached to a braided strap (tin plated copper braid with stainless steel wire core), which in turn crossed the flapping hinge and, in the case of the tail rotor, was earthed via insulated cables routed to terminal tags secured by attachment bolts on the tail rotor hub. Appendix A, Figure 3, shows leading edge anti-erosion shield, plastic cover overlying brass strip, and braided strap attached to root bolt on a sample tail rotor blade.

1.6.6 Emergency and survival equipment

1.6.6.1 Cabin layout and emergency equipment operation

At the time of the accident, the seating on G-TIGK conformed to an 18 seat passenger configuration, as shown in Appendix B, Figure 1.

There was a standard jettison handle for each cabin door, located immediately forward of each of the right and left-hand doors. Additionally, there was another jettison handle on the flight deck bulkhead behind the commander, located to the right of his headrest; this would also release the right-hand door.

All the windows in the passenger cabins of the BHL Tigers had been modified to be 'escape' windows. These transparencies were held in their apertures by rubber beading with a release tab attached inside and outside the cabin; when the tab was pulled, the beading stripped away from the aperture allowing the transparency to be jettisoned into, or out of, the cabin.

The aircraft cabin doors form both the normal (left) and emergency exit (right) routes for the passengers. They are of sandwich construction, with carbon fibre composite skins enclosing low density cores. They normally open outwards and then slide in a forward direction clear of their apertures on a system of 3 rails, the lower and middle rail each providing both vertical and lateral support. The top rail is a channel section having its open face orientated downwards and provides only lateral restraint. This is achieved by means of two spring-loaded arms mounted at the forward and aft ends of the upper edge of the door, each carrying a roller with a vertical axis, each roller engaging in the top rail. Appendix B, Figure 2, shows the right main cabin door.

The main cabin doors may be jettisoned in an emergency, in such a way that they move outwards and are then released from the two rails providing the vertical support, thus permitting downward movement and disengagement, whilst the rollers mounted on the spring loaded top arms are free to slide vertically out of the top rail.

A separate jettisonable cockpit door is provided alongside each pilot's seat.

Two '14 man' helirafts were carried, manufactured by RFD Limited as Type 14R Heliraft (Appendix B, Figure 3). They both incorporated a standard UK Survival Pack and each heliraft was designed to cope with an overload capacity of 21 occupants. The heliraft on the left side of the cabin was the primary heliraft, and was stowed within a box structure underneath seats No 10 and No 13, just behind the left-hand door. To deploy this heliraft, it had to be drawn from its stowage, its firing line attached to the fuselage,and the heliraft then deployed through the left door aperture. The other heliraft was packed in a special container adjacent to the base of the right-hand door. To deploy this heliraft, the right-hand door had to be jettisoned, the top cover of the heliraft removed, the release handles pulled and the heliraft and container then pushed out of the door aperture.

There was a First Aid Kit located on the aft wall of the right-hand controls cabinet in front of the forward right passenger seat. This was taken aboard the heliraft.

Two hand held fire extinguishers, charged with Freon gas, were located on the right hand side of the cockpit passageway.

One BE 369 Flotation Beacon was located underneath Seat No 8. This was not taken aboard the heliraft.

One Search and Rescue Beacon (SARBE) personal locator beacon (PLB) was stowed in the life vest of each crew member. When helicopter 56B was in their vicinity the first officer attempted, unsuccessfully, to use the speech facility of his PLB.

1.6.6.2 Automatically deployable emergency locator transmitter (ADELT)

The ADELT system fitted to G-TIGK consisted of the beacon, a launching spring, a pyrotechnic 'squib' and a lithium battery; all were in a carrier mounted externally on the left-hand side of the rear fuselage (Appendix B, Figure 4). The launching system could be initiated by any one of three signals from: a cockpit switch, a saline switch in the carrier, or from any one of three frangible 'crash switches' mounted in the airframe, close to the skin. Although the ADELT eventually radiated successfully, it is not known whether it deployed on ditching, during the subsequent period of floating, or from the sea bed.

1.6.6.3 Underwater Sonar Locator Beacons

There were 2 Ducane Beacons installed on G-TIGK. One was located in the transmission area and one was mounted on the face of the CVR. Such beacons are designed to transmit for 30 days after they are immersed. These functioned satisfactorily.

1.7 Meteorological information

1.7.1 Pre-flight briefing forecast (Issued at 0400 hrs: valid from 0600 hrs to 1600 hrs).

For the first half of the flight to the Brae oilfield, the forecast was: Visibility 30 km, 1 to 3 oktas of cumulus (Cu) and stratocumulus (Sc) base 2,500 feet and tops 5,000 feet, moderate turbulence and moderate icing; isolated conditions of 8 kilometres visibility in rain showers, or rain and snow showers, with 6 to 7 oktas Cu, base 1,500 feet tops above 10,000 feet.

For the remainder of the flight to Brae, the forecast was: Visibility 30 km, 2 to 5 oktas Cu Sc, base 2,000 feet tops 6,000 feet, moderate turbulence and moderate icing; occasionally 6 km visibility, rain showers or hail, rain and snowshowers, with 7 to 8 oktas Cu, base 1,500 feet tops above 10,000 feet; occasionally 1,500 metres visibility, hail and snowshowers, with 8 oktas stratus (St) with embedded cumulonimbus (Cb), base 700 feet tops above 10,000 feet; isolated thunderstorms with 8 oktas Cb, base 1,500 feet tops above 10,000 feet.

General sea state: Moderate in the south, very rough in the north.

1.7.2 Aftercast

The synoptic situation at 1300 hrs showed an unstable southerly airstream established over the area of the accident behind a cold front further east towards Norway with strong to gale force southerly surface winds.

Weather: Squally showers of rain, hail and snow. Visibility: Generally around 20 km or more but deteriorating to around 4 km in showers. Zero degree isotherm: around 2,000 feet. Surface temperature: +8°C.

Cloud: 3 to 7 oktas, base between 2,000 and 3,000 feet with occasional large Cu or Cb base between 600 and 1,000 feet, tops 18,000 to 20,000 feet.

Winds: Surface: 170°/25 to 30 kt, gusts 35 to 40 kt. 2,000 feet: 190°/35 to 40 kt.

The Dudwick Radar went off line at 1130 hrs, but the last relevant display (at that time) showed shower activity in the area and to the south, which was moving northwards. The METEOSAT infrared picture for 1250 hrs showed building cumuloform clouds in the area of the ditching position and an automatically located atmospheric discharge (SFERIC) was reported at 1300 hrs, at position 58° 50' North and 001° East , some 50 nm away (see also section 1.18.8).

1.7.3 The provision of lightning/storm data

The identification of areas of intense storm activity relies upon radar returns from water droplets in rain bearing clouds, and the ability to avoid them is achieved by means of both ground and airborne radar. However, the identification of isolated areas of potential lightning discharges has not in the past been considered a vital necessity, perhaps because of the previous lack of critical damage to aircraft arising from associated lightning strikes.

In the early 1990s, a Meteorological Information System (MIST) was provided by the Civil Aviation Authority (CAA) to The British Helicopter Advisory Board (BHAB) for the use ofthe offshore operators, as a part of the services paid for by navigation charges, and was used for the self-briefing of pilots during the planning stage of a flight. The associated 'SFERICS' (automatically located atmospheric discharge) service is based on data from five outstations in the UK and two further stations overseas. Lightning discharges are detected by these outstations and the associated information is transmitted to the Meteorological Office at Bracknell. This information is processed and is then available for transmission to the appropriate ATC users. The present estimate is that the geographical locations of the lightning discharges have an accuracy of 2.5 km if the detection has been made by UK stations and 10 km if an overseas station is involved. Additionally, there is a time delay of 15 to 20 minutes between the discharge and the information reaching ATC.

In May 1996, Aberdeen received a software programme to enable 'SFERICS' information to be displayed on their ATC screens. Following discussions between the CAA, Aberdeen ATC and the helicopter operators, a trial was planned to confirm the most effective way of utilising and distributing this lightning information; the trial was intended to have been completed by the end of October 1996.

The delay of 15 to 20 minutes before the information is received by Aberdeen ATC was intended to be improved in the future. However this improvement, for which no implementation time scale has been set, is not forecast to be better than 5 minutes, ie a resultant total time delay of between 10 and 15 minutes. Additionally, even at this stage, there are other limitations, in addition to the latter time delay, associated with relevant information reaching the crews. These are as follows:

(a) The controllers will only use the system if they can do so without degrading their primary role of air traffic control. This may result in additional time delays.

(b) Aircraft can be displayed on radar out to a range of approximately 80 nm at 2,000 feet. Beyond that range, they are working the rebroadcast (REBRO) network on procedural control; the REBRO operators do not have radar screens and rely on aircraft position reports. Thus the geographical references of the helicopter and reported lightning discharges will need to be co-ordinated by the REBRO operators for helicopters outside radar range, with associated time delays.

1.8 Aids to navigation

Not relevant.

1.9 Communications

The helicopter, callsign 56C, used the normal Aberdeen ATC communications, with radar monitoring out to a range of 80 nm, and the FIS to 120 nm. These frequencies were recorded automatically. Thereafter, 56C changed frequency to the Brae Traffic Watch which, following the first Mayday call, was recorded using a privately owned cassette recorder for the duration of the events.

Brae Traffic kept Aberdeen ATC aware of the events as they were occurring. 56B, using the REBRO network, also relayed progress to Aberdeen, whilst using the Brae Traffic frequency to co-ordinate the various assets.

The communications between the RAF Rescue Co-ordination Centre (RCC) at Edinburgh and the available civilian assets was achieved by the mutual co-operation of the Nimrod crew and the Marine Rescue Co-ordination Centre (MRCC) at Aberdeen.

1.10 Aerodrome information

Not relevant.

1.11 Flight recorders

The helicopter was equipped with a combined voice and flight data recorder (CVFDR), manufactured by Penny and Giles Ltd, part no 900/D51506. The CVFDR, which had been recording satisfactorily prior to the lightning strike, ceased recording at the time of the strike. It was determined that the recorder had lost its power supply as a result of operation of the G-switch due to the level of tail rotor vibration induced by the lightning strike. Electrical power was cut to the CVFDR sufficiently quickly that the audio effects of the lightning strike were not recorded on the audio tracks of the CVFDR.

1.12 Wreckage recovery and examination

1.12.1 Evidence recorded before AAIB arrival on site

Photographs and videos were examined immediately following the accident and these showed the helicopter floating after the ditching, with the aid of its flotation bags, but without its tail rotor or tail rotor gearbox. All four main rotor blades were visible, although one blade appeared to have been damaged by bending loads.

1.12.2 Observations made by AAIB personnel from remote viewing equipment on salvage vessel

When the aircraft was located on the sea bed by the semi-submersible MSV 'Stadive' on 21 January, at position 58° 41' 39.136" North, 01° 06' 20.289" East, it was found to be lying inverted, substantially intact but with only one main rotor blade present, separated near its root end but correctly orientated, beneath the rotor head. Only varying lengths of the root ends of the other main rotor blades remained attached to the rotor head.

The tail rotor gearbox, complete with the remains of all five tail rotor blades, was later successfully located on the sea bed at position 58° 35' 56.3" North, 01° 10' 11.9" East on 24 January, close to the reported position of the ditching. Visual examination of the exposed underside of the aircraft revealed no panel distortion or other damage due to the sea impact.

1.12.3 Salvage and recovery

Both the main wreckage and the tail rotor/tail rotor gearbox assembly were successfully recovered, under AAIB supervision, on the 23 and 24 January respectively. Appendix A, Figure 4A shows the damaged tail rotor and gearbox after recovery. The separated 5.94 metre section of the outboard 'Black' main rotor blade (s/n 269) was also recovered from the sea bed. The majority of the outboard lengths of the 'Blue' (s/n 499), 'Yellow' (s/n 517) and 'Red' (s/n 939) main rotor blades were not recovered, but some 2.9 metres, 2.8 metres and 1.9 metres respectively of their roots were salvaged. After initial examination aboard the deck of the salvage vessel, which showed clear evidence of lightning strikes on two main rotor blades and one tail rotor blade (see Appendix A, Figure 4B), the recovered wreckage was transported to the AAIB facility at Farnborough for detailed examination. Subsequently, one of the missing outboard sections of a main rotor blade was found on a beach in Norway and was returned to the operator and thence to the AAIB. It was identified as the missing 5.49 metres long section of the 'Red' main rotor blade.

At a later date both cabin doors were recovered from a beach in Scotland and returned via the operator to the AAIB.

1.12.4 Detailed examination

Examination of the aircraft tail boom pylon revealed evidence of a number of tail rotor blade impacts on the rear face and on the right side (Appendix A, Figure 5). The tail rotor gearbox had suffered failure of its two lower attachment lugs (Appendix A, Figure 6) and the bolt at the upper attachment position had also failed. Four of the five tail rotor blades were fractured at approximately 40% span; the outboard sections were not recovered. The fifth tail rotor blade was extensively damaged, but the whole span remained. With the exception of the 'White' tail rotor blade, all tail rotor blade damage appeared to be consistent with the effect of the blades striking the pylon after the gearbox had separated. The gearbox had been retained finally by 2 of the 4 stainless steel hydraulic lines, which served the tail rotor pitch control servo, before they severed after the ditching (Appendix A, Figure 7).

The aft coupling of the tail rotor drive shaft had suffered an overstressing failure and showed associated evidence of rotational damage. The output arm of the tail rotor pitch control swivel lever had severed due to overstressing, as had the quadrant output, but the cables were still attached to the broken quadrant. All four main rotor blades had separated within their inboard span areas (three blades having been apparently intentionally cut through during attempted salvage, as described earlier), and the 'Blue' blade exhibited evidence of lightning damage effects, with loss of its brass conducting strip and root/rotor head bonding strap. The other three blade root sections had retained their associated conducting strips and blade root/head bonding straps, each of which appeared undamaged.

Examination of the wreckage revealed three areas where clear evidence of lightning damage was present. These were as follows:

(1) The Blue main rotor blade (Appendix A,Figure 8), which had suffered complete loss of the brass strip linking the stainless steel leading edge anti-erosion shield to the braided earth cable, with attendant evidence of thermal damage and 'fissuring' to the composite material below the strip and failure of the braided earthing connection which crosses the flapping hinge. The bolt attaching the braiding to the blade hinge assembly inboard of the flapping hinge had been over-stressed.

(2) The Black main rotor blade (Appendix A, Figure 9A), which had evidence of 'arcing' between all adjacent sections of the leading edge anti-erosion shield, with overheating of the adjacent composite areas. (Figure 9B shows all recovered main rotor blade sections).

(3) The White tail rotor blade root section (Appendix A, Figures 4A, B, 10 and 11), which had suffered marked delamination of its composite skins and associated thermal damage of its root areas, together with loss of its anti-erosion shield, brass conducting strip and failure of the braided bonding strap and its attachment lug to the blade bolt (see also section 1.12.4.2).

The forward cabin roof above the cockpit had compressed downwards, as a result of the helicopter having struck the sea bed in an inverted attitude, with associated compressive deformation of the forward door frames and rupture of both lower transparencies, and radome. All four doors had detached, (jettisoned after ditching) and all four windows on each sideof the cabin were missing. The cabin was intact, although the aft roof section had pulled away with the main gearbox and rotor head assembly during salvage lifting operations as a result of associated structural damage induced by the inverted contact with the sea bed. All seats and associated restraint straps appeared undamaged. All three main landing gear legs were found extended. The automatically deployed emergency locator transmitter had deployed and was not recovered (section 1.6.6.2).

1.12.4.1 Detailed examination of tail rotor gearbox area

Examination of the tail rotor gearbox/pylon area confirmed that the gearbox had separated as a result of failure of the magnesium alloy gearbox casing at, or close to, the two lower attachment points, in addition to failure of the upper attachment bolt. Metallurgical examination of the separated head end of the upper attachment bolt revealed that it had fractured across the threaded portion in a plane between one and two threads from the point at which the thread runs out into the plain shank (see Appendix A, Figure 12A). Examination of the threaded portion remaining in the pylon structure showed that the failure was in a plane positioned slightly below the face of the barrel nut housing. Once the housing had been cut away from the structure and slit to release the barrel nut and the threaded fractured end of the bolt, it was evident that the bolt had only been engaged by two full threads at the time of fracture, as opposed to the normal engagement of approximately six threads.

Two major damage mechanisms were visible on both mating fracture faces. The first appeared to be annular fatigue propagation extending around the thread form and which had developed from multiple origins in the thread root. This fatigue had extended, in the form of a helical crack, through approximately two turns of the threaded bolt section in the barrel nut. This pattern of fatigue was consistent with the effect of either a cyclic bending load or cyclic tensile loading with an offset load axis with, in either case, the loading having been applied whilst the bolt was rotating.

The second mechanism was simple bending fatigue, covering most of the area of the remaining section, with only a very small area having finally separated in overload. The lower fractured surface of the bolt is shown in Appendix A, Figure 12B.

The annular damage was of medium-to-high stress/medium-to-low cycle fatigue, whilst the bending failure across the middle of the section was due to high stress/low cycle fatigue. A count of the fatigue striations on the central fracture face of the head/shank end indicated some 150 to 200 cycles, representing rather less than ten seconds of operation if the fatigue cycling had been induced by tail rotor imbalance. Although some 50 striations were visible on the annular fracture face of the head/shank end, the crack extended into the unfractured thread for a further thread turn where fatigue was presumed to be present.

The orientation of the final fatigue damage and overload failure were consistent with a bending load direction on the slackened bolt to the left and indicated that the lower right-hand gearbox attachment must have failed first to enable this bending load to have been applied to the bolt. The fracture surfaces of the magnesium alloy gearbox casting had suffered rapid salt water corrosion and hence their mode and direction of failure could not be established by metallurgical examination. It could only be deduced from the nature of nearby damage.

The upper part of the pylon immediately below the gearbox exhibited cracking of the two outer skins and the forward spar web. This cracking was in a position similar to that previously observed on AS330 and AS332 helicopters known to have lost a tail rotor blade tip balance weight, or to have suffered loss of part of a tail rotor blade whilst in flight, or while ground running.

Examination of the gears and bearings after the tail rotor gearbox had been dismantled revealed no evidence of damage, other than that due to salt contamination and the gearbox casing failure.

1.12.4.2 Detailed examination of tail rotor blades

Initial visual examination of the recovered root section of the White tail rotor blade (s/n 22810) revealed complete loss of the leading edge titanium anti-erosion shield and the fibreglass layer below it, together with extensive delamination and loss of material on both sides of the blade extending out from the root to the station at which the outboard section had broken away, some 46 to 51 cm from the root. The brass strip was missing and a longitudinal fissure some 15 cm long (see Appendix A, Figures 4B and 10) was visible in the exposed surface normally shielded by the strip. After removal of the strip attachment bolt from the blade, it became evident that the end of the brass strip was noticeably curled around the washer beneath the attachment bolt. An area of local delamination of the composite was evident around both root attachment steel bushes and was found to be quite extensive when subjected to a series of 'tap' tests. The braided bonding strap attaching the brass strip to the rotor hub inboard of the flapping hinge had been torn apart. The bolt securing the braid to the blade was bent.

A more detailed examination of the White tail rotor blade was carried out by the composite materials section of the Materials and Structures Department of the Defence Research Agency (DRA). It was found that visual examination and general optical microscopy were not productive techniques on such thin composite sections. X-ray examination revealed little useful data and so it was determined that examination of large numbers of individual fibres and small groups was necessary to 'map' the fracture faces and thereby determine modes of failure. This process entailed use of scanning electron microscopy which required small 'coupons' to be cut from the area of the fracture to be examined. The significance of the observations was established largely by comparison with similar examinations carried out on blades used for later lightning tests (see section 1.16).

It was noted particularly that overheating had occurred in the area of delamination close to the most outboard area of the White blade root section, ie close to the blade fracture. Three other blades showed evidence of fracture consistent with the effects of impact between the revolving tail rotor and the aft side of the pylon after the gearbox had detached from its mountings. The general characteristics of the fractures were not significantly different from that on the White blade. In the case of 'Red' and 'Yellow' tail rotor blades, which had been severed some 51 cm and 47 cm from their respective roots, the inboard sections of their anti-erosion shields had remained attached, the outboard sections having severed coincident with the fractures in the composites. 'Blue' tail rotor blade, which had severed some 47 to 56 cm from its root, had almost the whole of its anti-erosion shield disbonded from the leading edge of the composite section, but it had remained attached by a small area of bonding close to the root end. The remaining 'Black' tail rotor blade had not fractured within its mid area and had retained its complete erosion shield. However, the aerofoil aft of the outboard spar had suffered damage and loss of material. Appendix A, Figure 13, shows the recovered tail rotor blade sections (outboard/right sides uppermost).

1.12.4.3 Examination of main rotor gearbox

A strip examination of the main rotor gearbox was carried out. With the exception of salt water corrosion, no evidence was found of any unusual gear wear or damage. Damage was, however, found within the gearbox resulting from downward displacement of the rotor head relative to the gearbox. This was considered to have occurred as a result of the helicopter having come to rest inverted on the sea bed, the majority of the aircraft weight having thereafter been taken by the rotor head. Use of a Gausmeter on the gears confirmed that a number of planet wheels and a sector of the meshing annulus were heavily magnetised.

1.12.4.4 Examination of jettisoned cabin doors

Appendix A, Figure 14, shows G-TIGK onboard MSV Stadive, after recovery.

Both main cabin doors were recovered and returned to the AAIB some weeks after the accident. It is understood that they had been found on a beach in Scotland and that the operator had then been informed via the Coastguard. On examination, it was noted that the two rollers which guide the upper edge of one of the doors had broken off, as had the forward roller from the other door. The failure in each case had occurred at a point where a roll pin passes horizontally through the end of the spring-loaded mounting arm which guides the upper edge of the door during door movement. The roll pin secures the roller pivot pin. The arm is stiffened by a tapered flange which is at its deepest at the end opposite the roller. The roll pin is positioned at a point where the stiffening flange of the arm has tapered to leave only a flat section of thickness approximately three times the diameter of the roll pin. Excessive salt water corrosion prevented any useful metallurgical examination to determine the mode of this failure, but the relative dimensions of the components and the visible distortion suggested that the rollers had been loaded in bending such that the ends of the mounting arms fractured at the point where they were weakened by the holes which accommodate the roll pins.

The fractured ends of the hook-shaped roller mounting arms (Appendix B, Figure 5) were very sharp and were judged capable of inflicting tearing damage on inflatable equipment.

1.13 Medical and pathological information

Both pilots held valid medical certificates. There was no medical contribution to the causes of the accident.

1.14 Fire

There was no fire.

1.15 Survival aspects

1.15.1 General

As discussed in section 1.1, the first officer was the handling pilot for the accident flight and retained control of the helicopter throughout. After the loss of tail rotor effectiveness, the first officer concentrated on regaining and maintaining control of G-TIGK, whilst the commander carried out the necessary emergency procedures. Prior to ditching, the commander had shut down both engines and inflated the emergency flotation; the first officer had entered autorotation and made a gentle touchdown on the surface, approximately into wind. All the passengers were correctly strapped-in and, following the initial event, had fully zipped-up their immersion suits and pulled up their hoods. Subsequently, those passengers beside windows released the beading, to varying degrees, in preparation for a possible ditching and evacuation. Throughout the emergency, the passengers heard no verbal warnings from the crew, although the crew had attempted to pass information to them. This aspect is further discussed in section 1.18.3.

1.15.2 Evacuation

During the flight, the passengers were located in the seats shown at Appendix B, Figure 1. Following the initial 'bang', the passenger in seat No. 8 moved to seat No. 7. After the ditching, which all aircraft occupants reported as 'gentle', the crew released their cockpit doors and the commander operated the flight deck jettison handle for the right-hand cabin door. The commander remained in the cockpit and switched off all the non-essential systems before going back to the passenger cabin. The first officer, believing that he had already passed necessary evacuation instructions to the passengers via the PA system, had already gone back into the cabin.

Meanwhile, the passengers were preparing for evacuation and, before the first officer entered the cabin, both cabin doors had been jettisoned, most of the windows had been pushed out and the two helirafts had been released and deployed. At this stage, the wind was blowing onto the left side of the helicopter and the two passengers who had deployed the left side heliraft were experiencing difficulties; this was because the heliraft was blowing up against the open door of the helicopter, making boarding very difficult. When the first officer entered the cabin, he made the decision for all the occupants to board the right heliraft to keep everyone together. The final order of boarding the heliraft could not be positively established, although the two crew members were the last to board. Interviews with the helicopter occupants recorded their initial actions and their means of evacuation from G-TIGK; these are detailed in Appendix B, Enclosure 1.

Both helirafts (Appendix B, Figure 3), which could be used when floating 'either way up', had one short 0.91 metre firing/mooring line and another mooring line which was 11.89 metres long. The outboard end of each line is attached to the helicopter, and the heliraft ends are attached to separate 'bridles' which span both buoyancy rings, thereby enabling access whichever way up the heliraft is floating. Beside the short line bridle is another one, to which the sea anchor is attached. When all occupants are aboard, both the short mooring line bridle and the adjacent sea anchor bridle should be severed, leaving the heliraft attached to the helicopter by only the long mooring line. Two survival equipment bags are attached to a fourth bridle.

Following the rescue, the occupants of the heliraft reported some difficulties in utilising the equipment (see section 1.18.4). The lower buoyancy chamber had punctured, apparently due to contact with the edge of a floating door (as witnessed by a survivor) and the lifeline had become detached from the heliraft. It was not possible to erect the canopy fully, however the commander later stated that in view of the expected rescue timescale and his perception that some of the occupants may have felt claustrophobic, he did not think that this was a problem. The occupants were unable to locate the equipment bag containing the paddles and bailer. The commander was struck on the head by the inflation cylinder as a result of wave effects.

After being salvaged, the heliraft was initially inspected by the Bristow Helicopters Safety Equipment Inspector at Aberdeen and then delivered to the manufacturer for detailed investigation of the reported problems. An extract of the manufacturer's report is included at Appendix B, Enclosure 2.

1.15.3 Search and Rescue

Following the initial Mayday messages from 56C between 1236 hrs and 1240 hrs, the emergency services were quickly alerted. 56B relayed the final Mayday message on the REBRO frequency to Aberdeen ATC. By 1245 hrs, the RCC and MRCC had each ensured that the other was aware of the emergency and had initiated full Search and Rescue (SAR) action. Additionally, following the initial Mayday call, the Brae/Miller field had started their emergency actions.

The first visual contact with the survivors was made by 56B which had taken-off from Brae 'B'. This Tiger helicopter proceeded along the last known track of 56C and, at 1300 hrs, sighted some surface smoke from one of the two flares set off by the crew in the heliraft. It was overhead the heliraft at 1306 hrs and immediately passed its position to both Aberdeen ATC and Brae Traffic. At this time, 56B also assumed the role of OSC to guide the rescue vessels to the scene as soon as possible.

Several surface vessels were already attempting to locate the survivors, but some confusion had been caused by inaccurate position reports, caused by the necessary manoeuvring of the stricken helicopter after the initial emergency. However, this confusion was clarified by an accurate position report from 56B, and the surface vessels made best speed towards the survivors. First to arrive on scene were two Standby Vessels, one from the Brae/Miller oil field (the 'Grampian Freedom'), and the other from the Tiffany oil field (the 'St Patrick'). When they were at a suitable range from the heliraft, at about 1335 hrs, these vessels launched their Fast Rescue Craft (FRC) and, despite the high sea state, their coxswains were able to manoeuvre alongside the heliraft and take aboard all eighteen survivors.

By 1340 hrs Rescue 11, an RAF Nimrod, was overhead the area and, with the rescue proceeding well, left 56B to maintain the duties of OSC until 1430 hrs, when Rescue 11 took control. By 1406 hrs, all the survivors had been safely transferred to the Grampian Freedom.

1.16 Tests and research

1.16.1 Lightning simulation tests at LTT Culham

Since the outboard 60% span of the White tail rotor blade (TRB) had separated from this blade (and from another three TRBs) and had not been recovered, it was decided to conduct a series of simulated lightning tests on similar AS332L TRBs in order to attempt to reproduce the lightning-induced damage effects present on the inboard section of the White TRB. It was considered that such testing would enable an assessment of associated blade damage effects and related tail rotor out-of-balance forces which had been input into the tail rotor gearbox mountings, and would also allow comparison of required simulated lightning strike energy levels with modern lightning certification advisory criteria (ie AC20-53A). Section 1.18.5 describes AC 20-53A.

These tests, which were carried out over three separate series of tests using a total of 10 TRBs, were conducted at Lightning Test and Technology (LTT), Culham, Oxfordshire, which is part of AEA Technology. The tail rotor blades used in these tests were undamaged blades from service operation. All tests were recorded by photography, video and a series of three LTT test reports.

A detailed description of these tests and the associated results, which were covered in three related LTT reports (AEA-TSD-0562, AEA-TSD-0690, AEA-TSD-0935), is given in the following seven pages, the key findings of which may be summarised as follows:

1. The leading edge anti-erosion shield was found susceptible to debonding over most of its contact area during tests with input energies below AC20-53A criteria, and was instantaneously detached from blade leading edges with action integrals which were some two-fold the level stated in these criteria. The exposed composite leading edge was 'split open' over its outboard half span in the final test with an action integral 79% higher than AC20-53A.

2. Marked thermal damage and delamination of the composite skins adjacent and outboard of both root bolts/bushes was observed, the extent of which increased with applied arc energies up to the maximum action integral of $4.2 \times 10^6 A^2 s$ applied; comparison of the most marked root damage produced with that evident on the White tail rotor blade from G-TIGK led LTT specialists to state that the latter blade "may have had an action integral three times that of the Zone 1A certification level..", ie $6 \times 10^6 A^2 s$. (Action integral = $A^2 s$, where A is the current in amperes and s is the time in seconds).

3. Simulated lightning arc attachments to the trailing edge of these carbon composite blades produced gross damage to the aerofoil skins, particularly with attachment to points up to 0.5 metre from the tip, and including input energies just below AC2053A levels.

4. Despite high energy arc attachments to both steel tip weight bolts, these remained securely attached to the test blade tips.

Appendix C, Enclosure 1, includes extracts from AC20-53A. Appendix C, Enclosure 2, describes the test wave forms used and the test cell apparatus, the latter being illustrated in Appendix C, Figure 1A. A tail rotor blade sleeve and spindle assembly from G-TIGK was used to mount the root of test blades, using two standard attachment bolts through the steel bushes in the blade root.

The blade root bonding strap was connected, as on the aircraft, to the associated bolt on the sleeve assembly, with the inboard bonding strap connecting this bolt to the adjacent metal end plate of the test cell, as illustrated in Appendix C, Figure 1B.

The latter Figures 1A and 1B show the first test blade s/n 22313 in the test cell with two Rogowski current measurement coils in place around the root/sleeve area. The primary aim of using these coils in this first exploratory test was to establish the proportion of current which would flow off this TRB through the bonding strap. Since high current levels, of the type to be used in all the later tests, were expected to destroy the root bonding straps, this initial test was conducted at a comparatively low current of 12.7 kA (kilo-amperes) in order to avoid the risk of direct arc attachment to these coils.

Although this first test was therefore conducted at a very modest current to measure bonding strap current flows, the result was quite unexpected, since the titanium erosion shield 'peeled-back' from the adjacent brass conducting strip as shown in Figure 2 of Appendix C. The nature and extent of this peeling-back of the titanium shield suggested that a poor electrical bond had existed between the erosion shield and the brass bonding strip which linked the shield to the bonding strap stud at the blade root. It was therefore decided to carry out bonding resistance checks across this shield/brass strip joint on the three other TRBs (s/nos 22200, 20667 and 21667) which were to be tested in this first series of tests. The measured resistances were found to be 3 ohms, 3.4 ohms and 1.5 ohms respectively. These were very much higher than anticipated, since low bonding resistances of a few milli-ohms should have been present. However, upon discussing these results with Eurocopter representatives present, it was stated that instances had occurred on blade production in which resin had penetrated between the brass conducting strip and the titanium erosion shield where they overlapped to form the purely 'mechanical' (ie metal/metal) surface joint.

The second test was conducted on TRB s/n 22200, with current attachment via a 10 cm 'fuse wire' to the tip ofthe leading edge erosion shield. The applied current was 190.90 kA with an action integral of 1.92 x $10^6 A^2s$, and a total charge transfer of 19.13 coulombs. Inspection of this blade after the test showed that the titanium erosion shield had debonded from the blade over some 90% of its contact area; the brass bonding strip had 'vaporised'; the root bonding strap had 'blown-off', leaving remnants of its terminals still attached to the associated bolts; and there was some localised delamination outboard of both steel attachment bushes. Appendix C, Figure 3, shows the post-test condition of this blade over its inboard span, with the White TRB section for comparison.

In the third test, the fuse wire was attached to the trailing edge tip of TRB s/n 20667 and an applied current of 180.1 kA passed, with an action integral of 1.91x $10^6 A^2s$ and a total charge transfer of 20.4 coulombs. Although these energy parameters were again less than those median values specified by AC20-53A (ie -9.9% current; -4.5% action integral; and -27.2% respectively of the total charge transfer specified), the blade was markedly damaged by this test. The blade tip area was badly delaminated, as illustrated in Appendix C, Figure 4, with peel-back of the outer 10 cm of erosion shield and, to a lesser extent, of the shield inboard end. The titanium erosion shield appeared debonded over some 90% of its blade contact area. The brass bonding strip had vaporised, and the root bonding strap had blown-off, as before. The thermal delamination damage adjacent to both steel attachment bushes was more marked than that witnessed in the second test. Despite the damage to the blade tip area, both tip bolts appeared secure.

In view of the damage produced by the third test, it was decided to carry out another trailing edge tip arc attachment on the next test blade, s/n 21667, but at much higher current values. Test number 4 was carried out at 253.7 kA, with an action integral of 2.92 x $10^6 A^2 s$ and total charge transfer of 19.2 coulombs. These values were respectively +26.9%, +46.0% and -31.4% of the AC20-53A median values. Despite the much higher current used in this test, the tip area appeared less damaged than that in test number 3, however the outboard end of the titanium erosion shield was again peeled back, with a local 'burn-hole', and another burn-hole was present on the shield some 34 cm inboard from the tip. Appendix C, Figure 5, shows these holes and the delaminated tip area. The titanium erosion shield was again largely debonded from the blade. In addition, two chordwise 'splits', or cracks, were present within the mid-span area of the blade (on right side), some 56 cm and 69 cm from the tip respectively. The inboard crack was some 8 cm in length; the outer crack was some 8 cm chordwise, with a 1.5 cm extension inboard from the aft end of this crack. The brass bonding strip had vaporised, but a small longitudinal crack (some 6.0 cm long) was visible on the underlying blade surface, an effect which was evident on the White TRB, but to a much greater extent. The root bonding strap had blown-off. The blade root area appeared much more heat-affected than that in the previous test, although the visible extent of thermal delamination adjacent to both steel attachment bolt bushes appeared similar.

Whilst this first series of tests, which were conducted on the 24 February 1995, had indicated that simulated lightning strikes with energy levels less than that specified by AC20-53A could cause almost total debonding of the titanium leading edge anti-erosion shield and trailing edge tip strikes could, in addition, damage the tip aerofoil, the tip bolts had not appeared to suffer any marked degradation of their attachment and the blade root damage appeared much less than that evident on the White TRB.

A second series of tests was therefore conducted on the 6 April 1995 to explore the effects of simulated lightning attachments to each tip bolt; to the mid trailing edge; and to the inboard end of a leading edge anti-erosion shield.

Prior to this second series of lightning tests,TRB s/n 20625 was subjected to a series of high voltage pulses from a 12 cm diameter spherical ('ball') electrode which was positioned 16 cm above each of the tip bolts in turn. The object of these tests was to establish if conduction between each tip bolt and the blade structure was possible, and therefore if a high current simulated lightning attachment could occur at these bolts. Five high voltage discharges were fired with the spherical electrode above each tip bolt. Each discharge was recorded photographically and it was confirmed that attachments to the forward and aft tip bolts occurred.

The first simulated lightning attachment of this 2nd series of tests was carried out on TRB s/n 20636, with current injection via a 10 cm arc to its aft tip weight bolt. The applied current was 198.9 kA, with an action integral of 2.12x $10^6 A^2 s$ and a total charge transfer of 33.1 coulombs. These values were respectively -0.55%, +6.0% and +18.2% of the AC20-53A median values. Post-test inspection showed that the tip area around the aft bolt was damaged locally and the leading edge erosion shield had almost completely detached, as illustrated in Appendix C, Figure 6A. The brass conducting strip had vaporised and the root bonding strap had blown-off. The blade root showed the most marked thermal delamination damage witnessed in the tests up to this stage (Appendix C, Figure 6B) with visible areas of damage on both sides of the root. However, despite the damage around the aft tip bolt, it still appeared firmly attached to the blade.

Test No 2 of this second series was conducted on TRB s/n 20625 (which had earlier been used for the high voltage tests). This test was intended to simulate lightning attachment to the forward tip weight bolt, with a 10 cm arc attachment and an applied current of 194.9 kA, action integral of 1.99 x $10^6 A^2 s$ and total charge transfer of 35.45 coulombs. These values were respectively -2.6%, -0.5% and +26.6% of the AC20-53A median values. Post-test inspection of this blade showed some blackening around the forward tip bolt, but the tip of the erosion shield exhibited arc damage indicative of the attachment having transferred to the tip of the erosion shield. The latter had almost completely detached, as shown in Appendix C, Figure 7A. The brass conducting strip had vaporised and the root bonding strap had blown-off.No longitudinal 'fissuring', or cracking, was apparent on the blade substrate exposed by the loss of the brass conducting strip, which was also the case in the previous test. In addition, the damage within the blade root area appeared less (Appendix C, Figure 7B) than that in the previous test.

Since these two tests had not appeared to substantially weaken either tip bolt's retention by the blade tip structure, it was decided to conduct the third test of this series on the mid trailing edge area of TRB s/n 20646. An arc attachment was therefore made to the trailing edge at a point 0.5 metres from the tip, with an applied current of 188.2 kA, action integral of 1.96 x $10^6 A^2 s$ and total charge transfer of 26.81 coulombs. These values were respectively -5.9%, -2.0% and -4.25% of the AC20-53A median values. The effect of this simulated lightning attachment on the mid span structure of this blade is graphically illustrated in Appendix C, Figures 8A and 8B. The aerofoil structure was grossly disrupted, with delamination and disbonding of the composite over an area of approximately 50 cm x 15 cm. There was marked spanwise cracking and associated aerofoil distortion aft of the erosion shield (Figure 8B), which had debonded over some 75% of its length, inboard from the primary damage. The brass conducting strip had vaporised and the root bonding strap had blown-off. The blade root area showed marked delamination and disbonding of the carbon fibre skins over an area of approximately 10 cm x 9 cm on both sides of the blade.

Although the extent of the root thermal/delamination damage in this test was the most marked of the tests conducted up to this stage, it did not appear of the same order as that evident on the White TRB. It was therefore decided to test the effects of a simulated lightning attachment to the inboard end of an erosion shield.

Test No 4 of this second test series was thus conducted on blade s/n 20732, with a 10 cm arc attachment to the inboard end (outboard side) of its titanium erosion shield. An applied current of 206.9 kA with an action integral of 2.10 x $10^6 A^2 s$ and total charge transfer of 26.76 coulombs was used. These values were respectively +3.5%, +5.0% and -4.4% of the AC20-53A median values. Post-test inspection of this blade showed that the erosion shield had only been damaged locally, with the inboard 13 cm of shield peeled-back from the outboard surface of the blade, as shown in Appendix C, Figure 9A. The brass conducting strip had vaporised, with no cracking (or fissure) apparent on the exposed blade substrate. The root bonding strap had blown-off. The blade root showed skin delamination and disbonding over an area of 12cm x 10 cm on the outboard (ie right) side, with a corresponding area of 10 cm x 7 cm on the inboard side (Appendix C, Figure 9B).

In view of the inboard position of the simulated strike in this last test, the degree of root delamination still appeared modest in comparison with that evident on the White blade and, in addition,the lack of substantial damage to the erosion shield and the remainder of the blade indicated that such a strike location was unlikely to reproduce the effects observed on the White blade, or to lead to a substantive loss of blade mass.

It was therefore decided to carry out the last test (No 5) in this second series, on TRB s/n 20662, with a maximum energy attachment to its aft tip weight bolt. An applied current of 275.5kA was used with an action integral of 4.2 x $10^6 A^2 s$ and total charge transfer of 29.2 coulombs. These values were respectively +37.8%, +110% and +4.3% of the AC20-53A median values. This simulated strike caused explosive detachment of the leading edge titanium erosion shield, which was badly deformed as illustrated in Appendix C, Figure 10A. The shield was also thermally discoloured, indicative of a significant temperature rise to some 400°C. Evidence of 'sparking' and 'arc-erosion' was visible on its internal angle, with corresponding witness marks on the blade leading edge. Inspection of the blade tip indicated that the attachment arc had transferred to the carbon fibre skins,but the aft tip bolt (and the forward bolt) appeared firmly attached. The brass bonding strip had vaporised, and a longitudinal 'split' or fissure, was present on the underlying substrate, as may be seen in Appendix C, Figure 10B. The root bonding strap had been blown-off. The blade root surfaces exhibited marked delamination and disbonding over an area of 13 cm x 13 cm on the inboard (ie left) side (Appendix C, Figure 10C) and 10 cm x 10 cm on the outboard side. This fifth test of the second series had thus produced the most marked root delamination damage, with the largest 'fissure' under the brass bonding strip location, and complete detachment of the erosion shield. It had not, however, dislodged the aft tip weight bolt, despite the very high energy level of this simulated lightning strike on this bolt.

One of the features of the damage evident on the White tail rotor blade was that the skin laminate to which the leading edge erosion shield had been attached had been stripped off the outboard (ie right) surface of the recovered section of blade, as may be seen in Appendix C, Figure 3. Although general debonding of the erosion shield had been readily produced in these lightning simulation tests, in all these cases the erosion shield had separated 'cleanly' from the underlying blade skin over the debonded length, with no apparent tendency to tear off the underlying skin laminate. However, subsequent to each series of tests at LTT Culham, all post-test TRBs were subject to detailed damage assessment by DRA composite specialists. This work indicated that the test on TRBs/n 20646 (ie test No 3 of the second series; Appendix C, Figure 8A), which had simulated a strike on the trailing edge, 0.5 m from the blade tip, had produced some skin delamination adjacent the inboard area of the erosion shield. The root area of this blade had also shown marked delamination and disbonding of the carbon fibre skins of some 10 cm x 9 cm on both sides ofthe blade. In addition, the mid region of the aerofoil had been grossly disrupted. It was therefore decided that additional simulated lightning tests would be carried out on further TRBs in order to explore the effects of maximum energy attachments to the trailing edges.

Unfortunately, it became apparent that further blades were in short supply and so testing was limited to two available blades, s/n 20697 and s/n 22313 The latter blade had previously been unexpectedly damaged in the first low energy (ie 12.7 kA) test, although the damage had been localised with 'peel-away' of the inboard end of the erosion shield due to poor electrical contact with the underlying brass conducting strip (Appendix C, Figure 2). It was therefore decided to effect a localised repair to this blade in order to restore effective electrical contact between the erosion shield and brass strip, and to use this blade for an initial exploratory test at maximum energy on the trailing edge.

Since the trailing edge of the recovered inboard section of the White TRB showed no evidence of lightning damage (eg delamination)the spanwise position of the first, exploratory, strike had to be assessed in order to attempt the avoidance of any resultant damage within the corresponding inboard area of the test blade. In conjunction with LTT personnel, it was decided to position this simulated lightning attachment at a point on the trailing edge which was 34 cm from the blade tip. For this test on TRB s/n 22313, which was the first test of the 3rd series of tests conducted on 10 October 1995, an applied current of 253.3 kA was used, with an action integral of $3.58 \times 10^6 A^2s$. These values were respectively +26.55% and +79.0% of the AC20-53A median values. This strike produced the most damage of any previous test at LTT. The blade aerofoil was grossly damaged, as shown in Appendix

C, Figure 11A, with the central area (approximately 50 cm x 15 cm) of carbon fibre skin disbonding and delamination extending along the trailing edge outboard towards the tip, and inboard. The inboard 0.5 m of the leading edge titanium erosion shield had detached over some 80% of its length, with three 'burn-holes' and evidence of 'sparking' onto its inner surface. In addition, and in contrast to any of the previous tests, a 10 cm length of the blade leading edge composite structure exhibited marked localised disbonding of the carbon fibre skin and underlying glass fibre, as shown in Appendix C, Figure 11B. The brass conducting strip had vaporised, leaving an approximately 5 cm longitudinal fissure within the exposed blade substrate. The root bonding strap had been blown-off. The root area of the blade appeared very heat affected, with very marked carbon fibre disbonding and delamination,as illustrated in Appendix C, Figures 11C and 11D. With regard to the blade tip, slight 'tufting' of the carbon fibre skins was present, with some cracking extending inboard on the outboard (ie right) skin, just aft of the erosion shield. However, both tip weight bolts appeared firmly attached.

Whilst the above damage in this exploratory test was marked, the effects of the trailing edge strike had caused delamination of the trailing edge to an excessive extent inboard of the strike,such that this damage was not representative of that sustained by the White TRB. It was therefore decided to move the point of strike attachment, for the final test, outboard by 14 cm in order to attempt avoidance of excessive inboard trailing edge damage.

The final test, using TRB s/n 20697, was therefore set up to produce a 'maximum energy' simulated lightning attachment to the trailing edge of this blade at a point 20 cm from the tip. An applied current of 258.3 kA, with an action integral of 3.58 x $10^6 A^2s$ was used for this test. These values were respectively +29.15% and +79.0% of the AC20-53A median values. Post-test inspection of this blade showed that the aerofoil, as anticipated, was grossly disrupted over an area of some 50 cm x 15 cm about the trailing edge arc attachment point (Appendix C, Figure 12A). In particular, however, the trailing edge delamination did not extend into the inboard half of the blade. The most interesting aspect of the damage sustained by this blade was associated with the leading edge where, in addition to complete detachment of the titanium erosion shield, the exposed leading edge had 'split-open' from about mid-span to the tip, as illustrated in Appendix C, Figure 12B. The leading edge was also split at the inboard end of the erosion shield substrate, over a length of some 5 cm. The adjacent brass conducting strip had vaporised, leaving an almost 'full length' longitudinal fissure within the uncovered blade substrate. This may be seen in Appendix C, Figure 12C, which also shows the thermal disbonding/delamination damage present in the area of the attachment steel bushes on the outboard side of the root, with the corresponding inboard side damage shown in Appendix C, Figure 12D. With regard to the tip, slight 'tufting' and cracking of the carbon fibre skins was again present, but both tip bolts appeared secure.

With regard to the comparability of the blade root damage induced by the high energy tests to that sustained by the White TRB, the LTT Culham test report AEA-75D-0690 of June 1995 stated:

'At action integral 4.2 x $10^6 A^2s$, the damage in the blade root region was beginning to show an appearance similar to the salvaged blade and with the evidence of lug damage, it is thought likely that the lightning attachment to the G-TIGK blade may have had an action integral three times that of the Zone 1A certification level in reference 3. The certification level of 2 x $10^6 A^2s$ is based on data that show only approximately 2% of strikes exceed this level.'

and:

'Occasionally strikes beyond 2 x $10^6 A^2 s$ can occur, for example evidence from a Nimrod MR Mk 11 strike also over the North Sea was thought to have involved an action integral of about 6 x $10^6 A^2 s$.'

1.16.2 Analytical research

1.16.2.1 Introduction and summary

The lightning simulation tests at LTT Culham had demonstrated that, with the maximum applied energy levels available (ie up to 4.2 x $10^6 A^2 s$), similar root damage was induced in the test blades, but of a reduced extent to that apparent on the White tail rotor blade root section. In addition, while these tests had demonstrated that the titanium anti-erosion shield was readily disbonded and detached, the two steel tip weight bolts showed no tendency to detach as a result of such arc attachment energies, even with direct attachment of high energy arcs onto the bolts themselves.

It was therefore decided to conduct a stress analysis of the tail rotor and associated gearbox casing in an attempt to quantify the tail rotor out-of-balance force which would have been required to fail the gearbox attachments within the estimated 3½ minutes time scale. This static finite element analysis, which was conducted by Hawtal Whiting Engineering Ltd and is described later in section 1.16.2.2, indicated that:

'The failure time observed in the accident is consistent with the loss of the blade tip-weight and the possible loss of the anti-erosion strip and a portion of the main blade section.' (Report HWT 5654 of 11 January 1996).

In view of this analytical result, it was decided to conduct a computer model based 'flutter' analysis of the tail rotor blade design in order to assess any tendency for the blade to suffer related structural overstressing subsequent to lightning strike damage. This tail rotor dynamic analysis,which was conducted by the Defence Research Agency (DRA) Structures Department and is described later in section 1.16.2.3, however indicated that the inherent structural stiffness of this TRB design in bending and torsion was such that a far greater degree of structural damage than that produced in any of the LTT lightning tests would be required to produce the onset of blade flutter or resonance.

In view of this result, it was decided to check the effect of loss of lift coefficient by a badly damaged TRB upon the gearbox mounting stresses due to the rotating bending moment upon the tail rotor drive shaft which would be generated by the 'lift' from the remaining four undamaged blades, However the associated calculations, which are referred to in section 1.16.2.4, indicated that the resultant stresses in the H W finite element model of the gearbox would only be approximately 1/40th of those generated by the tail rotor imbalance caused by the loss of a titanium anti-erosion shield and one of the tip weight bolts.

It was thus decided to proceed with 'spin-rig' testing of some of the more damaged TRBs from the LTT lightning tests, which had been an intention from the outset of these tests, in order to assess the effects of continued operation of such blades for some 3½ minutes at tail rotor rotational speeds. These spin-rig tests,which were conducted at the manufacturer's blade erosion test facility at Marignane and are described later in section 1.16.2.5, however showed no tendency for continued operation of such damaged blades to produce further significant damage, or associated mass loss.

It was therefore decided to conduct a finals tress analysis, but taking into account the dynamic response of the pylon/tail boom assembly, in order to evaluate any change which dynamic excitation of this assembly may have introduced to the effects of tail rotor imbalance upon the associated gearbox mounting stresses. This dynamic analysis, which was conducted by Stirling Dynamics Ltd and is described later in section 1.16.2.6, indicated that the tail boom/pylon assembly would indeed have produced dynamic responses within the tail rotor rpm range which would have accentuated the stresses on the gearbox mountings so that a very much reduced mass imbalance of the tail rotor, equivalent to loss of the titanium anti-erosion shield, would have induced failure of the mountings within the required time scale of some 3 1/2 minutes.

1.16.2.2 Effect of rotor imbalance

Hawtal Whiting (HW) Engineering Ltd of Leamington Spa was tasked with carrying out calculations to establish the effect of varying degrees of rotor imbalance on the integrity of the tail rotor gearbox mountings. The aim was to establish an approximate fatigue life/imbalance relationship in order to estimate the degree of mass loss required to produce fatigue failure of the gearbox mountings in the approximate time period (ie 3 1/2 minutes) that the aircraft had flown between the initial lightning strike and the final roll/yaw/pitch-down which occurred before the ditching. It was initially assumed that the predominant cyclic loading on the gearbox after the lightning strike would have been the result of the mass imbalance due to the shedding of parts of the White TRB as a direct, or indirect, result of the lightning strike.

A simplified assessment of weight and mass distribution of elements of a tail rotor blade was made which indicated that approximately 500 grams was concentrated in the tip area and the mass of the anti-erosion shield was approximately 100 grams. The products of mass and effective radii of these masses was calculated to be approximately 0.75 kg metres for the tip mass and 0.1 kg metres for the anti-erosion shield.

The best assessment of time between the lightning strike and the loss of the tail rotor gearbox was approximately 3 1/2 minutes, based on related RT transmission timings. Using this figure and making a number of different assessments of crack growth mechanisms (and hence growth rates) it was calculated that the imbalance required to cause cracking to failure was in the range 0.85 to 2.7 kg metres. Measurements of mass distribution in the tail rotor blade design indicated that this imbalance could only be created by the loss of the tip mass, together with the anti-erosion shield and some of the composite structure inboard of the tip mass. It did not require loss of any of the composite structure inboard of the outermost surviving material of the White blade.

During development of the finite element model (see Appendix D, Figure 1) it became clear that the highest stress levels due to the static consequences of an imbalance effect would be experienced in the region of the gearbox lower left-hand attachment point (Appendix D, Figures 2, 3, 4 and 5).

1.16.2.3 Tail rotor dynamics analysis

The Structures Department of the DRA were then tasked with developing a mathematical model of the AS332L tail rotor in order to investigate the dynamic behaviour of a blade with selected changes to mass and stiffness distributions. These represented the effects of possible damage levels inflicted by the lightning strike which the White tail rotor blade had sustained. Measurements of mass, chordwise and spanwise centre of gravity positions, bending and torsional stiffness and shear centre position were made on a serviceable blade s/n 20697 (before associated lightning test) to establish the basic model. The computer model was then re-run using modified characteristics resulting from measurements of the above parameters made on blades after they had been subjected to various lightning tests at LTT Culham. It was found that even the most severe aerofoil damage inflicted by some of these lightning tests (ie tail rotor blade s/n 20646, mid trailing-edge strike: Appendix C, Figure 8B) did not modify the stiffness characteristics sufficiently to create resonance, or a flutter condition, within the operating rpm range of the tail rotor. The calculations showed that the stiffness of the blade design was such that a far higher degree of damage than anything produced in any of the tests was required before the blade design even approached a flutter or resonant condition.

1.16.2.4 Effect of lift coefficient loss of White blade

Discussions with rotor craft design specialists from the DRA confirmed that, although the tail rotor was of the articulated type, a rotating shaft bending moment, resulting in a fixed bending moment on the gearbox mountings, would normally be generated during forward flight, the magnitude depending on flight conditions. This results from the difference in flow conditions between the advancing and retreating blades and would create a steady bending moment on the gearbox casing and the pylon.

Damage to a blade of the type and magnitude seen in many of the Culham lightning tests would result in a modified (and obviously reduced) lift/incidence relationship. This in turn would cause a damaged blade to adopt a different coning angle to that of the other blades. This would create a small rotating imbalance due to the slightly altered effective radius of rotation, but more importantly a fixed bending moment would occur on the shaft due to the effective absence of lift from one of the five blades. This in turn would produce a cyclic loading at the gearbox mountings.

The finite element model of the gearbox was used in conjunction with an applied bending moment at the shaft location to estimate the position of highest stress levels and crack growth rates and hence time to failure for various bending moment values, assuming the known cycle rate (ie the rpm of the tail rotor).

A series of simple calculations of required torque reaction at the tail rotor position showed that approximately 532 kg was required in the flight condition existing during the majority of the time between the lightning strike and the point at which the gearbox mountings failed. This force would have been provided by a combination of tail rotor thrust and aerodynamic force generated by the aerofoil section of the pylon. An initial calculation was carried out using the finite element model of the gearbox, assuming all the torque reaction was provided by rotor thrust and the coefficient of lift of one blade was reduced to zero. This required the further assumption that the bending moment at the rotor shaft position was provided by the rotating vector representing 4 of the 5 blades applying load in an axial direction at points coincident with the axes of their flapping hinges.

The calculated stresses in the gearbox were found, with the aid of the finite element model, to be of the order of 1/40th of those resulting from the simple mass imbalance effect due to a loss of a tip weight and anti-erosion shield. Since a 'worst case' assumption was used (ie a White blade lift coefficient of zero and all reaction force produced by the tail rotor, without assistance from the aerofoil section of the pylon) it was considered that despite the very approximate method employed, it could safely be assumed that only the mass imbalance had a significant effect on the time to failure of the gearbox casing.

1.16.2.5 Tail rotor blade spin-rig tests

The four test blades (s/nos 20697, 20662,2213 and 21667) most seriously damaged during the LTT Culham simulated lightning strikes were subjected to spin-testing in a rig normally used by the manufacturer for blade erosion damage investigations and development.

The purpose of the testing was to establish the extent of any further disintegration to be expected under flight loading on each blade after a lightning strike of the magnitude and point of application simulated in the relevant LTT test. The spin-test rig consisted of a motor driving a vertical shaft on which was mounted a hub to which two blades could be attached with their chordwise axes set at a selected angle to the plane of rotation. The whole assembly was sited in a reinforced cylindrical building with a control room alongside. The shaft could be rotated at selected speeds up to well in excess of the normal tail rotor speed (ie 1,295 rpm).

The first test was carried out using an undamaged AS332 blade to balance the test blade, whilst a second test used two test blades together, one mounted on either side of the hub. Each test initiated with a period of one minute with the blades mounted at the 'zero lift' angle to simulate the effect of the initial autorotation carried out by G-TIGK immediately after the lightning strike, rotating the blades at the operating rpm. The blades were then removed and refitted at the positive pitch angle (+7°) considered to most closely represent the forward flight condition of G-TIGK after the initial autorotation. A further run was then carried out for 2 1/2 minutes.

On completion of these simulations the test blades were inspected and in all cases the additional damage suffered subsequent to the LTT Culham lightning testing was found to amount to no more than loss of small sections of CFRP laminate from skin areas, together with small amounts of foam core material. In none of the spin-tests was a significant amount of additional blade mass lost. In particular, the tip weight bolts remained securely attached.

1.16.2.6 Dynamic loading effects of rotor imbalance

A reassessment of all the factors involved was then made in consultation with an experienced structural specialist (a former leading structural design and development engineer on the Concorde SST programme). He pointed out that since the condition under examination was a cyclic loading at approximately 20 cycles per second, the use of a simple finite element analysis to determine the crack growth characteristics could be misleading. In practice, the time to failure and the actual failure mode would be heavily influenced by the mass and stiffness distribution characteristics of the gearbox and of its mounting structure. A resonant condition would probably produce the highest stresses and hence cause rapid fatigue cracking in either the casing, a mounting bolt or the pylon structure (or in all three). The initial failure would then occur in whichever element suffered the most rapid loss of strength due to such cracking. Experience has shown that the crack growth rate under such dynamic conditions is not only very rapid, but can be very difficult to calculate accurately and normally requires practical testing of the total system to produce valid results.

After re-consideration of the above factors, it was decided to commission a dynamic analysis of the tail boom and the masses mounted thereon to establish whether the stresses on the gearbox casing significantly exceeded those calculated by the non-dynamic finite element analysis.

The Stirling Dynamics Company of Bristol, UK, was then commissioned to develop a computer model of the mass and stiffness characteristics of the tail boom and pylon, tail rotor, tail rotor gearbox and stabiliser of the aircraft, in order to predict dynamic behaviour. This analysis showed that, when subjected to excitation forces, a number of dynamic response modes occurred, one of which, an overtone vertical/lateral bending mode, was at a frequency of 22.07 Hz, close to the rotational rpm ofthe tail rotor (Appendix E, Figure 1). It was also noted that this mode had a natural frequency which was, to some extent, sensitive to the stiffness of the upper mounting of the gearbox. Reducing this assumed stiffness reduced the natural frequency of the overtone vertical/lateral mode from 22.07 Hz, ie somewhat above the normal cruise rpm of 21.56 Hz, progressively through that figure to a lower value, with the reduction occurring steadily as the stiffness was reduced.

It was decided to carry out a resonance test survey on an AS332L helicopter to verify the dynamic model and provide additional data. Helicopter G-TIGM was selected (being in all significant respects identical to G-TIGK) and utilised over the weekend of 14 to 15 September 1996 at its operator's home base, Aberdeen.

The associated tests were carried out by Stirling Dynamics personnel and the resultant data, when analysed, showed close agreement with their predicted model, with an overtone vertical/lateral bending and tail roll mode occurring at 22.80 Hz (Appendix E, Figure 2). In addition, three other total aircraft modes (not modelled in the computer study) were identified, involving vertical and lateral motion of the fuselage/boom/pylon, occurring respectively at 20.80, 22.35 and 23.35 Hz. (Appendix E, Figures 3, 4 and 5). The normal cruise tail rotor rotational frequency (as supplied from the operator's Health and Usage Monitoring System (HUMS) archived data) being 21.6 Hz, ie 1,295 rpm. Appendix E, Table 1, shows the significant measured and predicted response frequencies.

The characteristics of the G-switch linked to the combined FDR/CVR (which suffered power loss at the time of the lightning strike, as a result of the action of the G-switch: section 1.11) were established, together with its position within the tail boom. The threshold figure for the associated exciting force, and hence the tail rotor imbalance, required to create the acceleration level at the G-switch station to trigger it (ie 6.4 G vertical), was calculated from the corrected dynamic model. The calculations showed that a minimum level of rotor imbalance equivalent to the effect of loss of one tail rotor blade anti-erosion shield would be needed to trigger the G-switch.

Forces at the gearbox attachments resulting from tail rotor imbalance due to the loss of one anti-erosion shield were calculated (Appendix E, Table 2) and compared with the corresponding cyclic out-of-balance forces calculated by the static finite element model produced by HW Engineering Ltd. These dynamic forces were found to rise to approximately six times the original non-dynamic values, increasing as the assumed stiffness of the upper gearbox attachment was reduced to a figure at which the natural frequency of oscillation equalled the tail rotor rotational frequency.

This analysis thus indicated that the degree of imbalance required to achieve failure of the lower gearbox attachment lugs, in the applicable time (3 1/2 minutes), would be generated by loss of the anti-erosion shield from one tail rotor blade, particularly with slackening of the upper attachment bolt (see section 1.12.4.1), which would have accelerated the time to failure.

1.16.3 The heliraft

RFD Ltd carried out a full inspection of the heliraft, used by the survivors, to establish the reasons for the apparent difficulties experienced. The relevant extracts ofthe report are discussed in sections 2.2.2 and 2.3.5, and detailed at Appendix B, Enclosure 2.

1.17 Organisational and management information

1.17.1 SAR Policy

As a Contracting State under the Convention on International Civil Aviation, the UK is committed to providing SAR services for international civil aviation throughout defined areas, on a 24 hour basis.

Responsibility for SAR for civil aircraft within the UK Search and Rescue Region (SRR) rests with the Department of the Environment, Transport and the Regions (DETR). The DETR is also responsible for SAR policy for civil aviation. At the time of this accident these responsibilities rested with the Department of Transport (DOT); this department has since been merged into the DETR.

The MOD is responsible, on behalf of the DETR, for the initiation and co-ordination of Civil Aviation SAR within the UK SAR region (UK SRR) and this responsibility was discharged through two Rescue Co-ordination Centres (RCCs) located at Edinburgh and Plymouth at the time of the accident (these RCCs are now located at Kinloss and Plymouth). Air assets, both helicopter and maritime patrol aircraft, are provided by the military for civilian SAR under the operational control of an RCC and are tasked by the MRCCs when engaged on maritime accidents. The Coast guard Agency, through its MRCCs and sub-centres (MRSCs) is responsible, on behalfof the DETR, for the initiation and co-ordination of civil maritime SAR in the UKSRR. Additionally, DETR-contracted SAR helicopters are located at Sumburgh (Shetland), Stornaway (Hebrides), Lee-on-Solent and Portland. These are under the operational control of HM Coastguard.

The responsibility for initiating and co-ordinating civil aeronautical search and rescue north of latitude 52°38' North in the UK rested with RCC Edinburgh, at Pitreavie. Where there is a maritime involvement, the RCC is supported by the appropriate MRCC; in this case it was Aberdeen.

1.17.2 Organisation of SAR for G-TIGK

During this search and rescue, RCC maintained operational control although MRCC Aberdeen, at one stage, had asked if they could assume control as they considered that they had more effective communications with the considerable assets available for the SAR operation.

Additionally, because the helicopter had ditched near to the Brae/Miller oil field, the Offshore Installation Manager (OIM) of that field activated his Company Rescue Plan.

1.18 Additional information

1.18.1 Lightning strikes - immediate operational actions

As a result of a meeting convened by the CAA on 1 March 1995 to which representatives of the North Sea helicopter operators, Eurocopter and the AAIB were invited to discuss the early findings of this AAIB investigation, associated findings from the initial lightning tests on tail rotor blades at LTT Culham and operational implications, it was agreed between these operators and the CAA that the operators would issue a Flying Staff Instruction (FSI), 'Flight in Lightning Conditions - AS332L'. This FSI described the operational procedures to be adopted when lightning activity is forecast for the area in which an individual flight is to be conducted, in order to minimise the exposure of the aircraft to the risk of a lightning strike. It required commanders, whenever lightning or thunderstorm conditions are forecast, to use 'best information available' to ensure that their flights can be safely carried out. The following sources of information were listed:

(a) 'Mist' (meteorological information system) information, to establish if forecasts of lightning activity are confirmed by evidence of actual discharges, if so their position(s) with respect to intended track(s). The FSI stated that discharge areas should be avoided by approximately 15 nm.

(b) Utilisation of lightning/thunderstorm activity reports from other aircraft, operators, offshore rigs etc. Such sources were also to be used in flight for updated information, in addition to weather radar and visual sightings, to enable avoidance of perceived or potential thunderstorms/lightning activity by at least 10 nm. In cases where such lateral separation could not be achieved from actual lightning activity, commanders were to consider diverting and/or landing (on a rig, if necessary) as soon as possible to await passage of such systems.

In addition, Eurocopter issued a 'Rush Revision' (RR) No. 8B which added the following paragraph (14) to the AS332LF light Manual:

'14. LIGHTNING STRIKE

CAUTION: BEAR IN MIND THAT DELIBERATE PENETRATION IN CLOUDS WITH MASSIVE VERTICAL DEVELOPMENT IS PROHIBITED.

- Symptom:

- Flash and bang which may or not be accompanied by any of the following:

- static noise in intercom, or radio.

- tripping of electrical or avionic equipment.

- erratic compass indications.

- Pilot action

- When necessary, try to reset equipments:

FLIGHT MAY BE CONTINUED

- If severe increase in vibration occurs:

LAND AS SOON AS POSSIBLE.'

Another requirement of the FSI was that the aircraft radar became a Minimum Equipment List (MEL) requirement for flight where thunderstorm and lightning conditions were forecast for the routes to be flown.

1.18.2 Stormscopes

At the meeting convened by the CAA on 1 March 1995, the AAIB raised the question of 'Stormscope' system fitment to North Sea helicopters. As a result of associated discussions at that meeting, Bristow Helicopters Ltd agreed to conduct related trials (see section 1.18.9 later).

1.18.3 The passenger address system

The first officer, although unable to rationalise his action, clearly remembered on one occasion pressing the RT transmit button on the (cyclic) stick at the same time as using the passenger address trigger under the (collective) lever. It was not generally realised at that time that by so doing, whilst the attention-getting chime still sounded in the cabin, an electronic prioritising system cut out the passenger address amplifier in favour of the transmitter.

However, the first officer had used the PA system to brief the passengers on several occasions during the in-flight emergency, including immediately following the lightning strike and before the ditching, but none of these PA announcements had been heard by the passengers.

It was therefore decided to examine the PA system amplifier, which was located in the tail boom, in order to ascertain whether it had suffered damage during flight. In this context, the AAIB had found vibration-induced mechanical damage to the PA amplifier on another AS332L Super Puma helicopter,G-PUMH, which had suffered prolonged in-flight vibration due to a tail rotor defect on the 27 September 1995.

The PA amplifier on G-TIGK was initially examined in situ and was still attached to its avionic equipment tray which was fitted to a horizontal panel by anti-vibration mounts. A number of other avionic components were similarly mounted on the panel. It was noted that the anti-vibration mounts of all the component trays on the panel were severely damaged, one of the trays having completely separated. The mounting of the panel had also partly failed. The amplifier was removed from G-TIGK and forwarded for strip-examination to the company which had repaired the damaged unit from G-PUMH.

No evidence of similar mechanical damage was found. It was noted, however, that electrical fuses within the G-TIGK unit had failed and that individual components in the unit could not be functioned. However, it could not be established conclusively whether the fuse and component failures were solely the result of salt-water effects or had occurred prior to the ditching due to vibration or lightning effects.

1.18.4 Passenger personal survival equipment

Within a few days following the rescue all the survivors were contacted to ascertain how effective they had considered their equipment, training and pre-flight briefing.

The passengers were wearing either Intrepid Pioneer Mk 9 or Pioneer Mk 7 immersion suits and all were wearing lifejackets. All survivors transferred directly from the helicopter to the heliraft, which was overloaded with one buoyancy chamber punctured. The result was that the survivor occupants were very congested, and were sitting in water for between 80 and 90 minutes.

However, the personnel equipment protected the survivors from serious injury in the prevailing conditions. All the immersion suits worked and 7 of the 16 passenger suits still had no leaks after the rescue. The remainder had leaks varying from 'pinpricks' to more substantial ingress of water; all the suits with leaks were the earlier Mk 7 versions. Nevertheless, while some survivors reported feeling extremely cold, all were able to transfer with minimal assistance from the heliraft to the FRCs and thence to the Grampian Freedom.

The survivors inflated their lifejackets at different times. Some inflated them as soon as they were clear of the helicopter, some decided to delay inflating them because of the congestion in the heliraft, but they were all inflated prior to transferring to the FRCs. However, there were reports of some difficulty with inflation and, in particular, the left lobe of some lifejackets appeared reluctant to inflate.

The other common complaint was that the gloves, contained within a pocket on the arm of the immersion suit, were difficult to find and release, particularly with lifejackets inflated.

The passengers commented, in some cases, that they had treated their survival training as a 'necessary evil' and had not previously been convinced of its necessity. However, they were unanimous in acknowledging its value in their ordeal. Many also made favourable comments about the safety briefing provided prior to boarding the helicopter.

1.18.5 Lightning certification

The AS332L type certificate was originally granted by the Direcion General de L'Aviation Civile (DGAC) in France.

The lightning protection design aspects of the type were certificated in accordance with Transport Supersonique (TSS) Standards (known as SST standards in the UK). This was an internationally agreed set of standards originally evolved to be used for the certification of Supersonic Transport aircraft proposed and under development during the period between approximately 1962 and 1975. This standard incorporated a general reflection of nationally accepted practices then current (in those areas not specific to supersonic operation) and as such was evolved approximately coincidentally with the earliest certification criteria (in the west) to incorporate specific numerical lightning protection criteria, as opposed to the earlier simply stated requirement that all elements of the aircraft must be effectively bonded. With the exception of the nose radome, composite structural elements were not used in the design of the only SST to enter service in the west; the external structure was metallic.

The associated TSS 8.6 standard document called for a single pulse of 200 kiloamps (kA), with an action integral of $0.6 \times 10^6 A^2s$ and a charge transfer of 500 coulombs, to be applied experimentally to areas of the aircraft structure without inflicting significant damage. No provision was made in the requirements for the differences in behaviour between static structure and rapidly revolving rotor blades.

It is understood that a process of 'read-across' was used to design the AS332 Mk 1 tail rotor blade protection, in which the main outboard section of metallic earthing path utilised was virtually identical (except that the leading edge erosion shield was changed from steel to titanium, with increased cross-section area) to that used in an earlier tail rotor design (AS350 Ecureuil) which used GRP rather than CFRP as the structural material. The AS350 tail rotor blade was tested to TSS 8.6, with arc attachment to the tip of the steel leading edge erosion shield; no debonding occurred. The electrical connections on the AS332 tail rotor blade between the anti-erosion shield and the bonding braid, together with the braid, are understood to have been copied from the corresponding blade features on the AS332 main rotor blades. No separate lightning testing of the AS332 Mk 1 tail rotor design was carried out as part of the related certification process in 1981.

The TSS8.6 standard was superseded by Advisory Circular (AC) No. 20-53 on 6 October 1967 and later by AC20-53A of 4 December 1985. The latter criteria were thus current at the time of this accident, although their use by manufacturers to achieve lightning certification was (and still is) only advisory, as clearly described in the opening paragraph of AC20-53A:

'Purpose. This Advisory Circular (AC) provides information and guidance concerning an acceptable means, but not the only means, of compliance with Parts 23 or 25 of the Federal Aviation Regulations (FAR), applicable to preventing ignition of fuel vapours due to lightning. Accordingly, this material is neither mandatory nor regulatory in nature and does not constitute a regulation. In lieu of following this method, the applicant may elect to establish an alternative method of compliance that is acceptable to the FAA for complying with the requirements of Section 23.954 and 25.954.'

Apart from the purely 'advisory' status of this document, it may be seen from the above that it was essentially focused on 'preventing ignition of fuel vapours due to lightning. 'Whilst AC20-53A does mention the lightning conduction problems associated with non metallic composite structures, such references are again related to fuel system effects. In addition, this document refers essentially to fixed wing aircraft, with Figures 1, 2 and 3 of its Appendix 2 showing 'swept-stroke phenomenon' and 'lightning strike zones (typical)' for fixed wing aircraft, with no corresponding information for helicopters. Indeed, AC20-53A does not mention helicopters at any stage in its text.

Extracts from AC20-53A (ie pages 6-10 and associated Appendices 1, 2 and 3) are included at Appendix C, Enclosure 1. These extracts describe the 'swept-stroke phenomenon', lightning strike zone definitions (ie zones 1A, 1B, 2A, 2B and 3), location of lightning strike zones, certification current test components (A, B, C and D), current waveform E, voltage waveform (A, B and D) and associated definitions (Appendix 1).

It may be seen from pages 8 and 9 of these extracts that component A, the initial high peak current, has an amplitude of 200 kA (±10%) with an action integral of 2 x 106A2s (±20%) and total time duration not exceeding 500 microseconds. Component B, the intermediate current, has an average amplitude of 2 kA (±10%) flowing for a maximum duration of 5 milliseconds. Component C, the continuing current, transfers a charge of 200 coulombs (± 20%) in a time between 0.25 and 1.0 second, associated with current amplitudes between 200 to 800 amperes. Component D, the restrike current, has a peak amplitude of 100 kA (±10%) and an action integral of 0.25 x 106A2s (±20%), with a total time duration not exceeding 500 microseconds. Figure 4 within these extracts from AC20-53A (see Appendix 3) shows the component waveforms.

There are thus considerable differences between the lightning certification criteria used at the time the AS332 was certificated and the criteria used for present day certification. Modern certification would require a much higher current to be applied to an individual test blade than would have been the case had a test been carried out at the time of AS332 certification, when it was widely assumed that the energy would be divided between two or more consecutive blades.

The present AC20-53A certification criteria must be interpreted to establish ways of applying them to revolving rotor blades. Only limited provision is made for the effects of the use of structural materials having widely differing conductivities. The levels and durations of pulses specified, whilst deemed appropriate to the structures of fixed wing aircraft, need to be interpreted in order to apply them in a valid manner to the rapidly revolving blades of rotorcraft. The passing frequencies of blades in relation to the duration of a lightning event are such that a simple application of an AC20-53A current pulse to a point on a fixed blade is not necessarily a valid representation of the real event; the phenomenon of 're-attachment' and other complexities brought about by rotational movement of the blade in flight, whilst to a certain extent present in fixed wing aircraft, can have a much greater effect on the degree and position of damage on a rotor blade in service: such rotating blades will generally suffer a reduced 'C' (continuing current) component than would a fixed wing aircraft.

Since AC20-53A does not include reference to helicopters, or rotorblades, there is no stated requirement to model the precise root attachment conductivity features of a blade; it has been common test practice to connect the earthing cable to the inboard end of the main metallic blade protection medium during lightning certification testing thereby failing to model current flow through blade attachment pins, and any associated composite structural damage.

It was noted that AC20-53A omitted any reference to helicopter lightning protection and that these criteria, which form the basis of modern lightning certification, were purely advisory in nature.

1.18.6 Origin of lightning protection criteria

1.18.6.1 Early research

Scientific lightning research began at the end of the nineteenth century and serious numerical studies of current magnitudes were underway late in the third decade of this century, largely as a result of the need to protect the transmission equipment of newly established power utilities from the effects of lightning strikes. The earliest recorded major aircraft lightning research programmes were carried out during the period 1940 to 1950 using lightning power assumptions derived from those adopted by the power utilities to define protection standards for their equipment. Aircraft service experience, however, indicated that a much higher level of damage was frequently produced than could be accounted for by strikes of the levels predicted in the research work.

Thus, during the 1950s levels of 200 kA peak current were specified by researchers, although they were not incorporated in any certification requirements. Different test laboratories used different wave forms and so many different values of action integral were proposed. Instrumented aircraft subsequently carried out research, deliberately entering areas where lightning activity was believed to be present. The highest recorded current peak in experiments of this type was 54 kA (obtained during such an investigation in the 1970s).

1.18.6.2 The lightning hazard

Lightning can result from a variety of phenomena, including cumulo-nimbus cloud formation, desert sand storms and volcanic action. Observations of clear air lightning have been reported periodically by researchers, although no satisfactory explanation for this effect has thus far been advanced.

With regard to the effects of cumulo-nimbus activity, it is generally believed that these cloud formations develop in such a way that internal discharges occur initially accompanied by 'cloud-to-cloud' discharges. Typically, after some 5 to 10 minutes there generally follows a period of 'cloud-to-ground' discharges. These tend to be negative (ie where associated cloud is negatively charged with respect to ground) in or near the rain shaft area, negative or positive further outwards, with isolated positive discharges occurring well away from the storm centres, usually descending from the developed storm 'anvils'. Inevitably, this information is based on 'over land' observations and the extent to which the same sequence occurs over the sea appears less known.

During aircraft operations, a majority of strikes occur in cloud and it is generally accepted that most of these are 'triggered' by the presence of the aircraft in the cloud electric field. Thus the intra-cloud and inter-cloud type of strikes can affect aircraft early in the development of a storm without any previous discharges in the cloud system and before a well defined cumuloform cloud develops.

The bulk of evidence available, however, strongly suggests that cloud-to-ground strikes, which occur once a storm is well developed, have greater energy content than inter-cloud or intra-cloud strikes. Most statistical knowledge is available on the former since extensive measurements have been made in lightning prone areas using ground based equipment which remains in place for very long periods. Levels have been established from such investigations as a result of a number of experimental methods and different assumptions of the effects of types of terrain, and using results recorded at differing geographic locations.

There is, unfortunately, no great unanimity among researchers in different countries as to the detailed validity of the measurement methods, or assumptions used, and hence views vary as to levels appropriate to certification. In addition, it has also been considered that most cloud-to-ground strikes are negative, although the proportion of positive to negative strikes varies markedly between geographic allocations. This has caused many researchers to propose standards based only on the intensity of measured negative cloud-to-ground strikes.

1.18.6.3 Significance of lightning standards

Lightning certification standards for protection of aircraft structures and systems have been developed over a long period in different parts of the world. The lightning threat consists of two distinct mechanisms:

(1) 'Direct Effects', comprising damage to aircraft structure caused by:

(a) the attachment of the lightning arc and,

(b) the passage of lightning current through the structure, together with,

(2) 'Indirect Effects', the damage caused to electrical and electronic equipment.

With regard to this accident, the first officer later reported that the weather radar had failed coincident with the lightning strike. Damage to structure due to (a) is a function of Charge Transfer, whilst damage due to (b) is a function of Joule heating and hence of the action integral, ie A^2s.

1.18.6.4 The effect of including positive and negative strikes

The recorded positive strikes are, on average,much more powerful than negative strikes. This is largely because they are of longer duration, resulting in a considerably larger action integral. Thus the decision upon whether to include, or exclude, positive strikes makes a marked difference in the levels of any proposed certification criteria. The occasional very severe strikes on aircraft are very much more powerful than anything measured during airborne investigations of intra-cloud lightning,and so there is now little doubt that cloud-to-ground measurements are very relevant to aircraft. In general, advisory levels have been established internationally by arriving at compromise figures, mid-way between existing nationally agreed levels.

A 2% criterion seems to have been accepted by lightning researchers on the basis that "it is clear that airworthiness authorities consider that the 2% level of severity of the negative ground flash is an acceptable basis for simulating the negative discharge in laboratory tests", ie 98% of the negative cloud/ground (or sea) strikes encountered should be tolerated safely, the remaining 2% being accepted as inflicting severe, but undefined, damage. The 2% figure changes slightly to approximately 3.5% if 10% of cloud/ground or sea strikes are deemed positive. Thus, in practice it was thought that the presently accepted AC20-53A criteria covered the action integral and charge transfer values of approximately 96.5% of all cloud/ground or sea strikes.

The basis for this approach, in terms of the frequency and hazard relationships of high intensity strikes on aircraft structures, appears unsound. No special consideration is given in any certification documents to the extent of damage which will be sustained by the limited number of aircraft which will inevitably suffer damage greater than that catered for in such certification criteria. No successful attempt seems to have been made to establish the likelihood of strikes above a particular level in terms of rates per flying hour or rates per flight cycle either for aircraft in general, or for particular categories of aircraft (eg helicopters).

Associated lightning strike damage may have very different safety consequences on rotorcraft, compared to fixed wing aircraft. The use of the former in a maritime role will also have further survival-related safety consequences not present in rotorcraft devoted to overland operation.

1.18.7 The effect of aircraft constructional materials

Although the wide variation apparent in views on the validity of lightning certification criteria might appear to be potentially detrimental to flight safety, it has not proved so in practice until recently. Whilst aircraft were of metallic construction, conductivity far above that required to limit Joule heating would be available in all but a few isolated parts of the structure without making special provision. The main hazard to such aircraft were arc root punctures of fuel tanks and effects on vent areas of 'wet' wings. Such effects are independent of action integral and designers generally guarded against such problems by ensuring tank and vent systems were positioned well away from the lightning-prone extremities of the aircraft. With entirely metallic structure in the regions of fuel systems, few other problems were encountered in such areas. Problems with damaged ball/roller bearings, small holes in aircraft skin and indirect effects were normally the limit of effects generated by such strikes.

However, the advent of modern aircraft having large amounts of composites in their primary structures and critical components has elevated the significance of lightning testing criteria and underlined the importance of action integral considerations. As stated earlier, the TSS standard used in certification of the AS332L was developed in the 1960's for metal aircraft and is believed to have been adequate in that application because, in practice,the metallic structure was quite capable of absorbing strikes with action integrals far above that recommended for certification.

Statistics from the manufacturer indicated that a large number of strikes had occurred to AS332 aircraft, particularly in the North Sea operating area.

1.18.8 Lightning strike energy

A number of documented lightning incidents worldwide have been simulated during the last 20 years under laboratory conditions in order to assess the action integrals responsible for the associated damage. The highest figure in this group was 7 x $10^6 A^2 s$. A Nimrod aircraft, operating low over the North Sea, suffered a strike on its composite radome structure with an estimated action integral of 6 x $10^6 A^2 s$. G-TIGK also appears to have suffered a tail rotor blade strike of a value of some 6 x $10^6 A^2 s$ in this accident (section 1.16.1).

EA Technology is a UK company which has specialised in the monitoring of cloud/ground, or sea, lightning discharges within the UK, North Sea and Irish Sea over the last 8 years, providing on-line real time data to a number of organisations on individual lightning strikes, typically within one second of each event. This company was requested to provide their lightning discharge data for the area of the North Sea over which G-TIGK was operating on the 19 January 1995, for a time span which encompassed the time of this particular strike. This data recorded a positive polarity discharge (ie polarity of cloud with respect to sea) at 1236:30 hours at position 58° 28' 31" North, 0°51' 08" East (probable position error of 4.6 nm) on the 19 January 1995. This position and associated error margin compared with the estimated position of GTIGK, at the time of the lightning strike, of 58° 27' North, 0° 50' East at 1236 hrs approximately.

SFERICS data obtained from the UK Meteorological Office at Bracknell for the northern North Sea area for the period between 1230 and 1240 hours UTC on the 19 January 1995 showed a lightning discharge (serial no. 13957) occurred at 1236 hours 59 seconds in position 58.456 North, 0.997 East (ie 58° 27'21.6" North, 0° 59' 49.2" East). The close proximity of this discharge to that recorded by E A Technology, and the associated timings, suggested that these recordings were of the same discharge which struck G-TIGK. The next closest discharge within this time span was recorded by EA Technology at 1231 hours 22 seconds, position 58° 25' 18" North, 01°06' 42" East (negative polarity), and by the SFERIC system at 1231 hours 51 seconds (note SFERIC recording 29 seconds after EA recording, as above), position 58° 27' 57.6" North, 0° 56' 38.4" East.

Corresponding SFERIC data for a later lightning strike incident to a Norwegian AS332L Super Puma helicopter, LN-OLB,which occurred on approach to Bergen just over one year later on 27 February 1996 (see section 1.18.10) recorded one isolated lightning discharge at 0912.52 hrs UTC at a position 60°27' 50.4" North, 04° 44' 9.6" East. This isolated discharge was within 2 minutes and 1 nm of the reported strike on LN-OLB and was thus considered to be the lightning discharge which caused that incident. EA Technology data for this incident recorded a positive polarity discharge at 0912:22 hrs UTC at a position 60° 40' 13" North, 05° 17' 33" East on the 27 February.

Japanese lightning researchers have recorded discharges of up to 300 kA, with associated action integrals of 10 x $10^6 A^2 s$, from tests with lightning 'towers' located along the western coast of Japan. Such towers are designed to attract naturally occurring lightning discharges from adjacent thunderstorms, but ground-to-air rockets are also used to 'trigger' lightning discharges onto such towers, the rockets being equipped with 'trailing wire' conductors of 50 to 100 metres in length. Winter storms in the Sea of Japan generate some severe lightning discharges, generally from fairly small, low altitude clouds (tops rarely exceeding 5 km).

LTT Culham has stated that recent studies suggest that the proportion of positive/negative discharges can also vary throughout the evolution of a storm system, with positive discharges more common during low precipitation phases and negative discharges more frequent when the storm produces heavy precipitation. In addition, recent studies in the USA have found that less than 2% of lightning discharges in Florida were positive, but up to 25% of discharges were positive at higher latitudes in the upper mid-west and Pacific north-west coast. It was claimed that the associated lower temperatures of northern latitudes might contribute to this variation.

At a meeting convened at LTT Culham on 1 February 1996, representatives of EA Technology described their lightning sensing system in the UK. This company have 5 out-stations in mainland UK and one in Ireland; located at Rhynie (N/E Scotland), Harwood (N/E England), Thetford (East Anglia), Melbury (S/W England), Churton (N Wales) and Portumna (Ireland). Each station has a 5 metre high antenna with four magnetic loop sensors which monitor extremely low frequency electromagnetic waves generated by atmospheric lightning discharges and utilise the attenuation of horizontally polarised waves at these frequencies to remove signals associated with cloud/cloud discharges and derive the position/times of such discharges, in addition to the associated polarity and energy levels. This system can detect strikes of 3,000 amps or greater at a distance of 1,000 km and has an accuracy of some 5 to 7 km over the North Sea, and some 1 to 3 km over land. It can detect and measure up to 100 lightning discharges per second. In response to the AAIB questions regarding the polarity of North Sea lightning discharges over EA Technology's operating period (1989 to 1995), data was produced relating to a sample of data taken in 1990 which indicated that some 80% of lightning discharges over the North Sea were positive discharges. The corresponding figure for positive discharges over the southern UK was 40%. LTT Culham has indicated that 40% positive discharge criteria would imply that 15% of cloud-ground strikes would exceed action integrals of 2 x 10^6A^2s,whilst 80% positive discharge criteria would imply that 30% of cloud-sea strikes would exceed 2 x 10^6A^2s.

The German military lightning standard, VG96901, does take positive strikes into account (10%) and assumes that only 1% of all probable strikes will exceed the associated specified action integral of 10 x 10^6A^2s, ie five times that advised in AC2053A.

1.18.9 Lightning warning systems

All warning systems currently in use, whether land-based or aircraft mounted, rely on the pre-existence of lightning discharges to give warning of the danger to aircraft flying in the vicinity of the lightning activity. As stated earlier, many inter-cloud and intra-cloud strikes are thought to be triggered by the presence of the aircraft in the charged air mass. As such, these are first, or 'surprise', strikes and cannot be predicted by such equipment in current use.

A thunderstorm is believed to develop in such a way that internal discharges occur initially, accompanied by cloud-to-cloud discharges. Later, there generally follows a period of cloud to ground discharges. As previously mentioned, these tend to be negative in or near the rain shaft area, negative or positive further outwards and isolated positive discharges occur well away from the storm centres, usually descending from the developed storm 'anvils'.

These later discharges, coming from well developed storms, can be reasonably expected to occur after the initial onset of detectable lightning discharges. Since cloud-to-ground discharges have been routinely measured having much greater power than any measured inter-cloud or intra-cloud discharges, and the most powerful cloud/ground discharges are positive, it appears that the more powerful and hence most damaging strikes frequently(but not exclusively) occur sometime after lesser, but nonetheless detectable, discharges have occurred in the general area of the relevant storm system.

Towards the end of the meeting at the CAA on 1 March 1995 (section 1.18.2), the AAIB representatives raised the question of 'Stormscope' type equipment fitment to North Sea helicopters.

Such equipment detects electrical discharges, whether visible or not, by analysing the associated radiated electromagnetic signals, for both azimuth and range, and displaying each detected discharge on a cathode ray tube (CRT) display. Such thunderstorm activity can be displayed for ranges of 25, 50, 100 or 200 nm, with either a 360° or 120° (forward) weather mapping presentation. Bristow Helicopters representatives present at that meeting stated that they had enquired about the B F Goodrich Avionics Systems 'Stormscope Series II' equipment at that time and had been informed that such equipment had been adopted quite extensively in USA military helicopter operations. They also stated that their company intended to conduct flight trials of this type of equipment on an AS332L Super Puma helicopter. A BHL AS332L helicopter, G-TIGW, was subsequently fitted with a B F Goodrich WX-1000 'Stormscope' system and associated flight trials initiated. The first trials were conducted through the summer months of 1995, with relatively little lightning activity. Electrical discharges were thus registered on only some 16% of the first 95 flights. Of the 15 occasions on which 'Stormscope' discharge indications were displayed, 8 crews thought that the equipment was a valuable aid, with one instance where the associated crew thought it was 'not a valuable aid'. Six flights experienced 'spurious indications', most of which occurred whilst operating close to Aberdeen Airport, or when flying in the area of Scotstownhead (radio masts). A member of the AAIB investigation team flew in G-TIGW in the Spring of 1996 and reported that such spurious indications observed on that flight were readily identifiable as such and many occurred during ground operations at Aberdeen Airport, or in the immediate vicinity, probably due to the proximity of industrial electrical equipment.

Whilst such equipment can detect electrical discharges, including early cloud-to-cloud discharges which often occur before the more powerful cloud/ground (or sea) lightning discharges, it cannot detect the increase in atmospheric voltage potentials which occur before electrical discharge phenomena initiate. Atmospheric voltage potentials of some 30 kilovolts (kV)/ metre, or more, produce discharge conditions and levels of some 400 kV/metre occur in charged cloud storm centres. Such values compare with levels of around 100 V/metre associated with 'fair weather' atmospheres. Equipment is available to measure such electrical energy fields and is generally termed 'E-field meters'. Such equipment is either electro-mechanical in operation, or electronic. The former type utilises a metal bladed 'rotor' to 'interrupt' the incident E-field over a metallic segmented static disc detector which outputs an alternating current (AC) which is then amplified and displayed on a CRT screen. The amplitude of the AC waveform is proportional to E-field strength. Whilst such devices have been used in electrical field research, no comparable equipment had been developed for airborne operational use.

However, during the Spring of 1996, the AAIB and the CAA were visited by the founder of Lightning Technologies Inc., with a former CAA lightning certification specialist (now a consultant), who expressed an interest in this accident and were briefed upon the AAIB investigation findings, including associated lightning test results. They described the potential benefits of developing an airborne E-field meter system for North Sea helicopters and subsequently presented proposals for such a project to representatives of North Sea oil companies (UKOOA), Operators, LTT Culham, the UK Meteorological Office and the AAIB at a meeting convened at the CAA on 22 May 1996.

The results of the first phase of this project were presented at a later meeting at the CAA on 30 September 1996. Their assessment of North Sea helicopter lightning experience was presented, showing that most strikes occurred between 1,000 to 3,000 feet amsl (ie lower heights than typical worldwide), in or near cloud, near freezing levels (0° ± 2°C), with many instances of no previous discharge warning, and with typical pilot reports of a single 'pop' indication of a strike, which was judged characteristic (by the presenters) of "positive polarity lightning strikes". (LTT later contended that "A negative cloud-to-ground strike might not give any indication of prior electrical activity"). The degree of associated structural damage was also consistent, in their view, with positive strikes. A significant number of such strikes were assessed as having been 'triggered' by helicopters. Their review indicated that winter conditions produced most lightning strike incidents,starting around October. Similar conditions were reported to occur in the Sea of Japan, and off the north-west coast of the USA (section 1.18.8).

With regard to the types of E-field meters which might be suitable for helicopter operational use, they had decided to assess electronic E-field sensors in order to avoid anticipated service reliability problems with electro-mechanical meters which would be sensitive to contamination of associated sensing apertures on air frame skins (ie water/dirt contamination), vibration and temperature effects upon associated rotating vane components, related wear problems etc. Of the available electronic approaches for measuring E-field voltages, they had concluded that a dE/dt (where t is time) sensor could offer advantages over a direct E-field voltage sensor which would require a high impedance sensor system which would be prone to 'current leakage' problems. It was envisaged that dE/dt sensor plates could be installed below helicopter main rotor blades so that the incident E-field would be 'interrupted' in phase with the passing frequency of the blades to produce an amplified sinusoidal output of induced current where signal amplitude was proportional to E-field voltage. Small scale laboratory tests with a 6 kV uniform incident 'E-field', interrupted by a small four bladed rotor of 69 cm diameter rotating at 12Hz, had demonstrated successful sinusoidal output from a 30 cmx 19 cm sensor plate. Related 'sensitivity analyses' had indicated that such an approach could measure atmospheric potentials down to (at least) the 100V/metre associated with typical 'fair weather' conditions.

Phase II of the programme was described as including system calibration studies (eg aircraft 'form factors'- ie 'shape' sensitivity to arc attachments, to assist E-field meter threshold criteria; modulation depth factors - ie relationship of output current modulation to E-field voltage; sensor position optimisation etc), development of computer-based calibration model, system software development, laboratory tests evaluation, electromagnetic interference survey, ground and flight verification testing. It was anticipated that prototype equipment flight trials could be achieved by July 1997, with successful completion of these leading to the availability of production systems for helicopter in-service operation (see section 2.5).

1.18.10 Other incidents

The manufacturer reported that a Norwegian AS332L helicopter had suffered a lightning strike whilst operating in the North Sea in November 1990. This had resulted in significant damage to a tail rotor blade, leading to severe vibration such that the pilot decided to conduct an emergency landing. The damage to the blade indicated that a strike had occurred with initial attachment on the trailing edge, close to the tip. The blade in question was of the original design standard (part no. 332A.12.0010), ie not incorporating the changes introduced on British registered aircraft after the blade shatter incident of May 1987 (section 1.6.4). As a result of this incident, a lightning test on a sample AS332L tail rotor blade was carried out by the manufacturer in January 1991 at the Suresnes Lightning Test Facility. The test was, however, reportedly carried out at a significantly lower maximum current (ie 174 kA) than that called for in both the AC2053A and the TSS criteria, mainly because the damage inflicted to the trailing edge tip, as the current rose, broke arc continuity before the 200 kA level was reached. In addition, the premature failure of the test resulted in a low action integral (ie $0.9 \times 10^6 A^2s$) being applied. The associated degree of damage, inflicted in simulated conditions much less severe than those required for certification, illustrated the shortcomings of the read-across method of validation when the structural material is changed to one having different electrical properties.

On 21 February 1995 an AS332L, G-TIGO, experienced a lightning strike whilst operating over the North Sea. No in-flight difficulties were encountered other than a failure of the automatic direction finding (ADF) equipment. On arrival at its Aberdeen base, considerable evidence of the strike was visible on the aircraft,which was withdrawn from service for more comprehensive checks. An AAIB engineering inspector examined the aircraft shortly afterwards. The main rotor blades were found to have suffered visible arc burn damage at a number of points, including some fasteners between the blades and the metallic blade tip pockets, damage to one pocket,and varying degrees of burn damage, failure and complete absence of parts of the conducting strips near the blade roots. On one blade, a large area of delamination was present at the trailing edge. Local lightning damage was also evident at a number of points on the tail boom and at the end of the tail skid/stinger. No evidence of any damage was found on the tail rotor. The main rotor blades and main rotor gearbox were removed and returned to the manufacturer.

The manufacturer had worldwide service data for the period from April 1980 to September 1994 for six of their types. This showed that of 113 recorded main rotor blade strikes, 96 had occurred on AS332 aircraft. The corresponding tail rotor blade figures were 29 total, with 27 strikes to the AS332. Of all the lightning strike incidents involving the AS332, only 15 had occurred to operators not working in, or adjacent to, the North Sea area. Although the type operates worldwide, the majority of machines not in North Sea operation are in military service where there is less of an imperative to operate on defined routes to fixed schedules. The North Sea area represents the greatest concentration of the type operating offshore in the world. The other types in this database were the AS330 (a type which operated only briefly over the North Sea and had metallic blades), the AS350 and 355 aircraft (not used in the North Sea and having CFRP in their blade structures) and the AS365 which has main blades made largely of CFRP but has no conventional tail rotor. The latter type did not operate extensively in the northern North Sea, but was used by one operator.

A Norwegian AS332L Super Puma helicopter, LN-OLB, of Helikopter Service suffered a high energy lightning strike to its main rotor blades on the 27 February 1996. The helicopter was inbound to Bergen when the crew reported a 'huge bang', followed by heavy vibration. However, since they were only some 10 nm north-west of Bergen and the helicopter was still under control, the commander continued his approach and landed at Bergen. Subsequent examination of the helicopter by the operator, the Norwegian authorities and a member of this investigation, found the following damage:

Main rotor blades: One blade had lost about 1/3rd of its 'tip cap' (trailing edge). Three blades had lost sections of their brass conduction strips. Two blades exhibited sleeve spindle damage. One blade root safety pin had been lost.

Main control servos: Three servo jacks exhibited 'arc-burns' on bodies.

Right transmission bay step arc-damaged. Right side hydraulic lines arc damaged. Small hole in right side of cabin skin, aft of cabin door. Right landing gear bonding strap missing.

In addition, residual magnetism effects were detected on the main gearbox epicyclic module, main rotor spindle and mast lower splines. The tail rotor showed no damage.

Since the strike occurred at 0915 hrs UTC approximately 2 nm north-west of the Vindenes reporting point, the UK Meteorological Office were requested to survey their archived data for the period 0850 hrs 0930 hrs on 27 February 1996 in the general area of the reported strike position. Only one isolated discharge was recorded in that general area during this period. This was a strike at 0912.52 hrs UTC at a position 60.464° North, 004.736° East. This position was within 1 nm of the reported position of the strike. Since this discharge occurred only some 2 minutes earlier than the reported time of the strike, it was judged that this recorded discharge was the strike which damaged LN-OLB. The Meteorological Office specialists were questioned as to the ability of their equipment to detect both cloud-to-ground and inter/intra-cloud discharges. Their response was that although the equipment could detect both classes of lightning, the higher amplitude characteristic of the cloud-to-ground strikes could be detected over a much greater distance than could the lower amplitude of the inter/intra-cloud discharges. In their opinion, their equipment would have been able to detect only cloud-to-ground strikes at locations as distant from their equipment as Norway.

Other types equipped with composite blades operating in the North Sea have suffered a very much lower incidence of damaging strikes than AS332 aircraft. An assessment of these types indicated that none used significant amounts of CFRP in main or tail rotor blades, being of a variety of combinations of GRP with, and without, metal spars. The one exception was the Dauphin helicopter which has operated largely in the lower latitudes of the southern North Sea and is equipped with a shrouded Fenestron rather than a normal tail rotor. The Sikorsky S76 tail rotor blades utilise aluminium wire mesh impregnated within the fibreglass skins and tip caps. Such 'earthed' wire mesh conduction paths can be very effective in protecting composite structures from lightning strike damage.

The AAIB examined a Bond Helicopters AS365N Dauphin helicopter, G-BTEU, which suffered a lightning strike in the southern North Sea area on the 26 November 1996 at 1453 hrs UTC. This type has main rotor blades with carbon fibre spars and skins, and a solid glass-fibre leading-edge covered with a stainless steel sheath. The sheath is in a number of sections with overlapping joggles where they join. A brass strip runs from beneath the inboard end of the innermost sheath section to a bolt passing through the blade close to the blade root, to which the braided bonding strap is attached.

This helicopter had undergone repair to the brass strip involving an additional length of strip which had been lap-joined to the outboard end of the original strip and attached to the upper face of the inboard end of the inner section of the leading edge sheath. This additional repair strip bridged a fracture in the original brass strip.

Examination after the lightning strike incident found that the brass repair strip had peeled back at its outboard end, although a short section remained attached to the stainless steel sheath. A further failure was present in the original brass strip, sited approximately 1.5 mm inboard of the inner end of the repair strip. Brass strip material from both sides of the inboard failure was curled up clear of the blade profile. A section of GRP covering was absent from the damaged areas.

A length of the trailing edge of the blade had suffered separation of the top from the bottom skin at the outboard extremity of the blade where the tip-cap joins, and a further similar disbonding had occurred a short distance further inboard. A 'bulge' had appeared in the leading edge anti-erosion sheath forward of this length of disbonded trailing edge and local bending of a joggle in the anti-erosion sheath was visible further inboard.

The shroud of the Fenestron exhibited a number of areas of small holes and separated paint/gel-coat. Closer examination revealed that these damaged areas were all sited where tooling holes were present and had been closed with a special-purpose filler during manufacture. Two external plates which acted as load spreaders for pairs of bolts securing an internal bracket (which supported the shroud-mounted ADELT unit) were curled up at their edges.

A number of avionic units appeared to have been damaged, or rendered inoperative, by the strike. These included one starter-generator and/or the generator control unit, the automatic direction finding (ADF) loop aerial and receiver, the P1 station box, the anticollision beacon power supply unit, a further power supply unit, the ADELT unit and elements of its deployment system, together with the FDR acquisition unit. It appeared that high voltage currents had passed through a large number of avionic units and although they remained generally operative, their future life may have been greatly reduced.

The ADELT unit was mounted at the extreme rear of the aircraft with its antenna pointing aft. The latter component had completely disappeared. This suggested that the discharge had travelled between the outboard trailing edge of the damaged main rotor blade and the ADELT antenna.

Checks on residual magnetism were made at various stations on the aircraft, as defined by the manufacturer. The resulting numerical information was passed to them for analysis. They subsequently informed the operator that they considered the aircraft fit to fly after replacement of the damaged main rotor blade and the inoperative avionic units, in addition to repair of the localised damage to the Fenestron shroud.

An analysis of data supplied by the UK Meteorological Office revealed that a lightning discharge had been recorded at the appropriate time and close to the position identified from the aircraft FDR system as the point of the lightning strike occurrence (ie 53°53' 24" North, 01° 27' 57.6" East). The position data was supplied to the FDR by the inertial navigation system (INS) system of the helicopter. The lightning identified by the Meteorological Office system was detected using equipment sited at a considerable distance from the area of the discharge. EA Technology was also requested to provide data on this strike and identified a 'very weak strike' at 1455 hrs on the 26 November in approximate position 53.59° North, 01.49° East with a position error of 18 km, due to the (claimed) 'weak nature of this negative polarity discharge'.

Although this aircraft suffered damage to a considerable number of avionic units (normally defined as secondary damage), the primary damage was limited. The lack of evidence of highly magnetised areas of the structure and transmission strongly suggested that this was a relatively low intensity strike. The 'offset' current path resulting from the presence of the repair at the region of failure of the brass strip on the damaged main rotor blade probably increased the local damage over and above that which would have been inflicted had a continuous unrepaired brass strip been present at this point.

1.18.11 Modified AS332L tail rotor blade

The manufacturer's Technical Support Department was involved from the earliest stage of this investigation and arranged continuous technical liaison as progress was made, particularly throughout the series of tail rotor blade simulated lightning tests commissioned at LTT, Culham. As a result of early information gained from the investigation and lightning testing, Eurocopter developed a modified tail rotor blade design, part no. 332A.12.0050, in a commendably short timescale and the new blades (certificated to AC20-53A requirements) were made available to AS332L operators towards the end of 1995.

The associated modifications included the addition of titanium sheathing to the tail rotor blade tip area which provided conductivity protection to the outboard trailing edge, tip area full chord, with two 'tabs' linking the heads of both tip weight bolts to the titanium tip sheath and leading edge anti-erosion shield. The shield was also extended inboard and secured to the root 'earthing' bolt, thereby strengthening shield/blade retention and deleting the previous brass conducting strip and associated strip/shield lap joint. In addition, the titanium tip sheath was riveted, with three monel rivets, to the outboard trailing edge of the blade, to provide positive retention in the event that associated debonding occurred as a result of a high energy lightning strike. This modified blade also included a fibreglass layer around the leading edge, ie underlying the erosion shield, and a new braided bonding strap between the root 'earthing' bolt and hub. Appendix C, Figures 13A, B and C show these blade modifications.

1.19 New investigation techniques

The use of meteorological recordings of lightning discharge occurrences was found very useful in identifying the likely discharges which had caused the strikes which were associated with the helicopter accidents and incidents examined in this investigation, particularly where the sources of recorded data were capable of also indicating the polarity of such discharges. This was especially important in assessing the adequacy of the current lightning certification criteria, AC20-53A, which did not take positive polarity discharges (the most powerful discharges) fully into account in assigning lightning test energies, on the basis that positive discharges were thought to account for only some 10% of all cloud/ground or sea, discharges.

2 Analysis

2.1 The flight

In the meteorological data provided to the crew there was no weather condition shown which should have prevented the commander from embarking on the flight. The crew would have quite reasonably expected that the described 'occasional' and 'isolated' patches of bad weather were either not likely to interfere with the planned flight, or could be avoided.

The flight was conducted in accordance with company operating procedures, with the first officer as handling pilot. Company policy stated that, should an emergency occur, the decision as to how the subsequent duties should be divided, between the commander and the first officer, rested entirely with the commander. Being the more experienced of the two pilots, a commander might elect to take physical control of the aircraft. In some cases, the continued safety of the flight might best be served by such a decision. However, by not so doing, the commander may free himself to take key operational decisions. On this occasion,the commander chose the latter course of action and it was apparent that the choice which he made was justified.

Once airborne and flying between cloud layers, there was nothing indicated on the weather radar which would have been likely to have caused the crew any problem. Although they commented, on the CVR, about a large cloud build-up to the north of their track on the northern side of the Brae oilfield, they still had a generally clear passage to their destination. The lightning strike was therefore totally unexpected, particularly as they were flying in an area where their radar had not shown any significant storm clouds. However, the crew correctly identified the problem and acted promptly. When they found that the helicopter was controllable after their initial autorotative descent this introduced another potential problem, ie whether to alight on the sea beside the platform, or whether to attempt landing on the platform.

Historically, although the circumstances and associated modes of failure vary considerably, many ditchings have resulted in helicopters rolling over in the sea, sometimes with consequent loss of life. There is therefore, understandably, a reluctance on the part of operating crews to ditch voluntarily. However, the degree of vibration produced by a tail rotor imbalance can be so severe that it may be only a short time before the tail rotor assembly and associated gearbox detaches from the helicopter. The dilemma facing a commander, in such a situation, is therefore whether to ditch and risk loss of life, or to attempt a landing on a platform, hoping that the tail rotor and gearbox will not detach whilst the helicopter is approaching the helideck as a result of the added stresses induced by the necessary changes in torque. The consequences of such an occurrence could be catastrophic due to the accompanying loss of yaw and pitch control.

The considerations that have to be taken into account by a commander when severe tail rotor vibration is experienced include the weather, particularly the sea state, the controllability of the helicopter, the size and proximity of the platform, in addition to the time available to make his decision. Following this accident, much discussion centred on whether a standard procedure should be recommended to crews to adopt in the event of such an emergency. However, bearing in mind the different types of emergency which crews could experience and the varying aspects detailed above, it was concluded that the final course of action must be left to the commander.

In the event, the need for this decision was obviated when the tail rotor gearbox separated from its mountings. The subsequent ditching was accomplished in an exemplary manner in view of the high sea state which prevailed at the time. Both the commander and the first officer carried out their duties with skill and professionalism.

Following the ditching, which resulted in the helicopter heading almost directly into wind, it is probable that it was the necessary action of applying the rotor brake which yawed the helicopter so that its left side came into wind and caused the subsequent problems with the heliraft on that side.

It was only at this point that the crew deviated slightly from the hitherto well observed emergency procedures. In the considerable swell which was running, it was not surprising that the crew's minds were concentrated on getting the passengers and themselves into the heliraft before the helicopter rolled over and sank. It is therefore, perhaps, understandable that the floatation beacon was left behind.

2.2 Survival

2.2.1 Crew activities

Once aboard the heliraft in the crowded conditions and heavy swell, with many of the occupants suffering from seasickness, the crew carried out most of their duties and it is likely that the failure to locate the second survival pack was due to the congestion within the heliraft. They did, however, omit to cut the sea anchor bridle, thereby obstructing operation of the canopy. It is again noteworthy that this action was not practised during recurrent training, although it has been introduced into the training schedule by the operating company since this accident. The recurrent emergency training undertaken by North Sea helicopter operators and associated oil companies is conducted to a commendably high standard, with much emphasis on 'hands on' practice and escape training from a submerged cabin simulator. Perhaps because of this emphasis on realistically critical escape situations, such training does not generally involve evacuation from a floating helicopter which, although less demanding, nevertheless has been the more frequent situation in North Sea accidents. The following Safety Recommendation is therefore made:

The CAA should ensure that the North Sea helicopter operating companies include in their very effective recurrent training for crews discussion and, where possible, 'hands-on' practice of the procedures necessary to accomplish a successful evacuation from a floating helicopter following a ditching or alighting on the sea. (Safety Recommendation 97-29)

2.2.2 The heliraft

The heliraft, although suffering damage due to crash debris (see section 2.3.5 later), performed its designed function and supported an overload complement of persons whilst partially swamped.

The problems which were associated with this accident, in particular the inability of the survivors to raise the canopy, were not due to design faults but were the result of incorrect operating drill.

Although it would be possible to implement design changes in order to remove a possible recurrence of the specific problems reported, these would in most circumstances have a detrimental effect on the overall performance of the heliraft.

2.2.3 Personal equipment

Although all personnel were rescued uninjured after at least 80 minutes in the heliraft and associated exposure to the elements, there were some problems noted with the personal survival equipment (see section 1.18.4). Some survivors reported experiencing difficulties in inflating their lifejackets, especially with the left lobes which appeared reluctant to inflate. In addition,many found the immersion suit mittens difficult to locate and extract from the associated pockets on the suit arms, particularly with life jackets inflated. Nine of the sixteen immersion suits suffered inward leakage during the period in the heliraft, ranging from 'pinprick' damage to more substantial ingress of water, and some survivors reported feeling extremely cold by the time they transferred from the heliraft to the FRCs. However, all the immersion suits which leaked were of the early Mk 7 version of the Pioneer Immersion Suits.

The parent oil company and the lifejacket manufacturer investigated possible ways of resolving the reported problems with the lifejacket inflation. However, there are conflicting requirements. The jacket lobes must remain in position under normal movement, particularly bearing in mind the weight of the survival equipment located on the lobes. Additionally, the jacket must be capable of inflating when required, possibly with the wearer injured. These conflicting requirements are not always compatible, but the present compromise is considered to be acceptable.

The parent oil company has already reviewed the reported problems with the immersion suits and initiated improvements. A neck seal type suit has since been adopted and the company has instituted a rule that, when the water temperature is 10° C or less, all helicopter passengers will be issued with, and wear, an internal thermal undersuit. Additionally, the mitten pocket has been modified by making three sides releasable, thereby making the contents more accessible. Finally, the mittens have been replaced by wet suit gloves which will be more adaptable for the wearer.

2.3 Rescue and recovery

2.3.1 Search and Rescue policy

The rescue was successful and no injuries were sustained. However, the operation highlighted a potential for confusion in that the RCC and MRCC each believed that they were best able to co-ordinate the rescue. The MOD is responsible, on behalf of the DETR, for the co-ordination of any civil aviation SAR operation associated with an aircraft accident within the UK Search and Rescue Region (UKSRR). The Coast guard Agency, through its MRCCs and sub-centres (MRSCs) is responsible, on behalf of the DETR, for the initiation and co-ordination of civil maritime SAR in the UKSRR (see section 1.17.1). In this operation the RCC retained control but, at one point, the MRCC asked if they could take over. This was because the MRCC consider that, in situations where the aircraft has ditched into the sea, their extensive communications, manning and knowledge of the maritime environment make them a more effective overall controller. The AAIB report on the Cormorant 'A' accident (AAR 2/93) highlighted the same aspect and recommended that the DOT should consult with the CAA and the MOD on the most appropriate co-ordinating agency for search and rescue operations associated with air accidents at sea. Following that recommendation, published in April 1993, discussions took place between the Coast guard Agency, the DOT Civil Aviation Division and the MOD which resulted in a Memorandum of Understanding (MOU) being signed on 3 March 1997, which is reproduced at Appendix B, Enclosure 3, and included the following provisions:

1. Control of SAR maritime incidents arising from aviation accidents shall rest with the rescue authority (whether ARCC or MRCC) that initiates the response, until it decides that the other is better placed to continue the response.

2. The initiating authority must immediately inform the other rescue authority of the incident. Consultation between the rescue authorities must also take place when the appointment of an on-scene co-ordinator is contemplated, including a review of which centre should most appropriately control the incident.

3. In an incident involving a military aircraft, control of the incident would always rest with the ARCC even if the Coastguard were first to learn of its ditching.

In addition, a working group was also established to ensure appropriate operating arrangements for enactment of the MOU and to keep the MOU and such operating arrangements under regular review.

2.3.2 On Scene Commander

The location of the heliraft and the subsequent co-ordination of the airborne assets was a task carried out by the commander of the company helicopter, 56B. The commander, whilst very experienced as a North Sea Commander, had received no formal training for this role, but carried out the task with great skill and notable success.

It should be noted that the title 'On Scene Commander' has since been changed by revision of the International Maritime SAR Convention and the new ICAO/IMO Joint SAR manuals to 'On Scene Co-ordinator.'

2.3.3 Rescue

The commander of the RAF Nimrod would normally have assumed the role of OSC but, by the time the Nimrod had arrived overhead the accident scene, he realised that the commander of 56B had a better overall knowledge of the situation. The Nimrod commander therefore decided to allow the commander of 56B to complete the task which he had begun, whilst he kept a watching brief on the situation, until he assumed control at 1430 hrs. This was clearly a sensible decision and one which contributed to the overall success of the task.

The captains of the two Safety Vessels, Grampian Freedom and St Patrick, reacted to the emergency with commendable speed and professionalism, as did the coxswains of the two Fast Rescue Craft. The survivors especially complimented the two FRC crews on their boat handling in the high sea state and the crew of the Grampian Freedom on their compassionate and skilful handling of those brought aboard their vessels.

2.3.4 Recovery

The commander of the third Safety Vessel, the Highland Pride, whilst acting under the helicopter operator's instructions brought the floating helicopter alongside and secured it to his vessel in the prevailing heavy seas. It was unfortunate that the helicopter's floatation bags then deflated and also that, having apparently cut-off some of the main rotor blades to prevent damage to the vessel, the crew could not prevent the detached main rotor blades from floating away, incurring a significant loss to the subsequent investigation. Since the helicopter then broke away from the Highland Pride and sank to the seabed it would, in retrospect, have been better if the helicopter had remained freely floating until it could have been recovered later in less difficult circumstances, or from the seabed if it had ultimately sunk.

2.3.5 Occupant survival considerations

The fractured ends of the upper locating arm(s) of both cabin doors were sufficiently sharp and narrow to form damaging projections should they come into contact with any inflatable equipment. A survivor stated that the lower chamber of the heliraft became punctured when it came into contact with the edge of a floating door. Examination of the door edges did not reveal any 'sharp points', apart from the fractured upper locating arms.

During an AAIB investigation into the loss of a Sikorsky S61 aircraft in 1983, it was found that both helirafts had been punctured and lost as a result of contact with projections on the exterior of the aircraft. Recommendations were therefore made that all offshore helicopters should be surveyed for existence of potentially damaging projections and that if present they should then be either shielded, or eliminated. This was apparently fully implemented and the AS332L fleet appears to fully comply with the intent of that recommendation.

At the time when the recommendation was made nearly all such aircraft had metal doors which sank when jettisoned. It is now evident that the Super Puma door, being of composite material skins separated by a low density core, will float for a period, if not indefinitely, after being released. This appears to affect the door in two ways. Firstly, when jettisoned in rough sea conditions with the aircraft rolling through a large angle, the buoyancy can prevent such doors from falling vertically, thus preventing the upper rollers from disengaging freely from the locating rails. Secondly, such doors will float in the region of the heliraft and become a potential hazard due to the fractured ends of the upper locating arms.

The only logical way in which the upper guide rollers could have broken from the locating arms would have been for the jettison system to have operated normally, the door restraints all to have released correctly, but the doors to have failed to descend from their guide rails as a result of their buoyancy preventing initial downward movement, whilst the lower edges of the otherwise unrestrained doors displaced away from the fuselage sides. Thus a torsional load would have been applied in a vertical plane to the rollers as the doors adopted an angle to the fuselage sides, causing the arms to break at their weakest points, exposing their jagged ends.

Examination of the door system indicated that such a mode of failure was unlikely to occur to a door on an aircraft floating in calm water, since the lower edge of the door would be only just immersed. In practice, however, this aircraft was rolling and pitching in a rough sea at the time that the doors were released. It is thus possible that the aircraft rolled in the direction of each door in turn as it was released. It would thus have been more deeply immersed for a brief period at, and after, its release and would have been supported by its buoyancy for a sufficient period to allow this type of failure to occur. In view of these findings, the following Safety Recommendations are made:

The manufacturer of the AS332L Super Puma helicopter should review the failure modes of the cabin door upper guide roller mounting arms which can occur during door jettison in rough sea conditions, and take action to prevent such mounting arm failures which can puncture helirafts when they subsequently come into contact with floating doors. (Safety Recommendation 97-30)

The CAA should call for a survey of jettisonable doors, of composite construction, fitted to North Sea public transport helicopters to determine if they are initially buoyant on jettison and, if so, to inspect such doors for projections likely to puncture floating helirafts, taking into account damage likely to occur to door mountings during jettison in rough sea conditions.

(Safety Recommendation 97-31)

Eurocopter responded to the first Safety Recommendation within their written response of 22 April 1997 to the draft report, stating:

'We have never been faced with this anomaly on jettisoning the sliding doors, and all the tests conducted to date confirm this. Nevertheless, we are going to check that it is still possible to jettison the doors in the most severe operating conditions without this type of failure occurring.'

2.4 Helicopter CVFDR power supply

Helicopter flight recorders to CAA specification No. 11 utilise direct current (DC) electrical power supplied by the DC essential/emergency busbar, assuring the availability of power to such recorders as long as battery power is available/on-line. In order to prevent the voice recorder from over-running, and therefore recording over previously recorded audio, after an accident where battery power might still be supplying a CVFDR, CAA specification No. 11 requires a means of interrupting the power supply to be installed, and states that a G-switch is an acceptable means of compliance. Such provision has been generally adopted, although the associated EUROCAE specification ED56A states that G-switches are not an acceptable method of stopping recorders after accidents.

The AAIB have encountered previous instances where helicopter recorders have stopped prematurely due to G-switch activation:

A Sikorsky S61, G-BEWL, fell from the Brent Spar platform on the 25 July 1990 as a result of tail rotor contact with a crane during landing. The last recording on the audio tracks was of the initial blade strikes (Aircraft Accident Report 2/91).

Another Sikorsky S61, G-AYOM, landed heavily on the Claymore platform on the 18 August 1995; the main rotor blades struck the tail boom, causing the G switch to stop the CVFDR (AAIB Bulletin 3/96).

In addition, there is evidence of 'nuisance' tripping of such G-switches during maintenance operations due to switch sensitivity.

It thus appears that such G-switches are unduly sensitive for helicopter operations, and have no time delay circuit to prevent inadvertent tripping. Although the CVFDR units fitted to North Sea helicopters are modern and reliable, such premature tripping of their power supplies denies subsequent investigations access to both the associated CVR and FDR information, completely negating the prime reason for fitting such equipment. In view of these findings, the following Safety Recommendation is made:

In order to prevent the premature cessation of electrical power supply to helicopter combined voice/flight data recorders caused by abnormal excessive vibration effects on associated G-switches, it is recommended that the CAA:

1 Require operators to render inoperative CVFDR G-switches, as an interim measure, and

2 Take action to identify a more suitable method of stopping such flight recorders during crash impact. (Safety Recommendation 97-32)

The CAA responded to part 1 of this Safety Recommendation within their written response of 9 April 1997 to the draft report, stating:

'Draft Safety Recommendation 4.4. The Authority would not be able to accept item 1 of this recommendation since such action may allow some recorders to continue running after an accident resulting in a crash impact, thus erasing the recorded data.'

The AAIB is unaware of any accidents where recorders have continued to run after crash impact, but has encountered accidents and serious incidents such as that which occurred to G-TIGK (and G-PUMH on 27 September 1995) where the CVFDR stopped prematurely due to G-switch activation as a result of excessive tail rotor vibration. A number of other air accident investigation authorities have also experienced such premature shut down of recorders, on both rotary and fixed wing aircraft, due to inadvertent activation of such G-switches. It is widely accepted within the air accident investigation community that G-switches are not an acceptable means of recorder shut down and that there are other much more effective ways to switch off recorders after accident occurrence.

2.5 Lightning avoidance systems

The use of aircraft-mounted lightning detection equipment, to assist avoidance of areas of a potential strike problem, has been advocated in recent years. Counter arguments, that such equipment will present too many spurious returns to be useful and that it will not give warning of first, or 'surprise', strikes have also been advanced.

The general view amongst meteorologists and lightning researchers is that 'surprise' strikes are usually the result of lightning within clouds occurring as a result of the presence of the aircraft triggering a discharge between highly charged areas. It is the general view that the lightning strikes which do major damage are cloud/ground or sea strikes and all current lightning design criteria are based on measurements made of the latter phenomenon.

In the normal course of events, lightning within clouds, ie conditions where 'surprise' strikes may be triggered, occurs early in the development of thunderstorms and precedes cloud/ground strikes. In the case of G-TIGK, an assessment of information derived from the SFERIC system and E A Technology data (section 1.18.8) showed a discharge occurring close to the estimated position of the aircraft at a time (ie 1236 hours and 30 to 59 seconds) very close to the most accurate estimated time of the associated strike. Considerable lightning activity was recorded throughout the North Sea area during this period, including one discharge within two nautical miles of the position of the discharge mentioned above, at a time some 5 minutes earlier. A radio message was received from another aircraft warning of a "major build-up", although no other discharges were observed. It is not known if lesser discharges could have been present in the immediate area which were not included amongst the discharges recorded by SFERIC.

The Bristow trials of 'Stormscope' equipment on G-TIGW in 1995 indicated that the equipment provided useful information, with some spurious data. A study of the results from these trials up to the autumn of 1995 showed the spurious returns occurred in two main geographical areas, these being at the coast north of Peterhead and in the immediate vicinity of Aberdeen Airport. Only two spurious returns were identified whilst operating over the open sea (section 1.18.9).

Whilst, as stated earlier in section 1.7.3, the provision of the SFERIC system data to Aberdeen ATC was under trial from May 1996 with a time delay, from discharge detection to ATC display, of some 15 to 20 minutes, it was earlier apparent that North Sea public transport helicopters fitted with composite rotor blades would be vulnerable to lightning strikes through the winter of 1995/96. It was also considered, from the capability of the 'Stormscope' equipment being trialled on G-TIGW, that the provision of such systems on North Sea helicopters could provide a 'real-time' indication of early cloud-to-cloud lightning discharge activity to associated commanders to enable them to avoid more damaging cloud-to-sea discharges. In addition, it was difficult to envisage that, with SFERIC data available in 1996 with processing times of some 15 minutes, that such a system could be superior to an on-board detection capability which could detect initial low energy discharges more reliably than the SFERIC system, due to range effects on the latter.

In view of the above considerations and the safety critical consequences which could arise from lightning strikes on composite tail rotor assemblies, it was concluded that all practicable measures should be taken to avoid, as far as possible, the risk of Public Transport helicopters encountering such discharge conditions. The following Safety Recommendation was therefore drafted to the CAA on 7 December 1995 and circulated on 15 February 1996:

In order to provide helicopter commanders with the necessary 'real time' information to enable them to avoid flight into areas of actual thunderstorms or ightning activity in Public Transport helicopters which have composite rotor

blades, the CAA and affected operators should jointly agree the fitment of lightning discharge mapping systems to such aircraft. The Authority should also inform other airworthiness authorities of the action taken in response to this recommendation.
(Safety Recommendation 95-45)

The CAA and North Sea operators responded to the above Safety Recommendation by insisting that further trials of 'Stormscope' equipment were required before any related decision could be made, and by pursuing the E-field sensing approach described earlier in section 1.18.9. Clearly, this latter approach appeared potentially more effective than 'Stormscope' type of equipment, since it offered the capability of detecting the presence of increased atmospheric voltage potentials before any associated lightning discharge activity was liable to initiate, or indeed be 'triggered' by a helicopter transiting in the vicinity of such charged air masses. However, the estimated time scales for the development of prototype E-field sensor equipment (associated flight trials were estimated to be initiated by July 1997), and the further time required to produce and fit (if accepted by the CAA and NorthSea operators) production units to affected helicopters, raised the prospect of helicopter operation through the autumn/winter period of 1996/97, and beyond, without any onboard equipment to assist in avoidance of potential lightning strike conditions.

On 4 November 1996 the Chairman of the offshore Helicopter Services Safety Group (HSSG) wrote to the President of Lightning Technologies Inc. (LTI) informing him that the HSSG would not fund Phase II of the E-field sensor development programme due to the associated costs and the view that such development was 'pure research' which should be resourced by LTI. The CAA appeared to concur with this decision and also declined to fund this programme. Thus the E-field sensor approach was effectively terminated at this time, certainly in terms of active support from the CAA and North Sea operators as a potential alternative to 'Stormscope' type systems.

The CAA later responded on 9 April 1997 to the this Safety Recommendation in the draft report as follows:

'Although the Authority would agree that an airborne lightning sensor mapping system may provide some benefit as a supplemental aid for North Sea helicopter operations and may lower the chances of a lightning strike attachment, there can never be any guarantee of this and it remains the case that adequate lightning protection provisions must be installed on the helicopter. The Authority would therefore have difficulty in justifying mandating the installation of lightning mapping systems for airworthiness certification purposes.'

2.6 Technical investigation

2.6.1 Introduction

Although witness evidence and photographs taken before the helicopter sank indicated that one main blade had been damaged, there is every reason to believe that this was bending damage inflicted either as a result of the effects of longitudinal pitching in the sea leading to forcible contact of the blade droop stop, or excessive blade sailing during shut-down on the rough seas.

The survivors observed, from their dinghy, that the tail rotor gearbox had broken away from its mountings, but was still suspended from the tail boom. Post-salvage examination of the fractured bolt forming the upper attachment of the gearbox confirmed that two modes of fatigue (one tensile and one bending) were present in its failure mechanism. In addition, extensive cracking of the skins and spar web of the tail pylon just below the gearbox were clearly the result of rapid cyclic loading.

The occurrence of such cyclic loading was indicative of imbalance of the tail rotor. Although the effect of salt water corrosion on the fracture faces of the gearbox casing lower attachment lugs precluded effective metallurgical examination, it appeared consistent that the cyclic loading had also led to fatigue failure of the gearbox casing adjacent to these two lower mountings.

The crew reported that after the onset of vibration, they had entered autorotation and had then resumed level flight. Some 3 minutes after they did so, a bang occurred, followed by roll, yaw and pitch-down. This motion in three axes was consistent with losing the thrust of the tail rotor and at the same time briefly losing the weight of the tail rotor gearbox. There is little doubt that the gearbox broke away from its mountings at this point.

Since there was clear evidence from examination of the upper TRGB mounting bolt that fatigue had played a part in the failure of the gearbox mountings, there was little doubt that operation of the tail rotor in a damaged state had caused this fatigue cracking and also caused the cracking of the pylon skins and spar web.

Damage to the lower part of the pylon was clearly inflicted by the tail rotor blades striking the structure. The position of the deep gash in the pylon was such that it could only have been inflicted after the gearbox separated from its mountings. There was no evidence that any of the tail rotor blade damage to the Red, Blue, Yellow, or Black blades was other than the result of impacts between the blades and the structure and thus little doubt that the associated severance of 4 blades occurred after the gearbox broke away from its mountings.

2.6.2 Lightning damage to tail rotor

Examination of the remaining inboard section of the White tail rotor blade, however, confirmed that it had suffered additional damage of a fundamentally different nature from that inflicted on the other blades. Severe thermal damage had occurred in the region of the attachment bolt reinforcements, delamination existed further outboard and laboratory analysis showed that overheating had occurred in the area of this delamination close to the fractured outboard end of the blade. The tests carried out at LTT Culham showed that all these damage characteristics could be produced in lightning simulations under various conditions. In view of the reported circumstances and the damage to the braiding and the conduction system bolt, it was thus confirmed that this unique damage to the composite structure of the White tail rotor blade had resulted from a lightning strike.

2.6.3 Lightning test simulations

The initial exploratory lightning simulation test on tail rotor blade s/n 22313 (section 1.16.1), which was conducted at only 12.7 kA, revealed that the purely 'mechanical' lap joint between the titanium anti-erosion shield on the blade leading edge and the inboard brass conducting strip produced a high resistance to the induced current flow, with consequent localised 'peel-back' of the shield. The high resistances measured across this joint on the other 3 tail rotor blades, which were to be used in this first test series, confirmed this problem, which was attributed to resin penetration between the titanium shield and the underlying section of the brass conducting strip during blade manufacture. The manufacturer's representatives present appeared to recognise the limitations of this particular design feature (which was subsequently deleted, see section 2.6.6).

The next two tests, on tail rotor blades s/nos 22200 and 20667, were carried out with applied currents of 190.90kA, action integral 1.92 x $10^6 A^2 s$ and 180.1 kA, action integral 1.91 x 10^6 respectively, both below the current certification (AC20-53A) requirements of 200 kA with an action integral of 2 x $10^6 A^2 s$. The first test utilised an attachment to the blade leading edge tip, whilst the second test located the attachment on the tip trailing edge. Despite the applied current levels being less than those specified by AC20-53A, both titanium erosion shields suffered debonding from the blade leading edges over some 90% of their contact areas, with marked damage to the blade tip area of the second blade.

The subsequent test of blade s/n 20646 (in the second series of tests) with an arc attachment to the trailing edge, at a point 0.5 metres from the tip, produced gross delamination and disbonding of the carbon composite blade structure over an area of approximately 50 cm x 15 cm, with spanwise cracking and distortion of the aerofoil aft of the erosion shield, which had debonded over some 75% of its length. The blade root area also exhibited marked delamination and disbonding of the carbon fibre skins on both sides of the blade. This scale of damage resulted from an applied current of 188.2 kA, action integral of 1.96 x$10^6 A^2 s$ and total charge transfer of 26.81 coulombs. These values were, respectively , -5.9%, -2.0% and -4.25% of the AC20-53A requirements.

Whilst this design of AS332L tail rotor blade was derived from an earlier TRB design certificated to the previous, much less stringent, requirements of TSS 8.6, the above tests demonstrated the marked damage which could arise from higher energy strikes approaching current lightning certification levels. However, it was also significant that the blade root damage produced by these energy levels did not appear of the same order as that evident within the root area of the White tail rotor blade from G-TIGK.

The last three lightning tests were therefore carried out using applied currents up to the highest energy levels which LTT Culham could produce, ie up to 275.5 kA, action integral of 4.2 x $10^6 A^2 s$ and 29.2 coulombs total charge transfer. These values were, respectively, +37.8%, +110% and +4.3% of the AC20-53A requirements. These tests simulated attachments to the aft tip bolt, and blade trailing edge at two positions, ie 34 cm and 20 cm from the tip. All three test blades exhibited more marked damage than in the previous tests, but the root damage was still less than that apparent on the White tail rotor blade. In this context, the LTT Culham Test Report AEA-75D-0690 of June 1995 stated:

'At action integral 4.2 x $10^6 A^2 s$, the damage in the blade root region was beginning to show an appearance similar to the salvaged blade and with the evidence of lug damage, it is thought likely that the lightning attachment to the G-TIGK blade may have had an action integral three times that of the Zone 1A certification level in reference 3. The certification test level of 2 x $10^6 A^2 s$ is based on data that show only approximately 2% of strikes exceed this level.'

and:

'Occasionally strikes beyond 2 x $10^6 A^2 s$ can occur, for example evidence from a Nimrod MR Mk 2 strike also over the North Sea was thought to have involved an action integral of about 6 x $10^6 A^2 s$.'

(The question of the adequacy of the current lightning certification advisory criteria, as contained in AC20-53A, to provide the requisite level of airworthiness assurance against the type of high energy lightning strikes which can been countered in service operation is discussed later in section 2.6.5 in the context of other pertinent data).

With regard to the last three simulated lightning test blades, whilst the blade root damage was not as marked as that present on the White tail rotor blade, certain other effects were notable. These included an almost full length longitudinal 'fissure' within the blade substrate exposed by the loss of the brass conducting strip on blade s/n 20697 (final test, with arc attachment to trailing edge 20 cm from tip; section 1.16.1). This was similar to the damage observed on the White tail rotor blade, and this test was the only one to produce such a markedly similar effect. In addition, whilst the titanium erosion shield was 'explosively detached' from blade s/n 20662 (ie 3rd last test, with arc attachment to aft tip bolt), more evidence of 'sparking' and 'arc-erosion' was observed on the shield internal angle, indicative of charge breakthrough from the composite leading edge to the titanium shield, which caused localised 'punctures' of the shield in several tests. Such effects appeared much more marked in the final test blade where, in addition to explosive detachment of the titanium leading edge shield, the blade leading edge composite skins split apart along the outboard half of this blade (s/n 20697), with a 5 cm long split at the inboard end of the leading edge uncovered by the detached shield. Both this blade and that from the penultimate test (s/n 22313) had also suffered gross disruption of their composite skins forward of their trailing edge arc attachments, although the associated delamination of the trailing edge on blade s/n22313 had extended inboard to such an extent that it was clearly unrepresentative of the damage to the White tail rotor blade, which exhibited no trailing edge delamination on the inboard blade section recovered.

2.6.4 Tail rotor gearbox detachment analyses and tests

The investigation thus focused upon the effect that a loss in mass from one blade would have on the tail rotor gearbox mountings due to rotational out-of-balance forces at normal tail rotor rpm. The associated analysis (section 1.16.2.2) used a finite element model of the gearbox and assumed rigid attachments of the gearbox casing at its three mountings. This analysis indicated that, under the assumed conditions, fatigue failure of the gearbox mountings within the timescale applicable (ie some 3 1/2 minutes) would require a tail rotor imbalance of 0.85 to 2.7 kg-metres. Such an imbalance appeared to imply that the White tail rotor blade would have to have lost the outboard area of its aerofoil, complete with both tip weight bolts, in addition to the titanium leading edge anti-erosion shield.

The mathematical modelling of the AS332L tail rotor to investigate the effects of a lightning damaged blade, in terms of the mass and stiffness distributions measured on the most damaged tail rotor blades from the LTT Culham lightning tests, indicated that such damage was insufficient to modify the blade stiffness characteristics to create a resonance, or 'flutter' condition, at the operating rpm of the tail rotor assembly (section 1.16.2.3).

In addition, analysis of the effects of the White tail rotor blade producing a lift coefficient of 'zero' (ie after lightning strike damage) and thus causing the remaining four undamaged tail rotor blades to generate a rotational bending moment on the tail rotor drive shaft (and thus generate a cyclic loading on the gearbox mountings) indicated that such a mechanism would only produce cyclic stresses in the finite element gearbox model which were approximately 1/40th of those caused by the mass imbalance case (section 1.16.2.4).

In view of the leading edge damage to tail rotor blade s/n 20697, and the similarity of the 'longitudinal fissure' underlying the vaporised brass conducting strip to that evident on the White tail rotor blade, it was decided to 'spin-test' this blade at full tail rotor rpm in order to explore the associated flight loading effects on the 'split' outboard leading edge to observe whether such damage might induce break-up of the outer aerofoil and release of the tip weight bolts under centrifugal and aerodynamic loading. Blade s/n 20662 was also subjected to a spin-test to provide an assessment of the security of its aft tip weight bolt following the high energy arc attachment to this bolt during the 3rd last test. In addition, blade s/n 22313 was also included in the spin-tests to provide additional assessment of any break-up tendency due to gross aerofoil skin disruption, included that around a localised area of its main spar (section 1.16.1).

These spin-tests (section 1.16.2.5), which were conducted at zero aerodynamic pitch for one minute (to represent the autorotative descent of G-TIGK immediately after the lightning strike), followed by 2 1/2 minutes at a representative tail rotor pitch of 7° and full tail rotor speed (to represent the final low level cruise part of the flight), did not cause any significant further damage to any of these blades. Whilst small sections of delaminated skin and expanded foam aerofoil core were detached from blades s/nos 20697 and 22313, and the width of the leading edge split on blade s/n 20697 increased to some extent, no significant mass was shed from any blade; the tip bolts remained securely attached to the blades, including the aft tip bolt on blade s/n 20662 which had suffered a direct high energy attachment during the LTT Culham tests.

Indeed, these tests indicated that the design and construction of this type of blade was impressively resistant to further flight loading damage subsequent to the marked damage induced by these lightning test simulations, certainly for short periods at operating rpm of several minutes, or more.

In view of such results, it was decided to perform a final analysis (section 1.16.2.6) which utilised a structural dynamic model in order to assess whether the dynamic reaction of the tail boom/pylon to tail rotor out-of-balance forces might generate the required cyclic stresses to fail the gearbox mountings in the required timescale, but at a lower level of tail rotor imbalance. The key question was whether any such indicated reduction in the required blade mass loss would be comparable to loss ofthe titanium leading edge anti-erosion shield, brass conducting strip and associated root bonding strap, since these items were readily detached from the tail rotor blades during the simulated lightning tests at LTT Culham.

The dynamic analysis, in contrast to the initial static finite element analysis under cyclic load, showed that low imbalance, equivalent to the loss of one anti-erosion shield from one tail rotor blade, was sufficient to rapidly fail the gearbox lower lugs. It also showed that the loss of an anti-erosion shield would cancel the CVFDR, as occurred in G-TIGK.

Examination of the fractured bolt from the upper attachment of the gearbox revealed conclusive evidence that the bolt had been slack at the time of its failure, having rotated whilst under cyclic loading and having then failed due to a cyclic bending load. Examination of another AS332L aircraft confirmed that the wire-locking of the three attachment bolts was of a very light gauge, unlikely to provide an effective restraint to rotation under excessive vibratory loads.

Examination of the fracture face of the threaded-end of the upper attachment bolt showed that the final fracture was in bending to the left. This suggested that the lower right lug of the gearbox had failed first. The finite element analysis indicated higher loads at the lower lugs than at the upper lug and so it was reasonable to expect that, with all bolts equally tight, the initial failures would occur at, or close to, the lower attachments. The exact rpm used during the initial autorotation is not known, but it is entirely reasonable that it could have been close, for a period, to one of the mode frequencies identified, ie 20.80Hz, 22.35 Hz, 22.80 Hz or 23.35 Hz (ie 1,248, 1,341, 1,368 or 1,401 rpm respectively; the available tail rotor rpm for auto-rotation ranging from 1,182 rpm to 1,399 rpm).

It is also reasonable to assume that when the aircraft was returned to horizontal flight, the tail rotor rpm was close to 1,296, the average cruise figure derived from the operator's HUMS data.

As stated above, it is clear from the metallurgical examination that the upper bolt became slack before it fractured. The gearbox was fitted some 18 operating hours before the accident and the two routine post-fitting mounting bolt torque checks were carried out, without any problems being revealed, the second on the night before the accident. There can thus be little doubt that the bolt was correctly torqued-up at the time that the aircraft was despatched on the morning of the accident (see section 1.6.3). The only unusual event to affect the bolt thereafter was the high vibration level following the lightning strike. It is concluded that this high vibration led to failure of the locking wire, allowing the bolt to begin slackening.

Once the top bolt began to slacken, and the aircraft was returned to horizontal flight, the slight reduction in natural frequency due to reduced stiffness of the upper attachment would have caused the system to rapidly reach a state where the tail rotor speed, and hence the forcing frequency, would approach and/or coincide with the natural frequency of the system. The loads on the lower lugs, resulting from unit imbalance, would therefore rise to many times the loads originally predicted by the static finite element analysis under cyclic loading.

In addition, increasing slackness of the upper bolt would apply bending loadings to the lower lugs not defined in any of the analyses. The lower gearbox lugs which, even under the assumption that all bolts were tight, would be more highly loaded than the upper lug, would therefore be able to fail in the 3½ minute period following the lightning strike with a very small degree of tail rotor imbalance present.

It is also clear that the close proximity of the natural frequencies of oscillation of the tail boom to the range of tail rotor rotation speeds used in normal flight and during autorotation had a critical effect on the short time between the lightning strike and the separation of the gearbox.

In view of the evidence that the severe tail rotor vibration must have caused breakage of the locking wire attached to the tail rotor gearbox upper mounting bolt and consequent loosening of this bolt, overstressing of both lower mounting lugs and fatigue failure of the upper bolt, the following Safety Recommendation is made:

The manufacturer of the AS332L Super Puma helicopter should introduce improved strength locking arrangements for the mounting bolts of the tail rotor gearbox assembly such that unlocking and loosening of these bolts does not occur under conditions of excessive tail rotor vibration resultant from tail rotor damage. (Safety Recommendation 97-33)

In addition, the dynamic stress analysis findings that the measured natural frequency responses of the tail boom/pylon assembly on the AS332L are very close to the range of tail rotor rotational frequencies used in normal flight, and during autorotation, raised the question of possible modification of the tail boom/pylon assembly to reduce associated dynamic coupling. Such modification, if successful, could reduce the extent of secondary fatigue damage which may otherwise occur following the onset of tail rotor out-of-balance operation, due to associated blade damage, and usefully extend flight time under related emergency conditions over the North Sea. In view of such findings, it is recommended that:

The manufacturer of the AS332L Super Puma helicopter should review the dynamic frequency responses of the tail boom/pylon assembly in relation to tail rotor rotational frequencies, with a view towards assessing the practicability of modifying the tail boom/pylon assembly to reduce associated structural dynamic coupling and related fatigue damage which may arise from in-flight tail rotor blade damage/loss of mass. (Safety Recommendation 97-34)

Eurocopter responded to these two further Safety Recommendations within their written response of 22 April 1997 to the draft report, stating:

'*Improved TGB Attachment:*

The analyses carried out subsequent to the G-TIGK accident have led us to design a modification which improves the strength of the gearbox on the tail boom. This modification, MOD.322A07 6653 was approved on April 14, 1997, and proposes the installation of a bolt made from a new material and an optimised tightening torque load. This modification will be presented to our customers by Service Bulletin No. 64.00.24, classified "Recommended.'

and,

'Tail Boom Dynamic Response:

The test results obtained from the modelling carried out by Stirling Dynamics as well as those obtained on the helicopter G-TIGM are currently being analysed by our Engineering Department. Once this analysis is completed, if tests are to be undertaken, this will most certainly be done with the participation of Stirling Dynamics.'

2.6.5 Adequacy of lightning certification standards

Although the lightning protection features of the AS332L tail rotor are reported to be identical to those of the design from which it was 'read across', the earlier tail rotor structural material is understood to have been GRP. CFRP differs electrically from GRP in being a series of fine conductors (the carbon fibres) embedded in an insulating material (the matrix) rather than being a total insulator with non-conductive glass fibres embedded in a non-conductive matrix. It is therefore possible for lightning attachments to occur to carbon composite areas of such blades under conditions where lightning attachments would not occur to corresponding points on geometrically similar blades manufactured from GRP.

The incident to a Norwegian AS332L in November 1990 (section 1.18.10) illustrated the extent of lightning damage which, under real conditions, could occur to this design of tail rotor. In the light of this damage, Eurocopter carried out a test of the AS332L tail rotor blade design, in accordance with AC20-53A criteria, in January 1991. The test was, however, reportedly carried out at a significantly lower maximum current (ie 174 kA) than that called for in both the AC20-53A and the TSS criteria, mainly because the damage inflicted, to the trailing edge tip, as the current rose broke arc continuity before the 200 kA level was reached. In addition, the premature failure of the test resulted in a low action integral ($0.9 \times 10^{6} A^{2}s$) being applied. The associated degree of damage, inflicted in simulated conditions much less severe than those required for certification, illustrated the shortcomings of the read-across method of validation when the structural material is changed to one having different electrical properties.

This test demonstrated in practice that the blade design did not meet the requirements of the TSS criteria, to which the aircraft was certificated, which were much less demanding than the AC20-53A criteria, to which modern aircraft types are certificated.

Although the potential hazard of lightning damage to aircraft has been well known for many years, the suitability of particular protection levels in assuring safety in all weather conditions likely to be encountered has evidently proved difficult to establish. Although it appears that widely used certification criteria may understate the magnitude of the problem, strikes do not appear to have created critical structural damage in metallic aircraft, since they generally have many alternative low resistance paths for electrical current flow in the structure and will generally withstand much more powerful strikes than those called for in certification without any special steps being taken. Where particular damage is likely, eg in mounting / hinge areas of control surfaces on fixed wing aircraft, the general redundancy of such controls limits the hazard of even serious lightning strikes. The main area of concern in metallic aircraft has been the effects of lightning strikes on wing fuel tanks, with the attendant risk of fire.

Composite structures are clearly a very different proposition. All electrical current paths must be specifically engineered to withstand a particular current level. Composites using a conductive fibre within a non-conductive matrix must be expected to experience lightning attachments to the composite material during the more severe discharges. Although current will pass through CFC provided the current density is below a certain value, since CFC is approximately 1,000 times as resistive as aluminium alloy, the Joule heating effect becomes a major damage mechanism, the action integral now being the major controlling parameter. In addition, for local arc attachment damage, charge transfer is also significant. Suitably engineered current paths need to be positioned in such a way that discharges do not route through structural fibres and destroy the matrix materials in which they are embedded.

The assessment of LTT Culham, based on the results of the lightning strike simulation tests, that '... it is thought likely that the lightning attachment to the G-TIGK blade may have had an action integral three times that of the Zone 1A certification level ...'. (section 1.16.1), was a notable observation from the associated lightning specialists.

The CAA responded to this LTT observation, within their written responses of the 9 April 1997 to the draft copy of this report, as follows:

The report focuses on the theory that suggests the energy level of the lightning attachment to the rotors of G-TIGK, may have produced an action integral equal to three times that of the present certification test threat levels. This theory appears to be based on a comparison of the damage to the root area of the white tail rotor blade recovered from the accident aircraft to that produced by the various tests conducted on new tail rotor blades at LTT Culham. Although the Authority cannot disprove this theory, it must be pointed out that the Culham tests also revealed that the tail rotor lightning protection provisions were suspect and that they did not provide adequate lightning protection. This is borne out particularly by the fact that the erosion shield peeled back from its adjacent brass lightning conducting strip when being subjected *to calibration test currents in the order of only 10% of the present certification test threat level. This indicates that the lightning protection provisions would be virtually ineffective and that damage could therefore be caused to the composite tail rotor blades by strikes that do not necessarily produce high energy. The Authority would therefore question the assumption that the root damage apparent on the white tail rotor blade may have been the result of an attachment that produced an action of three times the present certification test threat levels.'*

'It may be seen from the above response that the CAA questioned that the White tail rotor blade had suffered a high energy lightning strike of some three times the action integral advised by AC20-53A, on the basis that the lightning protection provisions of this TRB may have been 'virtually ineffective' in view of the LTT lightning test findings concerning the excessive electrical resistance detected on some of the test blades at the leading edge anti-erosion shield/brass conducting strip 'lap' joint (see sections 1.16.1 and 2.6.3) and, in particular, the test result on TRB s/n 22313. In the latter test, the anti-erosion shield deflected away from the underlying brass conducting strip when only 12.7 kA was applied at the tip of the shield (see Appendix C, Figure 2), effectively breaking any conductive path which had existed across this lap joint. As stated in section 1.16.1, such observations caused the Eurocopter representatives present at these tests to comment that instances had occurred on blade production in which resin had penetrated between the brass conducting strip and the titanium anti-erosion shield. The inference in the CAA response was that the White TRB may have had a similarly defective shield/strip lap joint which rendered the associated conductivity provisions 'virtually ineffective'.

However, if the White tail rotor blade had such a defective lap joint between its titanium anti-erosion shield and the brass conducting strip, there was certainly no evidence of this since the brass strip had clearly been exposed to sufficient current to destroy it and to generate a full length 'fissure' within the underlying composite substrate (see Appendix A,Figures 4B and 10). It should be noted that the latter effect was only reproduced, to a lesser extent, during TRB lightning tests at very high action integral values (section 1.16.1). Such evidence indicated that the titanium anti-erosion shield/brass conducting strip system on the White TRB had performed as intended and had passed high current to the root 'earthing' bolt and associated root braided bonding strap, which had also failed (Appendix A,Figure 4B) in the manner consistent with the passage of high current flow, as demonstrated frequently in the LTT tests. There was thus clear evidence that the lightning conduction system on the white TRB had been fully effective to the extent of its design capability.

In view of this, it followed that the marked damage apparent within the root area of the White TRB, which extended outboard of both attachment bushes, occurred despite part of the current having been successfully channelled through the leading edge anti-erosion shield/brass conducting strip system, as indeed occurred during the high energy lightning tests conducted on test blades at LTT, Culham. It was the LTT lightning specialists who, on comparing the root damage apparent on the White TRB with the less marked root damage produced during the high energy (ie up to an action integral of $4.2 \times 10^6 A^2s$) tests at Culham, stated that they "thought it likely that the lightning attachment to the G-TIGK blade may have had an action integral three times that of the Zone 1A certification level ....". On the basis of the test results and this LTT assessment, it would appear reasonable to conclude that the White tail rotor blade must have been subjected to a lightning strike which input energy levels with an action integral between $4.2 \times 10^6 A^2s$ and $6.0 \times 10^6 A^2s$. It is thus considered beyond dispute that the White TRB was struck with a high energy lightning strike which was well above the AC20-53A certification level of action integral.

The CAA also made the following statement:

'There is no evidence or experience to suggest or conclude that where adequate provisions are installed and have been properly verified by testing to the defined agreed criteria, that any lightning strike will not be tolerated safely.'

This statement relies upon the appropriateness of the applicable 'defined agreed criteria'. TSS 8.6 was the original lightning certification standard and represented the associated' defined agreed criteria' at that time, however its inadequacy was subsequently accepted and it was later superseded by AC20-53 on 6 October 1967 and then by AC20-53A on 4 December 1985 (section 1.18.5).

The possibility that aircraft may encounter lightning strikes of energy levels in excess of the AC20-53A advisory criteria was acknowledged by the associated standard, which was apparently only intended to provide protection assurance against some 98% of negative cloud/ground (or sea) lightning strikes thought likely to be encountered in service. From a structural viewpoint, whilst such a limited protection goal may appear reasonable for fixed wing aircraft where the effects of a higher energy strike may only cause limited structural damage to nose cones, wing and tail surface extremities, the corresponding effects on helicopter rotor blades, and particularly the relatively lightly constructed tail rotor blades, can quickly lead to critical control problems, as demonstrated by this accident. The loss of yaw control resulting from a detached tail rotor gearbox may be successfully countered by prompt autorotative descent and ditching, or landing, if the gearbox and damaged tail rotor assembly is, by some fortuitous means, restrained from complete separation from the tail boom/pylon. However, should the tail rotor/gearbox completely separate from the latter, the accompanying forward displacement of the helicopter's c.g. will induce marked pitch-down problems, which may lead to a non-survivable accident. The consequences of high energy lightning strikes on helicopter tail rotors are thus potentially very serious. It is therefore concluded that the currently accepted probability, within the AC20-53A lightning certification advisory criteria, that some 2% of in-service negative cloud/ground (or sea) lightning strikes may exceed the specified energy levels, should not be accepted as a basis for the lightning certification of rotary wing aircraft, but that specified energy levels should be increased to a level sufficient to provide airworthiness assurance against the highest energy lightning strikes which such aircraft may encounter in service.

Whilst such an increase in lightning certification standards may be viewed as an unwarranted response to the potential effects of only some 2% of likely negative cloud/ground (or sea) lightning strikes on helicopters, the underlying basis for this 2% probability assessment does not appear well founded. It is derived from the inclusion of negative cloud/ground/sea lightning discharges, but excluding the more powerful positive cloud/ground, or sea, discharges. This exclusion was made on the basis that such positive discharges were deemed to account for only some 10% of cloud/ground or sea discharges. If this frequency of positive discharges is included, the 2% probability of higher energy discharges increases to some 3.5% (section 1.18.6.4).

The data provided by E A Technology for lightning discharges over the North Sea area in which G-TIGK was operating (section 1.18.8) indicated that it had been struck by a positive discharge (ie polarity of cloud with respect to sea) at 1236:30 hrs at position 58° 28' 31" North, 0° 51' 08" East (probable position error of 4.6 nm) on the 19 January.

With regard to other instances of high energy lightning strikes over the North Sea, section 1.16.1 includes the additional comment by LTT Culham related to an RAF Nimrod MR Mk 2 aircraft, which suffered marked lightning damage to its radome assembly, that 'was thought to have involved an action integral of about 6 x$10^{6}A^{2}s$' (ie 3 times the AC20-53A action integral). In addition, some two weeks after the AAIB issued Safety Recommendation No 95-45 (section 2.5) on the 15 February 1996, recommending that ' ....the CAA and affected operators should jointly agree the fitment of lightning discharge mapping systems to such aircraft', another AS332L helicopter suffered a high energy lightning strike. This Norwegian aircraft, LN-OLB, was inbound to Bergen on the 27 February 1996 when it was struck, resulting in heavy airframe vibration. The commander elected to continue to land at Bergen where subsequent inspection revealed marked damage to its main rotor blades, with further damage to its hydraulic system components and airframe, although the tail rotor showed no evidence of lightning attachment (section 1.18.10). The information requested by the AAIB from the UK Meteorological Office, Bracknell, in relation to this particular lightning strike showed one isolated discharge detected in the area in which LN-OLB had been operating during the associated timespan, ie a strike which had occurred at 0912.52 hrs UTC at position 60° 27'50.4" North, 04° 44' 9.6" East. This isolated discharge was within 2 minutes and 1 nm of the reported strike and was thus considered to have been the lightning discharge in question. Corresponding data from EA Technology recorded a positive polarity discharge at 0912:22 hrs UTC at 60° 40' 13" North, 05° 17'33" East, on the 27 February.

Such evidence of high energy positive polarity lightning strikes appeared consistent with the other data provided by EA Technology (section 1.18.8) which indicated that up to some 80% of lightning discharges over the North Sea could be positive discharges, with some 40% positive discharges over the southern UK (EA data sample from 1990). In addition, Japanese lightning researchers have recorded very high energy discharges of up to 300 kA, with associated action integrals of $10 \times 10^6 A^2s$, ie up to five times the specified action integral within AC20-53A, along the western seaboard of Japan (section 1.18.8).

The CAA response of 9 April 1987 stated the following in this context:

'The Authority is aware of the information that suggests a higher ratio of cloud to ground strikes in the North Sea are positive, than is assumed at the present. If this were the case then it could also mean that a higher percentage of strikes produce higher energy levels. The Authority has already initiated and has agreed to fund research to establish if the characteristics and frequency of lightning strikes in the North Sea are different to that generally accepted at present.'

and,

'The Authority would point out that even if the lightning strike energy levels are higher than present certification test threat levels, it does not follow that the lightning protection provisions that are installed to meet present test criteria would not also be adequate to protect against higher energy levels.'

Whilst this last statement reflects that lightning protection provisions which meet AC2053A criteria might also provide adequate protection against higher energy level lightning strikes, the acceptance of such an approach would undermine the primary reason for the use of such certification standards, which is to provide associated airworthiness assurance for all designs which are so certified. If realistic maximum energy levels are not used for lightning certification testing, any assurance deemed to be gained from such certification tests must be undermined. Indeed, the objective of such lightning certification was stated by the CAA later in their response:

'The Authority considers the Report should make it clear at the outset that with regard to airworthiness certification, the primary objective is for the helicopter to be provided with lightning protection provisions such that lightning strikes can be tolerated without endangering the aircraft.'

This response described the 'primary objective' of helicopter lightning certification in a commendably clear manner, which served to highlight that it was precisely this primary objective which was demonstrably not achieved in this case due to inadequacies in the lightning certification process associated with the AS322L tail rotor blade design.

In view of the above findings, it was concluded that the existing purely advisory criteria of the AC20-53A lightning certification standard require substantive strengthening (in certification terms) and improvement if helicopters with carbon composite rotor blades are to be suitably equipped to withstand high energy lightning strikes of positive polarity without incurring critical damage, particularly to their tail rotors. The following Safety Recommendation is therefore made:

The CAA, in conjunction with the appropriate industry committees, should review aircraft lightning certification requirements, and the advisory nature of AC20-53A, to introduce the following more stringent requirements for rotary wing aircraft with composite rotor blades:

1. Increase in the specified Zone 1A action integral from 2 x 106A2s to a level compatible with the highest energy positive polarity lightning discharges likely to be encountered in service.

2. Replace the existing 98% probability assurance with 100% probability target.

3. Addition of specified arc attachment points to be used in the lightning certification tests on rotor blades, to include: leading edge tip; tip weight bolt(s) if used; trailing edge tip; trailing edge up to 0.5 metres inboard of tip.

4. Specified use of representative blade root attachment assemblies during all lightning tests to simulate related current flow/thermal affects on root structure.

In addition, the CAA and appropriate committees should review lightning certification requirements with regard to any corresponding, or other, improvements which may be deemed necessary for fixed wing aircraft with significant composite material structural elements. (Safety Recommendation 97-35)

2.6.6 Modified AS332L tail rotor blade

As described in section 1.18.11, the manufacturer was informed at an early stage of the investigation of the findings regarding this accident, in addition to witnessing the subsequent simulated lightning tests at LTT Culham, and had immediately begun to explore methods of improving the design of the AS332L tail rotor blade to reduce the damaging effects of such lightning strikes. The resultant modified blade, part no. 332A.12.0050, which was certificated to the AC20-53A criteria and was made available to operators towards the end of 1995, featured several improvements. These included the addition of titanium sheathing to the tip area which provided conductivity protection to the outboard trailing edge, tip area full chord, with two titanium tab attachments linking both tip weight bolts to the tip sheath and to the titanium leading edge anti-erosion shield. The latter was extended inboard and secured to the root 'earthing' bolt, thereby deleting the previous brass conducting strip and associated strip/shield lap joint. In addition, the tip sheath was riveted to the outer trailing edge of the blade to provide, with the attachment of the leading edge shield to the root bolt, increased strength retention of the titanium conduction elements in the event that associated debonding occurred as a result of a high energy lightning strike. Appendix C, Figures 13A, 13B and 13C show these changes. Furthermore, this modified blade design included a fibreglass layer around its leading edge, ie underlying the titanium anti-erosion shield,which was designed to prevent charge transfer from the carbon composite skin layers, at the leading edge radius, to the internal angle of the titanium shield which had caused 'sparking' and 'arcing', with associated 'punctures', of the titanium shield during many tests at LTT Culham (section 1.16.1).

3 Conclusions

(a) Findings

(1) The crew members were properly licensed, medically fit and adequately rested to operate the flight.

(2) The weather conditions were within the permitted operating envelope of the helicopter.

(3) The crew exhibited a high degree of skill in carrying out a successful ditching into the rough sea conditions.

(4) Only the right heliraft was utilised because of difficulty in using the left heliraft due to the wind relative to the ditched helicopter.

(5) There were minor errors of procedure made by the crew during the evacuation into the heliraft and within the heliraft, but none of these errors affected the safety or rescue of personnel in this accident.

(6) The right heliraft operated well, despite suffering a puncture and being loaded above its normal complement, although within its stated overload capability. Apart from the puncture, the minor problems noted were because of errors in operating procedures.

(7) The crews of the Fast Rescue Craft exhibited a high degree of skill in the transfer of personnel.

(8) The survival of all the passengers reflected well on all the individuals, and on their training and pre-flight briefing.

(9) The rescue co-ordination, whilst successful in this case, highlighted the potential problem regarding who is primarily responsible for the co-ordination of a rescue operation concerning an air accident in a maritime environment.

(10) There were some minor deficiencies and failures associated with the passengers' safety equipment, however none of these problems affected the safety or rescue of the individuals in this accident.

(11) One main rotor blade and one tail rotor blade had suffered high energy lightning strike damage, however the main rotor continued to operate satisfactorily.

(12) The 'White' tail rotor blade was sufficiently damaged by the lightning strike to induce severe vibration which later caused the complete detachment of the tail rotor, associated gearbox and pitch servo assembly due to cyclic overstressing of the gearbox attachments within some 3 1/2 minutes of the strike.

(13) The detached mass of the damaged tail rotor, gearbox and pitch servo was fortuitously restrained from complete separation from the tail boom pylon by two of the four stainless steel hydraulic pipes connected to the pitch servo, which had held it suspended alongside the right side of the pylon, allowing retention of effective helicopter longitudinal pitch control until the ditching had been successfully completed.

(14) Simulated lightning tests conducted on this type of tail rotor blade produced similar root damage to that observed on the White blade, with various forms of corresponding damage, including disbonding/detachment of the leading edge anti-erosion shields and gross aerofoil damage; however detachment of the tip weight bolts did not occur in these tests, or during later spin-rig testing of such damaged blades.

(15) The tail rotor gearbox detached due to the effects of tail rotor imbalance and associated dynamic response of the gearbox/pylon boom assembly which caused unlocking/loosening and fatigue failure of the gearbox upper attachment bolt and associated cyclic overstressing of the two lower mounting lugs, within some 3 1/2 minutes of the lightning strike.

(16) The dynamic stress analysis used indicated that the White tail rotor blade lost mass equivalent to the detachment of its leading edge anti-erosion shield to produce the required out-of-balance forces to overstress the gearbox attachments due to cyclic loading.

(17) The forces generated in the tail boom would also have been sufficient to 'trigger' the G-switch in the Combined Voice and Flight Data Recorder electrical power supply, as occurred.

(18) The failure of the locking wire attached to the upper attachment bolt head and consequent loosening of this bolt, as a result of the cyclic forces induced by the tail rotor out-of-balance condition, increased the loading on the two lower mounting lugs both by load transfer and by altering the natural frequency of the tail boom/pylon assembly, and highlighted the need for strengthened locking provisions for this bolt.

(19) This design of carbon composite tail rotor blade was not subjected to lightning testing during its certification in 1981 for the AS332 Mark 1 helicopter, since it was considered merely a development of an earlier fibreglass blade fitted to the SA350 Ecureuil which had been satisfactorily certificated to the lightning test criteria of TSS8.6, the latter having been superseded by the more demanding criteria of advisory circular (AC) 20-53 in 1967, and by AC20-53A in 1985.

(20) The White tail rotor blade may have suffered a lightning strike with an action integral of 6 x 106A2s, ie three times the certification level advised in AC20-53A, since the maximum action integral of 4.2 x 10^6 A2s attained during tests produced root damage similar to, but less than, that apparent on the White blade.

(21) This accident demonstrated the potential for critical damage to be sustained by helicopters, equipped with carbon composite tail rotor blades, as a result of high energy lightning strikes.

(22) Helicopters currently operating in the North Sea have no onboard means of detecting areas of potential lightning discharge conditions.

(23) While North Sea flight trials of the 'Stormscope' Weather Mapping System are continuing on one AS332L helicopter, in November 1996 the offshore Helicopter

Services Safety Group declined to continue sponsorship of the alternate programme to develop onboard E-field sensor equipment for North Sea helicopters, due to the associated costs of the required research.

(24) The helicopter buoyancy system operated effectively to maintain the aircraft in a stable condition, despite the prevailing high sea state.

(25) The heliraft was punctured by contact with a sharp projection on one (probably the right) jettisoned cabin door which floated due to inherent buoyancy.

(b) Causes

The investigation identified the following causal factors:

1. One of the carbon composite tail rotor blades suffered a lightning strike which exceeded its lightning protection provisions, causing significant damage and mass loss.

2. The dynamic response of the gearbox/pylon boom assembly to the tail rotor system imbalance induced rapid cyclic overstressing of the gearbox attachments which was accelerated by the early failure of the upper mounting bolt locking wire, allowing consequent loosening and fatigue failure of this bolt.

3. Complete loss of the yaw control system and a momentary pitch-down as a result of detachment of the tail rotor, gearbox and pitch servo assembly.

4. The lightning strike protection provisions on this design of carbon composite tail rotor blade were inadequate due to it having been developed from an earlier fibreglass blade which had been certificated to lightning test criteria which have since become obsolete.

4 Safety Recommendations

It is recommended that:

4.1 The CAA should ensure that the North Sea helicopter operating companies include in their very effective recurrent training for crews discussion and, where possible, 'hands on' practice of the procedures necessary to accomplish a successful evacuation from a floating helicopter following a ditching or alighting on the sea.

(Safety Recommendation 97-29)

4.2 The manufacturer of the AS332L Super Puma helicopter should review the failure modes of the cabin door upper guide roller mounting arms which can occur during door jettison in rough sea conditions, and take action to prevent such mounting arm failures which can puncture helirafts when they subsequently come into contact with floating doors.

(Safety Recommendation 97-30)

4.3 The CAA should call for a survey of jettisonable doors, of composite construction, fitted to North Sea public transport helicopters to determine if they are initially buoyant on jettison and, if so, to inspect such doors for projections likely to puncture floating helirafts, taking into account damage likely to occur to door mountings during jettison in rough sea conditions.

(Safety Recommendation 97-31)

4.4 In order to prevent the premature cessation of electrical power supply to helicopter combined voice/flight data recorders (CVFDRs) caused by abnormal excessive vibration effects on associated G-switches, it is recommended that the CAA:

1 Require operators to render inoperative CVFDR G-switches, as an interim measure, and

2 Take action to identify a more suitable method of stopping such flight recorders during crash impact.

(Safety Recommendation 97-32)

4.5 In order to provide helicopter commanders with the necessary 'real-time' information to enable them to avoid flight into areas of actual thunderstorms or lightning activity in Public Transport helicopters which have composite rotor blades, the CAA and affected operators should jointly agree the fitment of lightning discharge mapping systems to such aircraft. The Authority should also inform other airworthiness authorities of the action taken in response to this recommendation.

(Safety Recommendation 95-45)

4.6 The manufacturer of the AS332L Super Puma helicopter should introduce improved strength locking arrangements for the mounting bolts of the tail rotor gearbox assembly such that unlocking and loosening of these bolts does not occur under conditions of excessive tail rotor vibration resultant from tail rotor damage. (Safety Recommendation 97-33)

4.7 The manufacturer of the AS332L Super Puma helicopter should review the dynamic frequency responses of the tail boom/pylon assembly in relation to tail rotor rotational frequencies, with a view towards assessing the practicability of modifying the tail boom/pylon assembly to reduce associated structural dynamic coupling and related fatigue damage which may arise from in-flight tail rotor blade damage/loss of mass.

(Safety Recommendation 97-34)

4.8 The CAA, in conjunction with the appropriate industry committees, should review aircraft lightning certification requirements, and the advisory nature of AC20-53A, to introduce the following more stringent requirements for rotary wing aircraft with composite rotor blades:

1 Increase in the specified Zone 1A action integral from 2 x 106A2s to a level compatible with the highest energy positive polarity lightning discharges likely to be encountered in service.

2 Replace the existing 98% probability assurance with 100% probability target.

3 Addition of specified arc attachment points to be used in the lightning certification tests on rotor blades, to include: leading edge tip; tip weight bolt(s) if used; trailing edge tip; trailing edge up to 0.5 metres inboard of tip.

4 Specified use of representative blade root attachment assemblies during all lightning tests to simulate related current flow/thermal affects on root structure.

In addition, the CAA and appropriate committees should review lightning certification requirements with regard to any corresponding, or other, improvements which may be deemed necessary for fixed wing aircraft with significant composite material structural elements.

(Safety Recommendation 97-35)

E J TRIMBLE

Inspector of Air Accidents

Air Accidents Investigation Branch

Department of the Environment, Transport and the Regions

July 1997

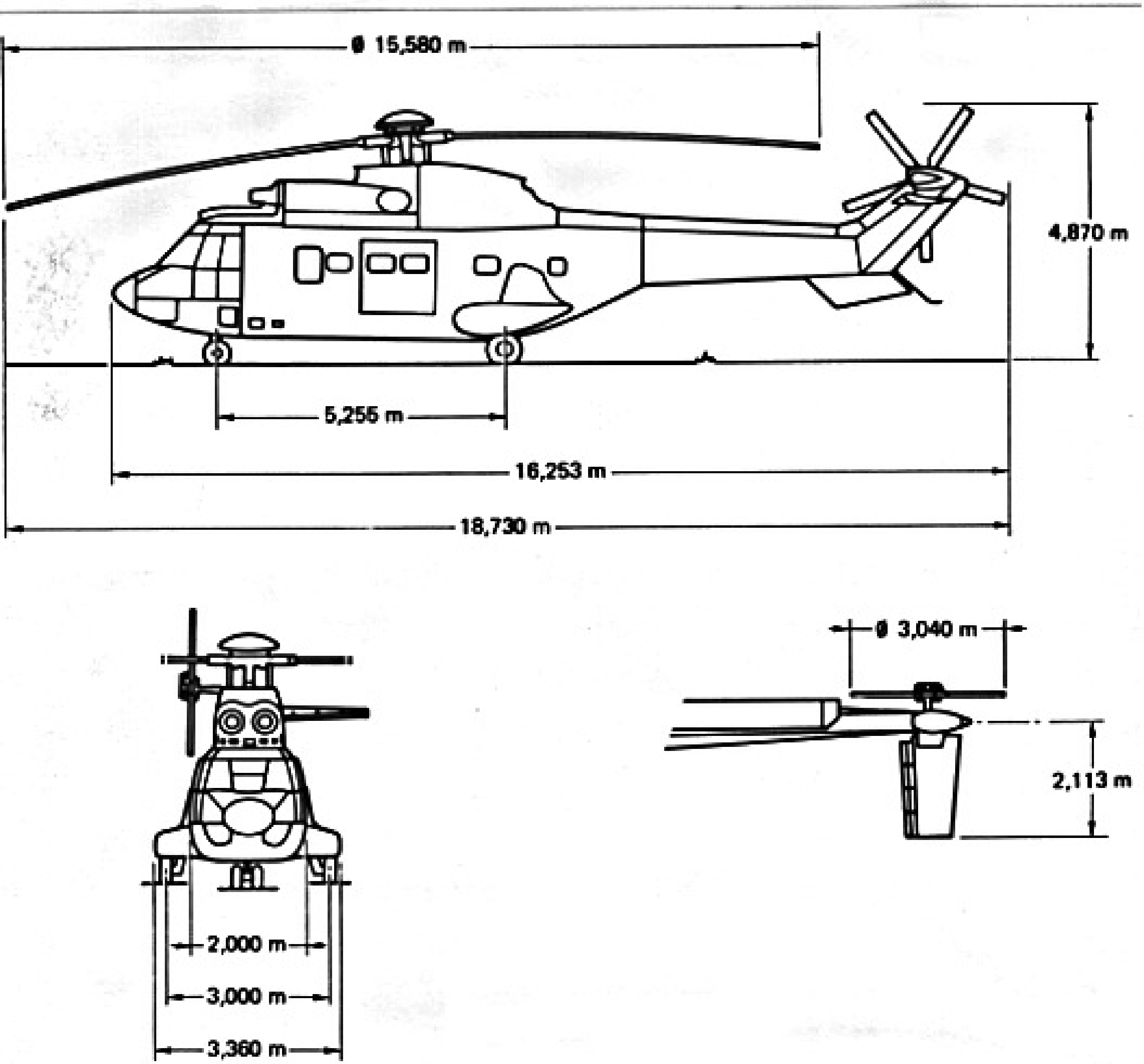
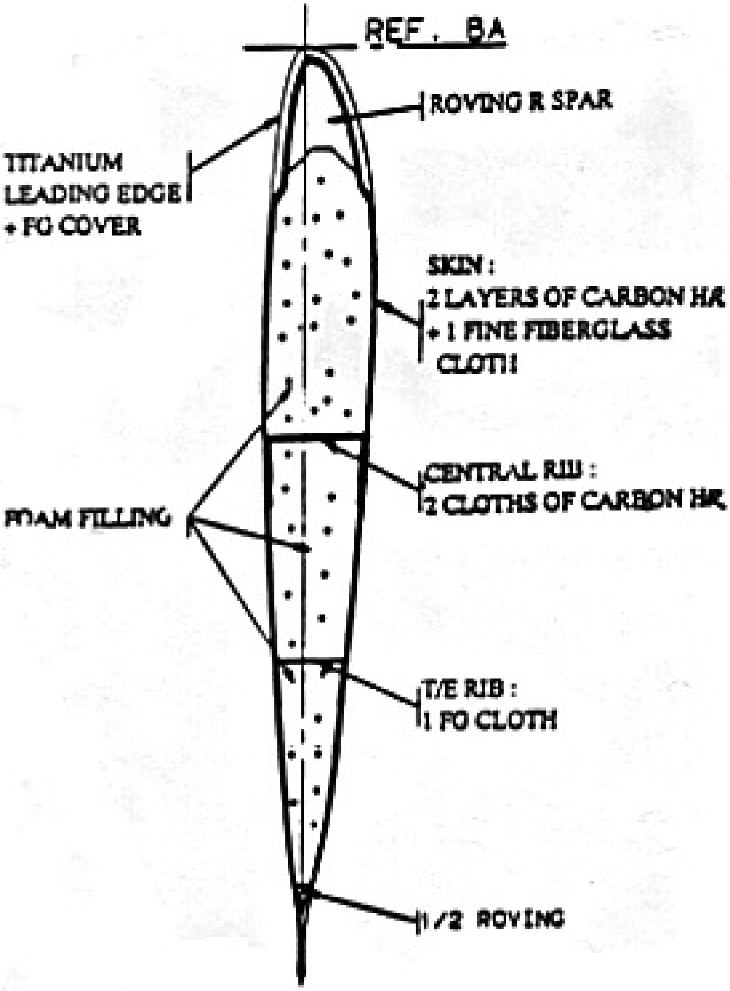


Figure 1: Showing general layout of AS332L



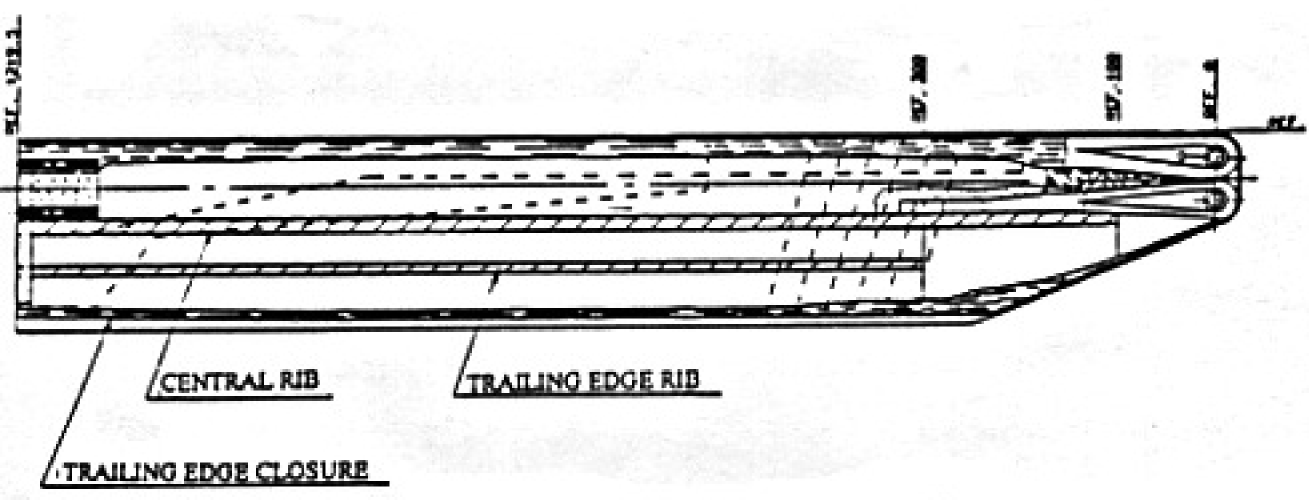


Figure 2: Showing tail rotor blade structure.

Figure 3: Showing a sample tail rotor blade with leading edge anti-erosion shield, plastic cover overlying brass strip and braided bonding strap to root bolt.

Figure 4A: Showing recovered tail rotor, gearbox and pitch servo assembly, with 'White' blade root section uppermost.

Figure 4B: Showing outboard side of 'White' tail rotor blade root with leading edge erosion shield and brass strip missing, and failed braided bonding strap.

Figure 5: Showing deep gash in trailing edge of tail boom pylon and tail rotor blade impact damage on right side.

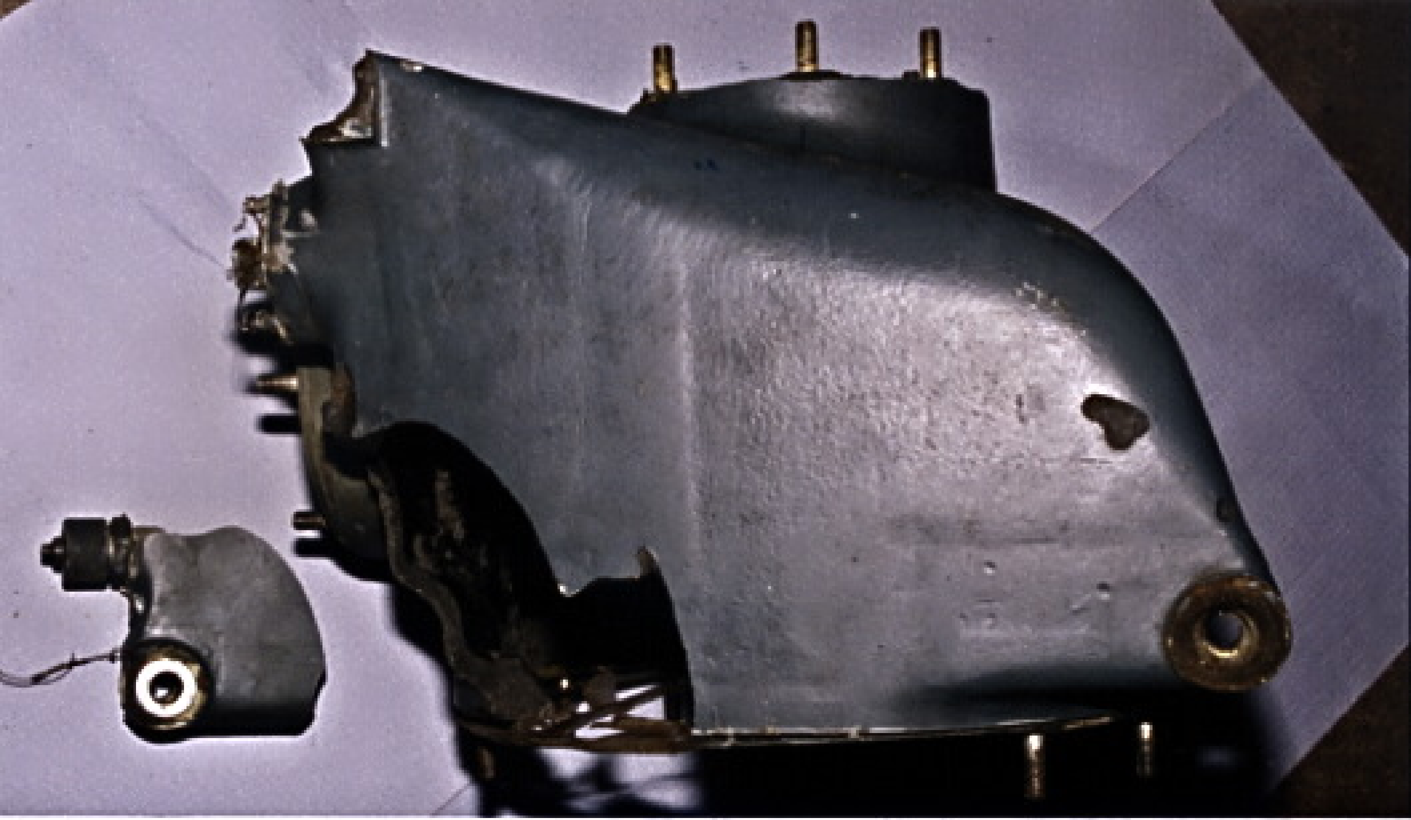


Figure 6: Showing failed lower attachments of gearbox (left attachment is upper one in this photograph, right is lower).

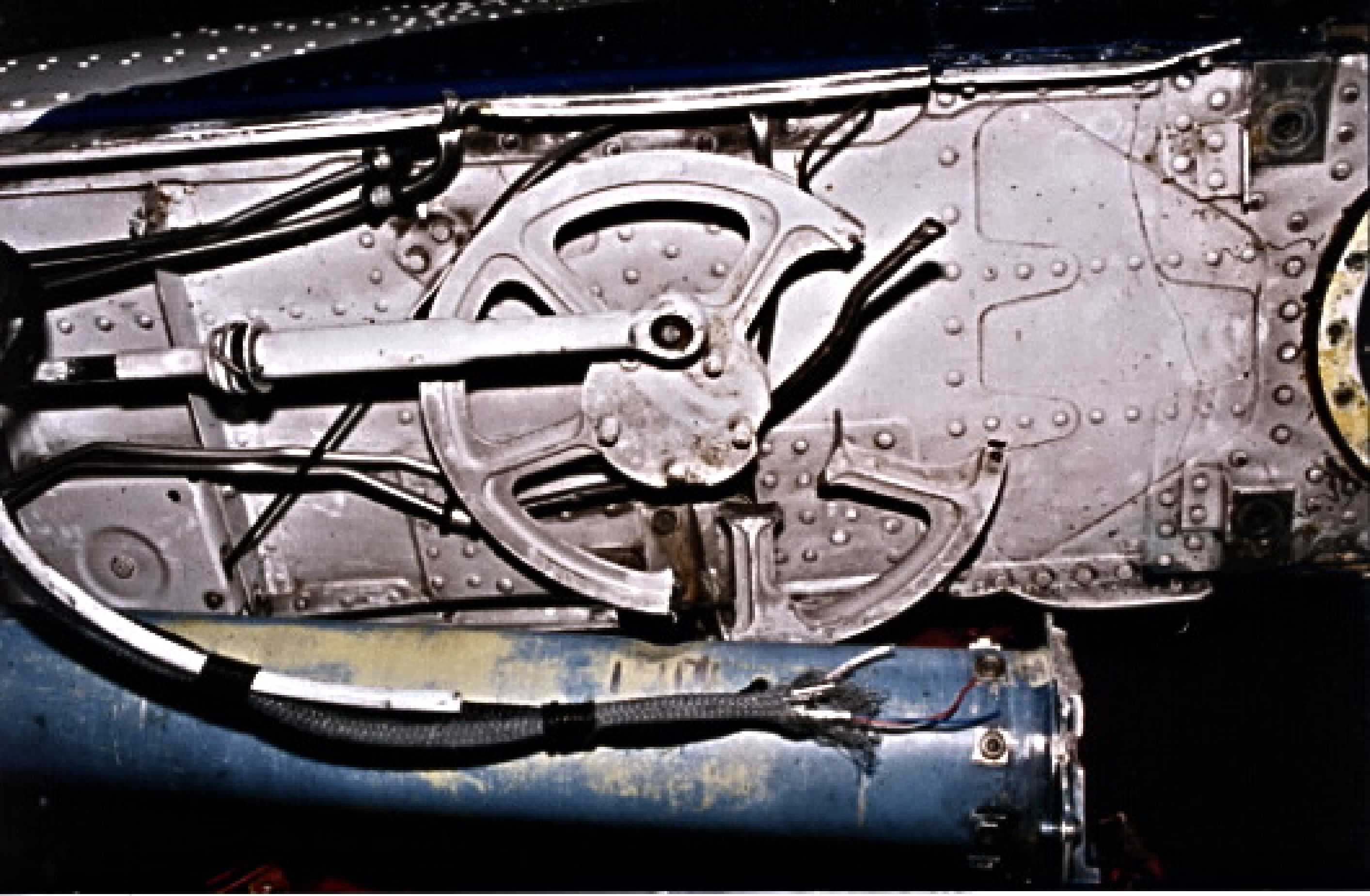


Figure 7: Showing the four severed hydraulic pipes, with two right side pipes sharply bent around damaged right support flange.

Figure 8: Showing recovered inboard section of 'Blue' main rotor blade with bonding strip missing, alongside 'Yellow' MRB for comparison.

Figure 9A: Showing localised blade skin damage at overlap of leading edge anti-erosion shield sections due to related arcing on 'Black' MRB.

Figure 9B: Showing all recovered main rotor blade sections, with 'Blue' blade in foreground and 'Black' blade sections in background.

Figure 10: Showing damaged outboard (right) side of 'White' tail rotor blade, with thermal delamination of root area, full length fissure of composite within bonding strip recess and removal of leading edge skin layer under deatched anti-erosion shield.

Figure 11: Showing damaged inboard (left) side of 'White' tail rotor blade, with thermal delamination of root area and general delamination outboard, including the leading edge from which the anti-erosion shield detached.

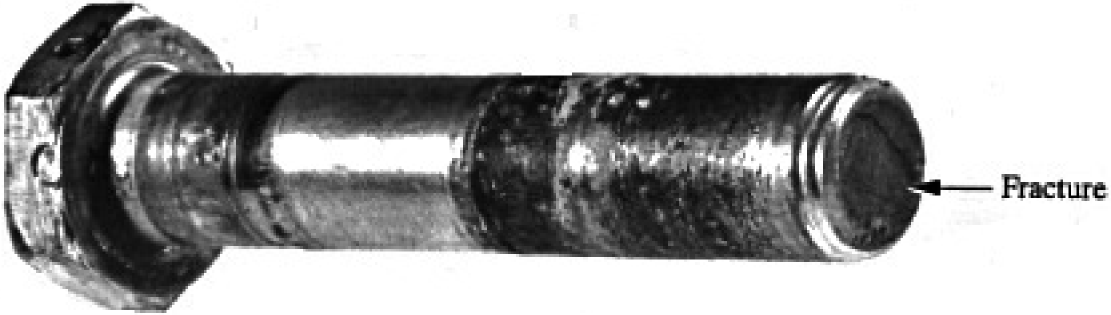


Figure 12A: Showing upper length of tail rotor gearbox upper attachment bolt with fracture face arrowed.

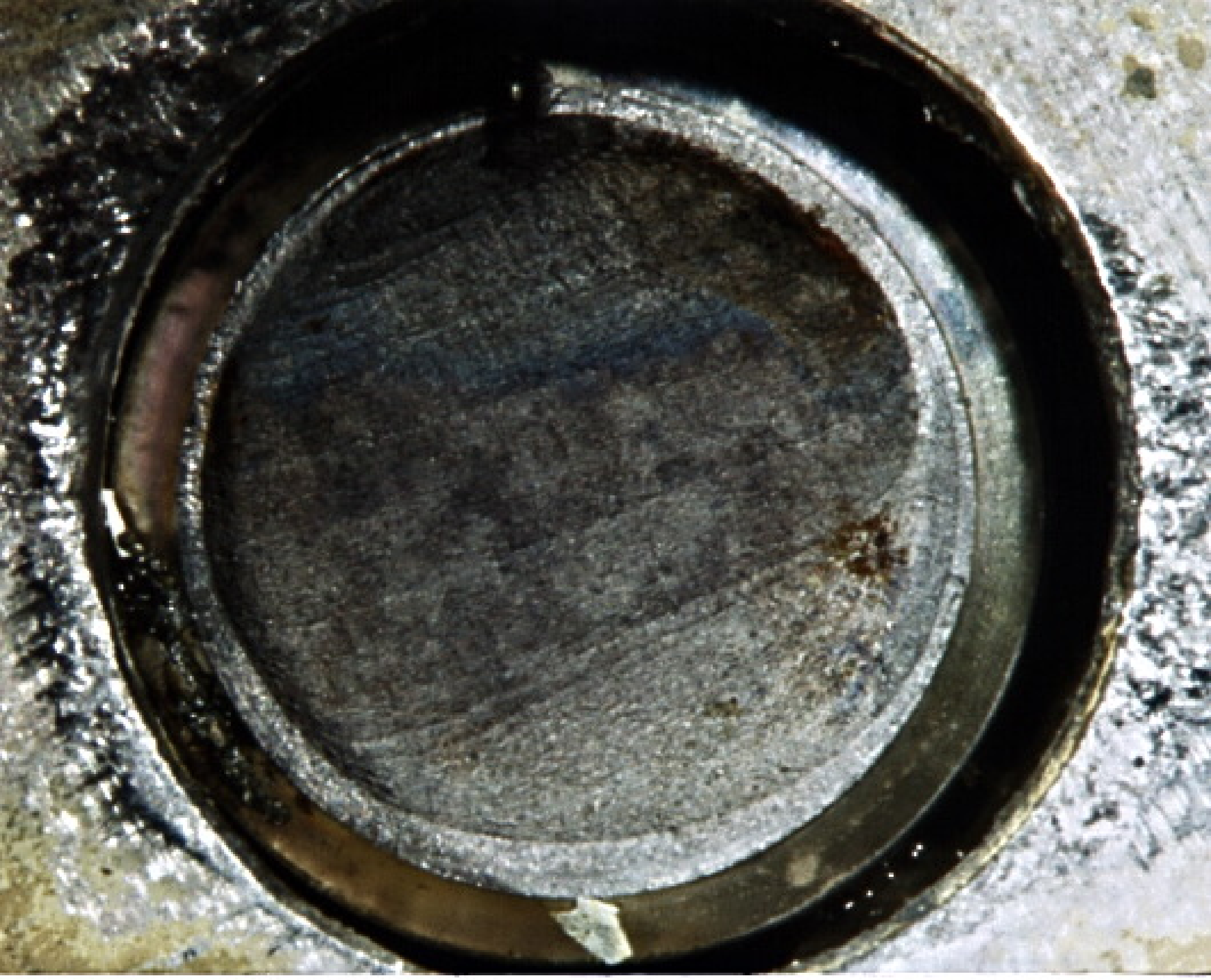


Figure 12B: Showing fracture surface of lower (threaded) end of tail rotor gearbox upper attachment bolt, with shallow (bright) annular band of initial radial fatigue propagation from the thread root, and secondary bending fatigue striations clearly evident emanating from upper arc, before the final overload failure evident within lower segment of fracture.

Figure 13: Showing the recovered tail rotor blade sections with, left to right in this photograph, 'White', 'Red', 'Blue' and 'Black' blades, outboard (right) sides uppermost. Note similar lengths of first four severed blades, caused by rotational penetration into aft side of pylon (Figure 5, A-6).

Figure 14: Showing the recovered helicopter onboard MSV Stadive without its main rotor head and main gearbox assembly which detached during the first associated 'lift' from the seabed and was recovered before the main airframe structure shown here.

Aerospatiale AS332L Super Puma, G-TIGK: Appendix B: Enclosure 1

Aircraft Accident Report No: 2/97 (EW/C95/1/1)

Report on the accident to Aerospatiale AS332L Super Puma, G-TIGK, in North Sea 6 nm South West of Brae Alpha Oil Production Platform on 19 January 1995

Appendix B

(Enclosure 1)

THE EVACUATION

Interviews with the occupants of the helicopter revealed the following information regarding their initial actions and their means of evacuation from G-TIGK:

Cockpit:

Commander (right seat): After the ditching, he applied the rotor brake, released his side door, operated the jettison handle for the right hand cabin door and then switched off all non-essential systems before moving back to the cabin, picking up a survival pack from the back of the cockpit/cabin bulkhead and evacuating through the right door and into the heliraft.

First officer (left seat): After the ditching, he released his side door before going back to the cabin and evacuating through the right door and into the heliraft.

Cabin:

Seat No. 1: After the second bang, the occupant released part of the window beading from the front right window; after the ditching, he knocked the front right window out and was the second man out of that window and into the heliraft.

Seat No. 2: The occupant knocked out the front left window after the ditching and then was the fifth man out of that window and into the heliraft.

Seat No. 3: After the ditching, the occupant was the fourth man out of the front right window and into the heliraft.

Seat No. 4: After the ditching, the occupant had started to release the second left window, but then went back towards the left door; as the left door aperture had the inflated heliraft blowing against it, he went to the right door and evacuated into the heliraft.

Seat No. 5: After the ditching, the occupant pulled the right door emergency release mechanism, and then was the third man out of the front right window.

Seat No. 6: After the ditching, the occupant began to pull the beading from the second right window, but then assisted in releasing the front right window and was the first man out of that window and first into the heliraft.

Seat No. 7: Initially this seat was unoccupied but after the first bang the occupant of Seat 8 moved to this position; just before the ditching, he removed the beading from both windows of the left door and then knocked them both out as the helicopter alighted. After the rotors stopped, he assisted in pushing the left door out, pulled the heliraft from under Seat 10, connected the painter and threw the heliraft out of the left door. It inflated, but kept blowing against the open door. He then went to the right door and boarded the heliraft.

Seat No. 8: The occupant moved to Seat 7 following the initial bang.

Seat No. 9: As the helicopter was descending the occupant retained a grip on the beading of the front window of the right door and, on ditching, released the window and assisted in kicking the right door out. He assisted in inflating the right heliraft and was first out of the right door, and second into the heliraft.

Seat No. 10: After the ditching, the occupant assisted in opening the left door and inflating the heliraft. With some problems apparent in launching the left heliraft, he went to the right door and boarded the heliraft.

Seat No. 11: After the ditching, the occupant assisted in pushing the right door out and was fourth, or fifth, out of that door and into the heliraft.

Seat No. 12: As the helicopter alighted, the occupant was removing the beading from the rear right door window. He then assisted in pushing out the right door and inflated the heliraft; he was second through the right door and into the heliraft.

Seat No. 13: After the ditching, the occupant was the sixth man through the right door and into the heliraft.

Seat No. 14: After the ditching, the occupant evacuated through the right door and into the heliraft.

Seat No. 15: After the ditching, the occupant started pulling the beading from the second rear window, but then evacuated through the right door and was the fifteenth man into the heliraft.

Seat No. 16: After the first bang, the occupant removed the beading from the rear right window; after the second bang he pushed the window out. Following the ditching, he evacuated through the right door into the heliraft.

Seat No. 17: Unoccupied.

Seat No. 18: After the ditching, the occupant evacuated through the right door and into the heliraft.

Aerospatiale AS332L Super Puma, G-TIGK: Appendix B: Enclosure 2

Aircraft Accident Report No: 2/97 (EW/C95/1/1)

Report on the accident to Aerospatiale AS332L Super Puma, G-TIGK, in North Sea 6 nm South West of Brae Alpha Oil Production Platform on 19 January 1995

Appendix B

(Enclosure 2)

EXAMINATION OF THE HELIRAFT BY RFD

Punctured buoyancy chamber: There was a large tear in the buoyancy chamber directly below the boarding ramp position (not in the fender as initially thought). The tear extended across the complete panel and some of the survivors heard air escaping from this area after boarding the heliraft. There was evidence of a puncture initiation point approximately at the centre of the panel, from where the tear propagated outward. The length of the cut was indicative of a large object forcing itself into the chamber, thus elongating the tear.

Detached floor lifeline: The lifeline is designed to enable survivors to stabilise themselves in rough conditions, but it is attached to the floor by a patch in a way such that, if sufficient force is applied to the line, the patch is pulled off the floor, rather than ripping the floor itself. In this case, the heliraft was swamped and carrying an overload of passengers and the force which had been applied to the patch was sufficient to detach it. If this had not been a design feature, the floor would have been damaged or torn, with serious consequences for the occupants.

Canopy erection: Having boarded the heliraft, normal procedure is to cut the appropriate two bridle loops, freeing the sea anchor to drop into the water and releasing the short blue firing and mooring line from the helicopter. This frees the heliraft and permits the canopy to be raised. In this instance, only the bridle for the short blue firing line was cut, which released the heliraft to float away from the helicopter. Although the sea anchor bridle was not cut, this did not prevent the anchor from being deployed, but it did inhibit it from dropping into the water and streaming effectively. It also prevented one side of the canopy from being raised because the roof support tube was partially restrained by the bridle.

Paddles and bailer: The survivors were able to locate the equipment bag containing the First Aid kit etc, which was stored in one of the two bags, but had difficulty in finding the paddles or the bailer. Because of the considerable number of agencies through which the heliraft had passed, before being available for examination, it was not possible to identify the reason for this.

The inflation cylinder: One of the survivors was hit on the head by the heliraft inflation cylinder. The cylinder was attached by a hose and umbilical cord to the inflation valves, causing it to hang in the water after deployment. This design is the most suitable system for reversible life rafts as attaching it to the floor on one side reduces the occupancy rating on that side. Depending on which way up the heliraft is inflated the distance from the water line to the cylinder varies because it must travel over the fender and into the water. This results in the cylinder being closer to the surface of the water in one orientation than in the other. This could have resulted in the cylinder being lifted from the water by wave action and causing the reported injury.

MEMORANDUM OF UNDERSTANDING ON THE CO-ORDINATION OF SEARCH AND RESCUE MARITIME INCIDENTS ARISING FROM AVIATION ACCIDENTS BETWEEN THE COASTGUARD AGENCY, THE DEPARTMENT OF TRANSPORT (CIVIL AVIATION DIVISION) AND THE MINISTRY OF DEFENCE

Whereas in the United Kingdom the Department of Transport ("DOT") is the authority responsible for civil maritime and civil aviation search and rescue ("SAR");

and whereas the Ministry of Defence ("MOD"), through the Aeronautical Rescue Co-ordination Centres (ARCC), is responsible, on behalf of the DOT, for the initiation and co-ordination of civil aviation SAR within the United Kingdom SAR Region ("UKSRR");

and whereas the Coastguard Agency, through Maritime Rescue Co-ordination Centres (MRCC), and sub-centres (MRSC) is responsible, on behalf of the DOT, for the initiation and co-ordination of civil maritime SAR in the UKSRR;

The Coastguard Agency, The Department of Transport and the Ministry of Defence desiring to draw up arrangements to ensure clear co-ordination of SAR maritime incidents arising from aviation accidents have reached the following understanding:

1. Control of SAR maritime incidents arising from aviation accidents shall rest with the rescue authority (whether ARCC or MRCC) that initiates the response, until it decides that the other is better placed to continue the response.

2. The initiating authority must immediately inform the other rescue authority of the incident. Consultation between the rescue authorities must also take place when the appointment of an on-scene co-ordinator is contemplated, including a review of which centre should most appropriately control the incident.

3. In an incident involving a military aircraft, control of the incident would always rest with the ARCC even if the Coastguard were first to learn of its ditching.

Signed at London on 3 March 1997

For the Department of Transport

For the Coastguard Agency

For the Ministry of Defence

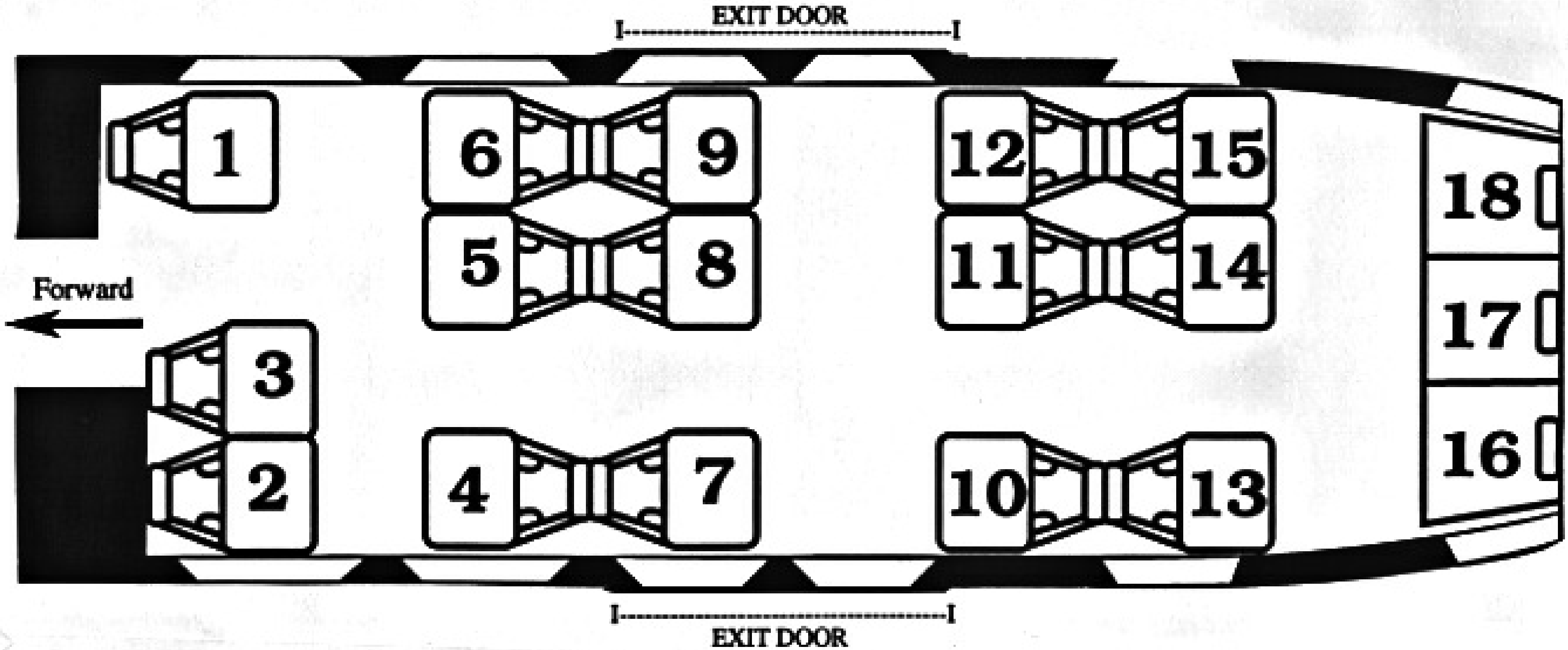


Figure 1: Showing cabin seating layout.

Figure 2: Showing right main door emergency exit with both spring-loaded arms arrowed.

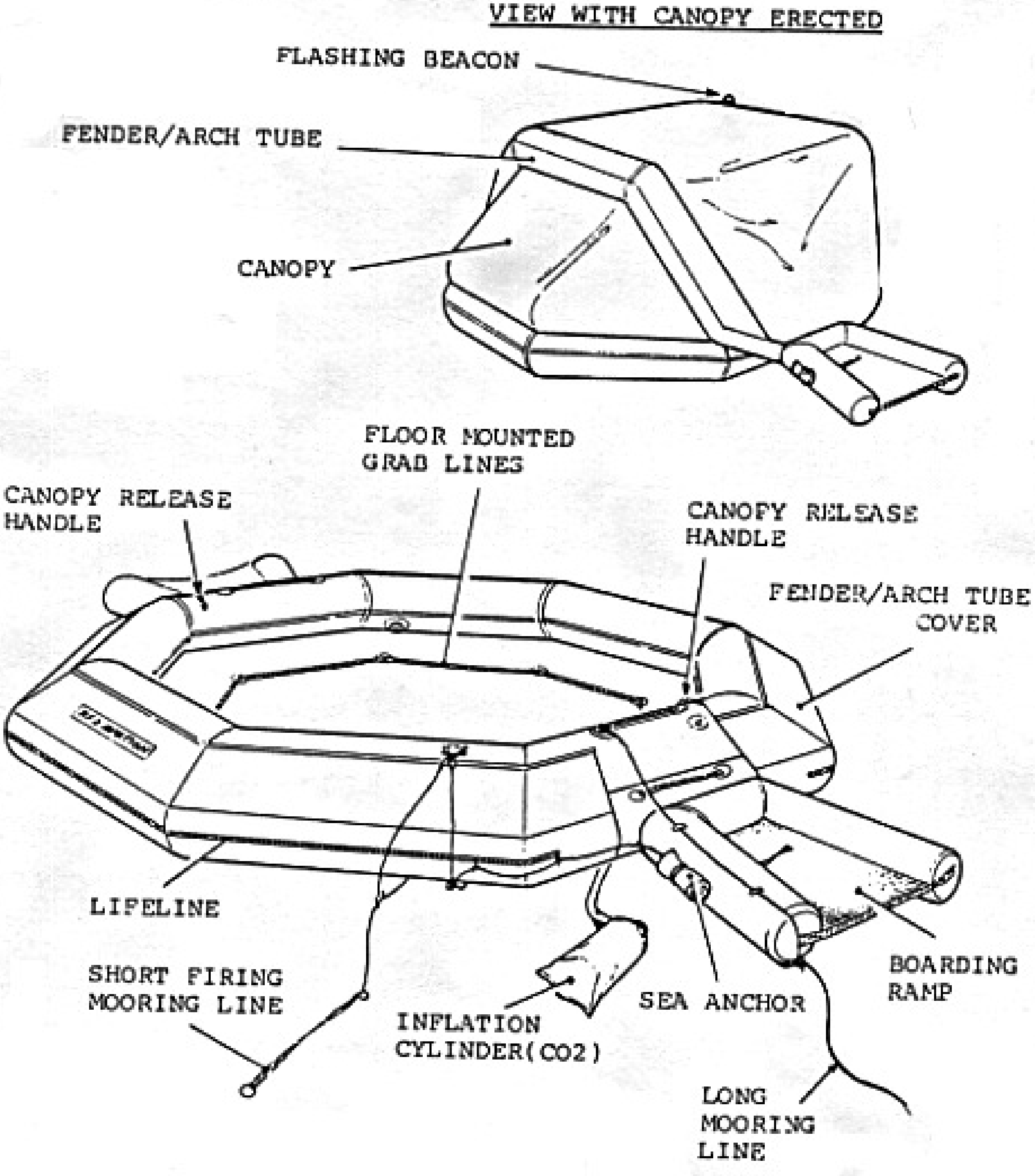


Figure 3: Showing general design features of the RFD Type 14R MK1 Liferaft.

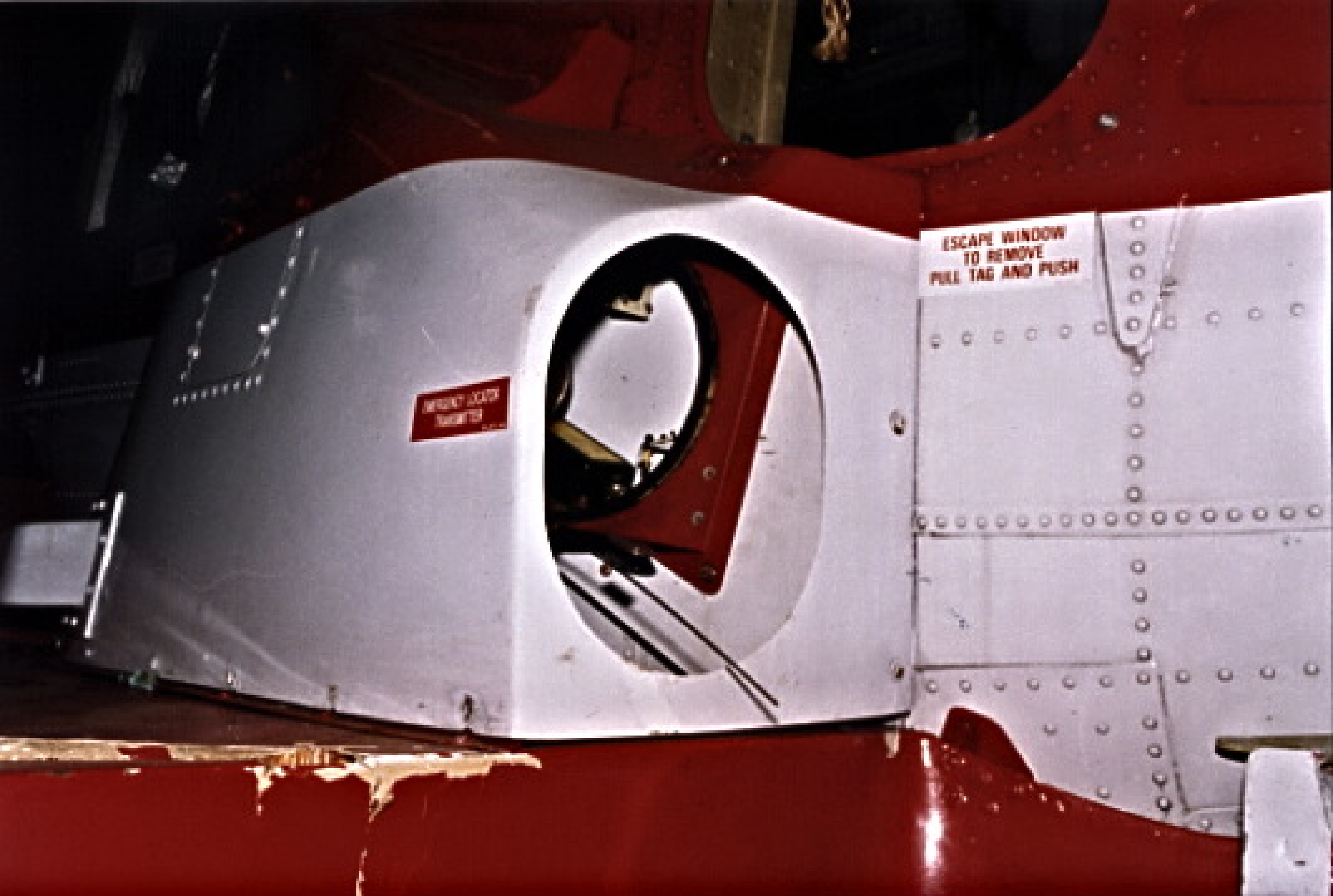


Figure 4: Showing location of the automatically deployable emergency locator transmitter (ADELT) housing.

Figure 5: Showing hook-shaped broken end of spring-loaded arm at upper forward corner of left main door, after detachment of roller end, with new arm/roller for comparison; aft arm on this door and forward arm on right door were also broken in this manner.

EXTRACTS FROM AC20-53A
(pages 6-10 and Appendices 1-3)

10. LIGHTNING ATTACHMENT PHENOMENA.

a. Swept-Stroke Phenomenon.

(1) The lightning channel is somewhat stationary in air while it is transferring electrical charge. When an airplane is involved, the airplane becomes part of the channel. However, due to the speed of the airplane and the length of time that the lightning channel exists, the airplane can move relative to the lightning channel. When a forward extremity, such as a nose or wing mounted engine pod is an initial attachment point, the movement of the airplane through the lightning channel causes the channel to sweep back over the surface as illustrated in figure 1 of appendix 2, producing subsequent attachment points. This is known as the swept-stroke phenomenon. As the sweeping action occurs, the characteristics of the surface can cause the lightning channel to reattach and dwell at various surface locations for different periods of time, resulting in a series of discrete attachment points along the sweeping path.

(2) The amount of damage produced at any point on the airplane by a swept-stroke depends upon the type of material, the dwell time at that point, and the lightning currents which flow during the attachment. Both high peak current restrikes with intermediate current components and continuing currents may be experienced. Restrikes typically produce reattachment of the arc at a new point.

(3) When the lightning channel has been swept back to one of the trailing edges, it may remain attached at the point for the remaining duration of the lightning event. An initial attachment point at a trailing edge, of course, would not be subjected to any swept-stroke action, and therefore, this attachment point will be subjected to all components of the lightning event.

(4) The significance of the swept-stroke phenomenon is that portions of the vehicle that would not be targets for the initial attachment points of a lightning flash may also be involved in the lightning strike process as the lightning channel is swept backwards, although the channel may not remain attached at any single point for very long. On the other hand, strikes that reach trailing edges must be expected to remain attached there (hang-on) for the balance of their natural duration.

b. Lightning Strike Zone Definitions. To account for each of the possibilities described in the foregoing paragraphs, the following zones have been defined:

(1) Zone 1.

i. Zone 1A: Initial attachment point with low possibility of lightning arc channel hang-on.

ii. Zone 1B: Initial attachment point with high possibility of lightning arc channel hang-on.

(2) Zone 2.

i. Zone 2A: A swept-stroke zone with low possibility of lightning arc channel hang-on.

ii. Zone 2B: A swept-stroke zone with high possibility of lightning arc channel hang-on.

(3) Zone 3. All of the vehicle areas other than those covered by Zone 1 and 2 regions. In Zone 3, there is a low possibility of any attachment of the lightning channel. Zone 3 areas may carry substantial amounts of electrical current, but only by conduction between some pair of attachment points.

(4) The zone definitions are in basic agreement with the definitions of earlier versions of this Advisory Circular, except that the former Zones 1 and 2 have been subdivided to account for low and high possibilities of the lightning arc channel hang-on (figures 2 & 3) shown in appendix 2. The locations of these zones on any airplane are dependent on the airplane's geometry and operational factors, and often vary from one airplane to another.

c. Location of Lightning Strike Zones. With these definitions in mind, the locations of each zone on a particular airplane may be determined as follows:

(1) Extremities such as the nose, wing and empennage tips, tail cone, wing-mounted nacelles, and other significant projections should be considered as within a direct strike zone because they are probable initial leader attachment points. Those that are forward extremities or leading edges should be in Zone 1A, and extremities that are trailing edges should be in Zone 1B. Most of the time, the first return stroke will arrive shortly after the leader has attached to the airplane, so Zone 1A is limited to the immediate vicinity (i.e., approximately 18 inches (0.5m) aft) of the forward extremity. However, in rare cases the return stroke may arrive somewhat later, thereby exposing surfaces further aft to this environment. This possibility should be considered if the probability of a flight safety hazard due to a Zone 1A strike to an unprotected surface is high.

(2) Where questions arise regarding the identification of initial attachment locations or where the airframe geometry is unlike conventional designs for which previous experience is available, scale model attachment point tests may be in order. Information on model testing can be found in the User's Manual.

(3) Surfaces directly aft of Zone 1A should be considered as within Zone 2A. Generally, Zone 2A will extend the full length of the surface aft of Zone 1A, such as the fuselage, nacelles, and portions of the wing surfaces.

(4) Trailing edges of surfaces aft of Zone 2A should be considered Zone 2B, or Zone 1B if initial attachment to them can occur. If the trailing edge of a surface is totally non-conductive, then Zone 2B (or 1B) should be projected forward and/or inboard to the nearest conductive surface.

(5) Surfaces approximately 18 inches (0.5m) to either side of initial- or swept-attachment points established by steps (1) and (2) of paragraph c should also be considered as within the same zone, to account for small lateral movements of the sweeping channel and local scatter among attachment points. For example, the tip of a wing would normally be within Zone 1A (except for its trailing edge, which would usually be in Zone 1B). To account for lateral motion of the channel and scatter, the top and bottom surfaces of the wing 18 inches (0.5m) inboard of the tip should also be considered as within the same zones.

(6) Surfaces of the vehicle for which there is a low possibility of direct contact with the lightning arc channel that are not within any of the above zones, but which lie between them, should be considered as within Zone 3. Zone 3 areas must carry substantial amounts of electrical energy.

11. LIGHTNING ENVIRONMENT. For verification purposes, the natural lightning environment (which comprises a wide statistical range of current levels, duration, and number of strokes) is represented by current test Components A through E, and voltage Components A, B, and D (per figures 4, 5 and 6) shown in appendix 2. When testing or analysis are required, the following waveforms should be used. (Applications of waveforms and lightning zones are detailed in appendix 3.)

a. Current Waveforms. There are four current components (A, B, C, and D) that are applied to determine direct effects. Current waveform E is used in tests to determine indirect effects. Components A, B, C, and D each simulate a different characteristic of the current in a natural lightning flash and are shown in figure 4 of appendix 2. They are applied individually or as a composite of two or more components together in one test. The tests in which these waveforms are applied are presented in appendix 3.

(1) Component A - Initial High Peak Current. Component A has a peak amplitude of 200kA ($\pm$10 percent) and an action integral ($\int i^2 dt$) of $2\times10^6 A^2 s$ ($\pm$20 percent) with a total time duration not exceeding 500 microseconds. This component may be unidirectional or oscillatory. For analysis purposes, a double exponential current waveform should be used. This waveform represents a return stroke of 200,000 amperes peak at a peak rate of rise of 1×10^{11}A/s. This waveform is defined mathematically by the double exponential expression shown below:

$$i(t) = I_o (\epsilon^{-\alpha t} - \epsilon^{-\beta t})$$

where

$$I_o = 223{,}000 (A)$$

$$\alpha = 11{,}000 \ (s^{-1})$$

$$\beta = 460{,}000 \ (s^{-1})$$

$$t = \text{time}(s)$$

(2) Component B - Intermediate Current. Component B has an average amplitude of 2kA ($\pm$10 percent) flowing for a maximum duration of 5 milliseconds unidirectional; e.g., rectangular, exponential, or linearly decaying. For analysis purposes, a double exponential current waveform should be used. This waveform is described mathematically by the double exponential.

$$i(t) = I_o (\epsilon^{-\alpha t} - \epsilon^{-\beta t})$$

$$I_o = 11300 (A)$$

$$\alpha = 700 \quad (s^{-1})$$

$$\beta = 2000 \ (s^{-1})$$

$$t = \text{time (s)}$$

If the dwell time is more than 5ms, apply an average current of 400A for the remaining dwell time. The dwell time shall have been determined previously through a swept-stroke attachment test or by analysis. If such determination has not been made, the dwell time shall be taken to be 50ms.

(3) Component C - Continuing Current. Component C transfers a charge of 200 coulombs ($\pm$20 percent) in a time of between 0.25 and 1 second. This implies current amplitudes of between 200 and 800 amps. The waveform shall be unidirectional: e.g., rectangular, exponential or linearly decaying. For analysis purposes, a square waveform of 200A for a period of 1 sec. should be utilized.

(4) Component D - Restrike Current. Component D has a peak amplitude of 100kA ($\pm$10 percent) and an action integral of $0.25 \times 10^6 A^2$ s ($\pm$20 percent). This component may be either unidirectional or oscillatory with a total time duration not exceeding 500 microseconds. For analysis purposes a double esponential current waveform should be used. This waveform represents a re-strike of 100,000 amperes peak at a peak rate-of-rise of 0.5×10^{11} A/s. The waveform is defined mathematically by the double exponential expression shown below:

$$i(t) = I_o (\epsilon^{-\alpha t} - \epsilon^{-\beta t})$$

$$I_o = 130{,}000 \ (A)$$

$$\alpha = 27{,}500 \ (s^{-1})$$

$$\beta = 415{,}000 \ (s^{-1})$$

$$t = \text{time (s)}$$

(5) Current Waveform E - Fast Rate-of-Rise Stroke Test for Full Size Hardware. Current waveform E has a rate-of-rise of at least 25kA/μs for at least 0.5 microseconds, as shown in figure 4 of appendix 2. Current waveform E has a minimum amplitude of 50kA. Alternatively, components A or D may be applied with a 25kA/μs rate-of-rise for at least 0.5 microseconds and the direct and indirect effects evaluation conducted simultaneously.

i. Indirect effects measured as a result of this waveform must be extrapolated as follows. Induced voltages dependent upon resistive or diffusion flux should be extrapolated linearly to a peak current of 200 kA.

ii. Induced voltages dependent upon aperture coupling should be extrapolated linearly to a peak rate-of-rise of 100 kA/μs.

b. Voltage Waveforms - Test. There are three voltage waveforms, "A," "B," and "D," which represent the electric fields associated with a lightning strike. Voltage waveforms "A" and "D" are used to test for possible dielectric puncture and other potential attachment points. Voltage waveform "B" is used to test for streamers. The tests in which these waveforms are applied are presented in appendix 3.

(1) Voltage Waveform A - Basic Lightning Waveform. Waveform A has an average rate-of-rise of 1×10^6 volts per microsecond ($\pm$50 percent) until its increase is interrupted by puncture of, or flashover across, the object under test. At that time, the voltage collapses to zero. The rate of voltage collapse or the decay time of the voltage if breakdown does not occur (open circuit voltage of lightning voltage generator) is not specified. Voltage waveform A is shown in figure 5 of appendix 2.

(2) Voltage Waveform B - Full Wave. Waveform B rises to crest in 1.2us ($\pm$20 percent). Time-to-crest and decay time refer to the open circuit voltage of the lightning voltage generator, and assume that the waveform is not limited by puncture or flashover of the object under test. This waveform is shown in figure 5 of appendix 2.

(3) Voltage Waveform D - Slow Front. The slow-fronted waveform has a rise time between 50 and 250 microseconds to allow time for streamers from the test object to develop. It should give a higher strike rate in tests to the low probability regions that might have been expected in flight. This waveform is shown in figure 6 of appendix 2.

J. A. Pontecorvo

JOSEPH A. PONTECORVO
Deputy Director, Office of Airworthiness

PURPOSE. For the purposes of this AC, the following definitions apply:

a. Action Integral. The action integral concept is difficult to visualize, but is a critical factor in the production of damage. It relates to the energy deposited or absorbed in a system. However, the actual energy deposited cannot be defined without a knowledge of the resistance of the system. For example, the instantaneous power dissipated in a resistor is by Ohm's Law, $i(t)^2R$, and is expressed in watts. For the total energy expended, the power must be integrated over time to get the total watt-seconds (or kilowatt hours). The watt-second is equivalent to the joule. Without a knowledge of R, we cannot specify the energy deposited. By specifying the integral of $i(t)^2$ over the time interval involved, a useful quantity is defined for application to any resistance value of interest. In the case of lightning, therefore, this quantity is defined as the action integral and is specified as $\int i(t)^2dt$ over the time the current flows.

b. Attachment Point. A point of contact of the lightning flash with the airplane surface.

c. Average Rate-of-Rise of Voltage. The average rate-of-rise, dv/dt, of a waveform is defined as the slope of a straight line drawn between the points where the amplitude is 30 percent and 90 percent of its peak value.

d. Charge Transfer. The charge transfer is defined as the integral of the time-varying current over its entire duration, $\int i(t)dt$.

e. Corona. A luminous discharge that occurs as a result of an electrical potential difference between the airplane and the surrounding atmosphere.

f. Decay Time of a Voltage Waveform. The decay time of a waveform is defined as the time interval between the intersect with the abscissa of a line drawn through the points where the voltage is 30 percent and 90 percent of its peak value during its rise, and the instant when the voltage has decayed to 50 percent of its peak value.

g. Direct Effects. Physical damage effects caused by lightning attachment directly to hardware or components, such as arcing, sparking, or fuel tank skin puncture.

h. Lightning Attachment. Contact of the main channel of a lightning flash with the airplane.

i. Dwell Time. The period of time that the lightning arc channel remains attached to a single spot.

j. Indirect Effects. The results of electromagnetic coupling from lightning (such as induced sparking in fuel quantity probe wiring).

k. Leader. The stepped leader is initiated by a preliminary breakdown within the cloud. The preliminary breakdown sets the stage for negative charge to be channeled towards the ground in a series of short, luminious steps.

l. Lightning Flash. The total lightning event in which charge is transferred from one charge center to another. It may occur within a cloud, between clouds, or between a cloud and ground. It can consist of one or more lightning strokes.

m. Lightning Strike. Any attachment of the lightning flash to the airplane.

n. Lightning Stroke (Return Stoke). A lightning current surge, return stroke, that occurs when the lightning leader makes contact with the ground or another charge center.

o. Streamering. The branch-like ionized paths that occur in the presence of a direct stroke or under conditions when lightning strokes are imminent.

p. Swept-Stroke. A series of successive attachments due to sweeping of the flash across the surface of the airplane by the motion of the airplane.

q. Time-to-Crest of a Voltage Waveform. The time-to-crest of a waveform is defined as 1.67 times the time interval between the instants when the amplitude is 30 percent and 90 percent of its peak value.

r. Time Duration of a Current Waveform. The time duration of a current waveform is defined as the time for initiation of current flow until the amplitude (peak amplitude in the case of a damped sinusoid) has reduced to 5 percent of its initial peak value.

T_0 - Initial Attachments

T_1 - Subsequent Attachments

T_n - Final Attachment Points

(LIGHTNING CHANNEL POSITION SHOWN RELATIVE TO AIRPLANE)

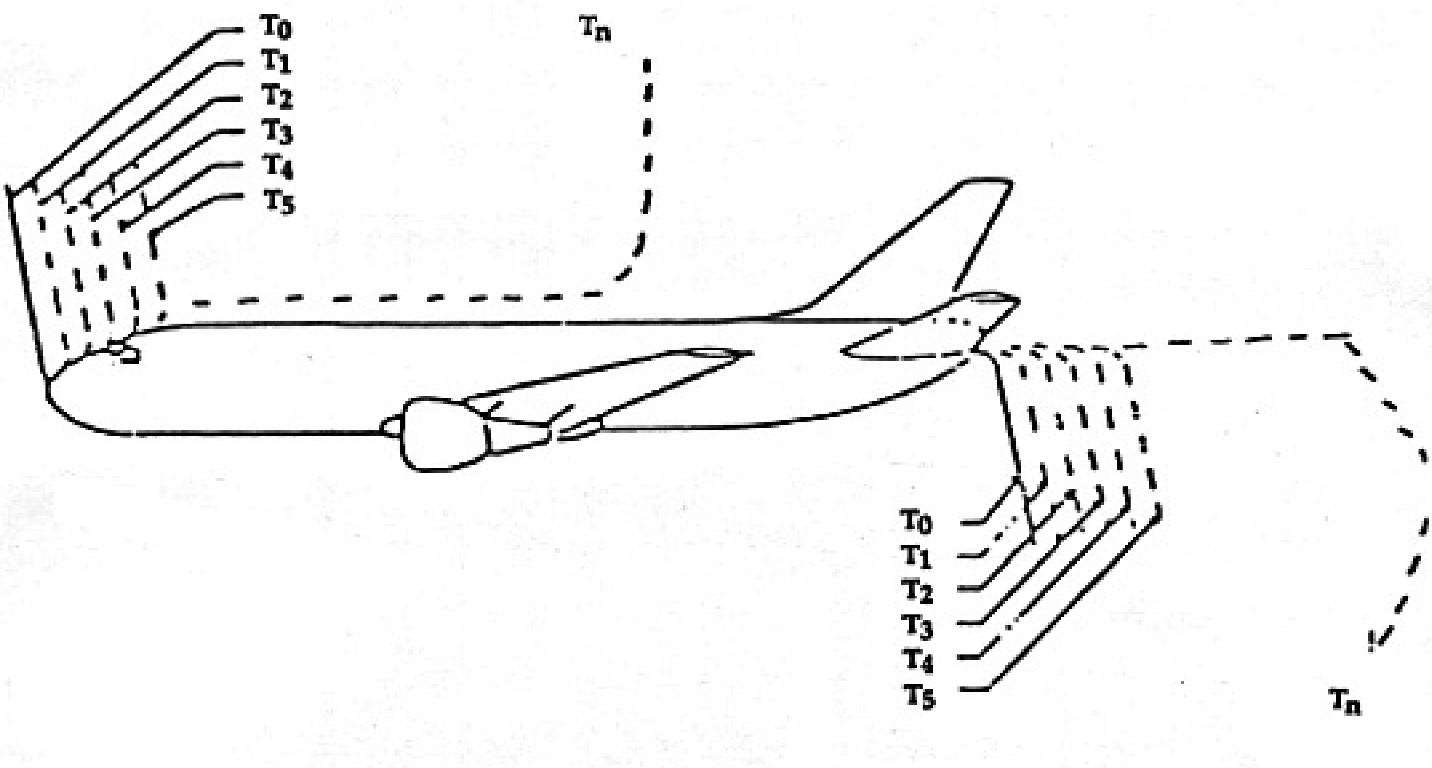


FIGURE 1 - SWEPT-STROKE PHENOMENON

LIGHTNING STRIKE ZONES

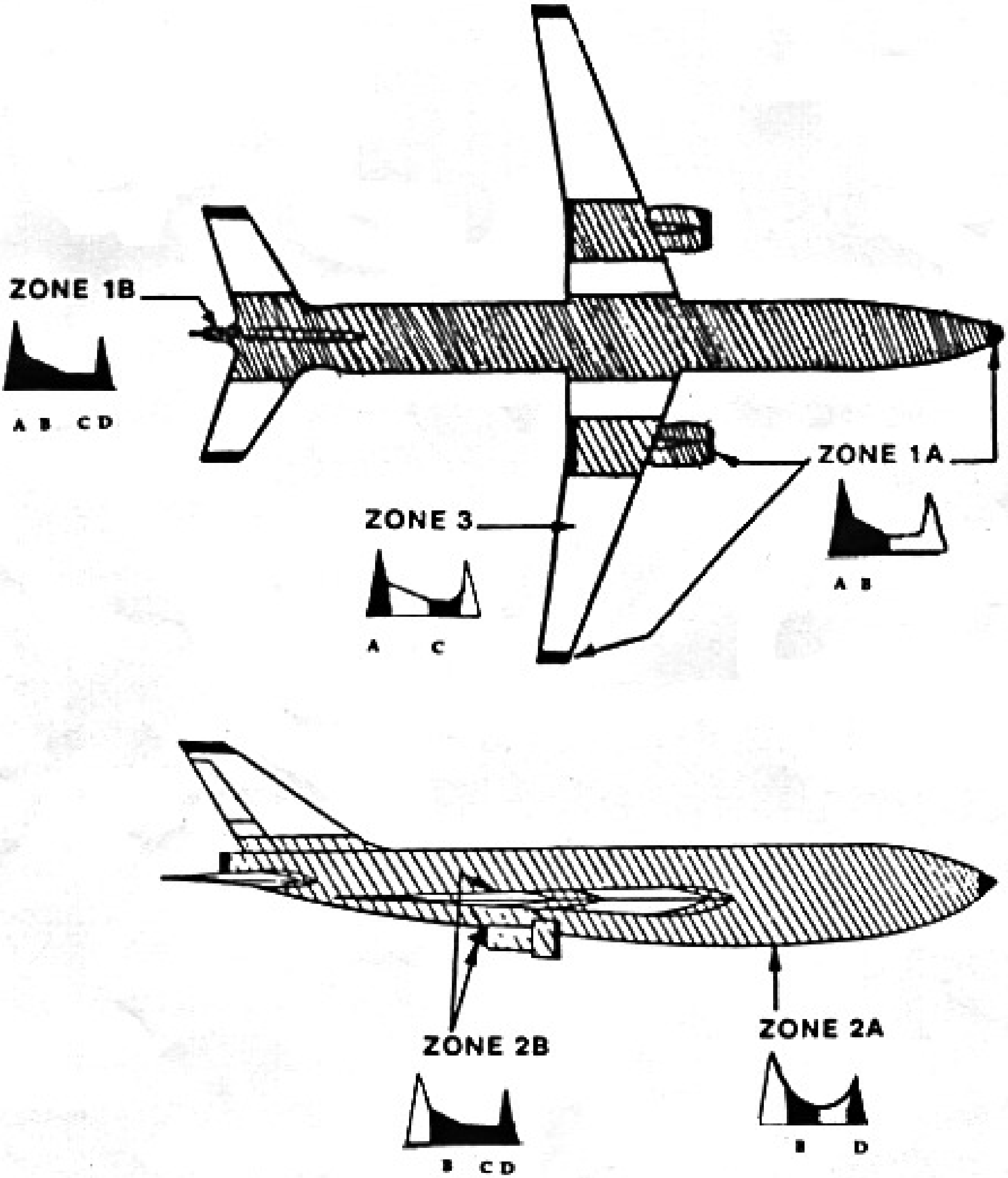


FIGURE 2 LIGHTNING STRIKE ZONES (TYPICAL)

(See paragraph 10C)

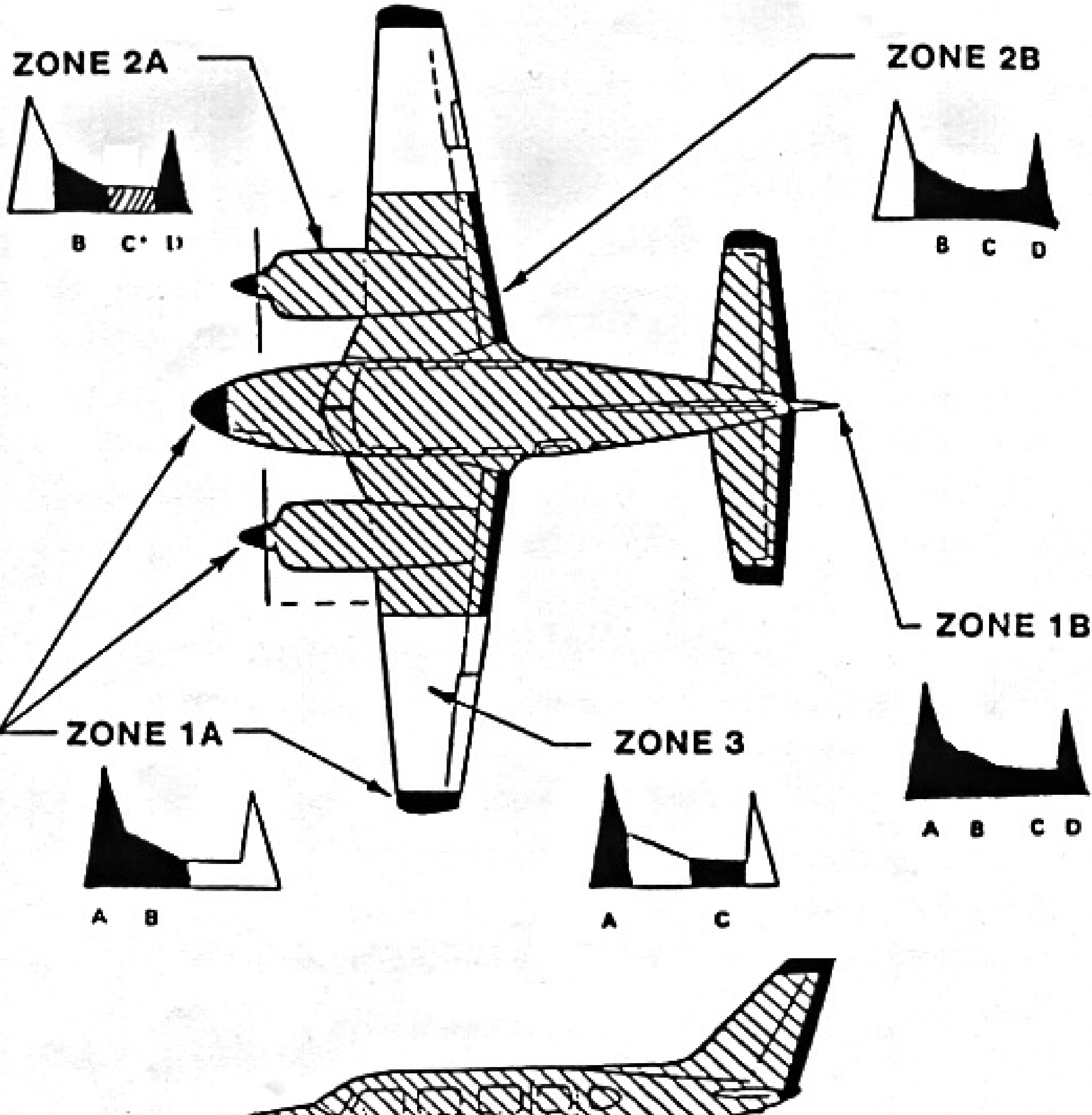
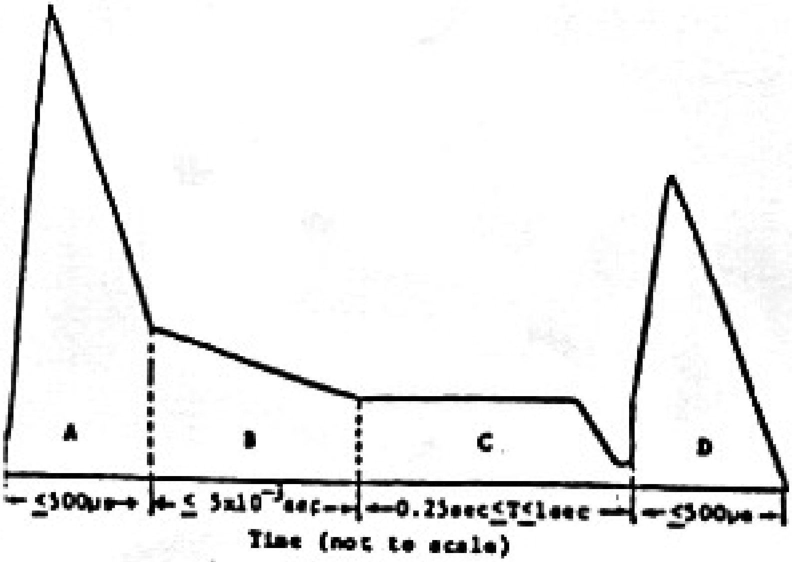


FIGURE 3 LIGHTNING STRIKE ZONES (TYPICAL)
(See paragraph 10C)



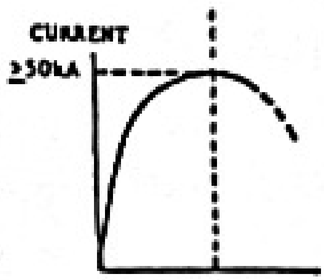
COMPONENT A (Initial Stroke)
- Peak Amplitude = 200kA (±10%)
- Action Integral = $2 \times 10^6 A^2 s$ (±20%)
- Time Duration = ≤500 μs

COMPONENT B (Intermediate Current)
- Maximum Charge Transfer = 10 Coulombs
- Average Amplitude = 2kA (±10%)

COMPONENT C (Continuing Current)
- Charge Transfer = 200 Coulombs (±20%)
- Amplitude = 200-800A

COMPONENT D (Restrike)
- Peak Amplitude = 100kA (±10%)
- Action Integral = $0.25 \times 10^6 A^2 s$ (±20%)
- Time Duration = ≤500 μs

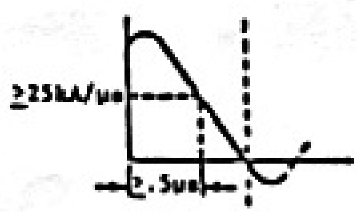
COMPONENTS A THROUGH D WAVEFORMS



COMPONENT WAVEFORM E
- Peak Amplitude = ≥ 50kA
- Rate of Rise = ≥ 25kA/μs for at least 0.5μs

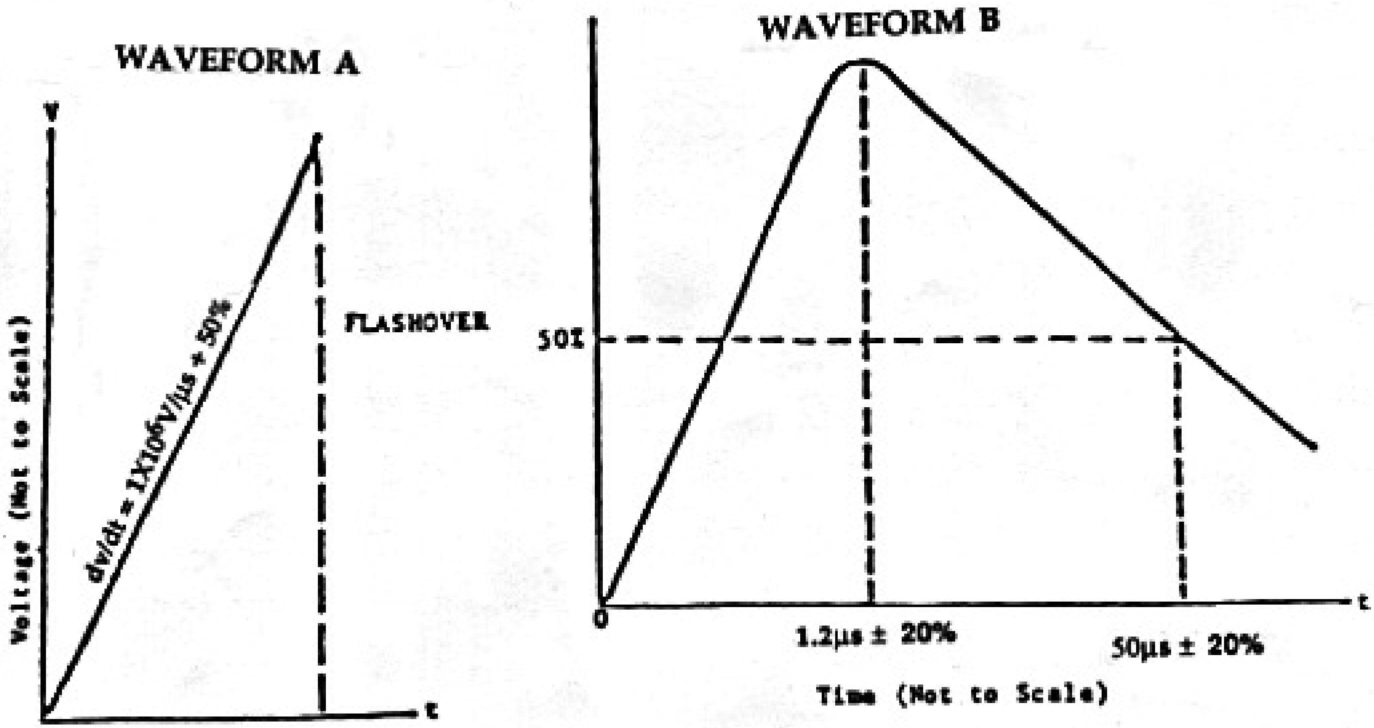
FIGURES NOT TO SCALE

Rate of Current Rise



Definition of rate of rise requirement of waveform E

FIGURE 4 CURRENT WAVEFORMS



NOTE: Voltage Waveform "B" Full Wave - Waveform "B" rises to crest in 1.2 us (±20 percent). Time-to-crest and decay time (refer to open circuit voltage) of the lightning voltage generator, and assume that the waveform is not limited by puncture or flashover of the object under test.

FIGURE 5 VOLTAGE WAVEFORMS 'A'&'B'

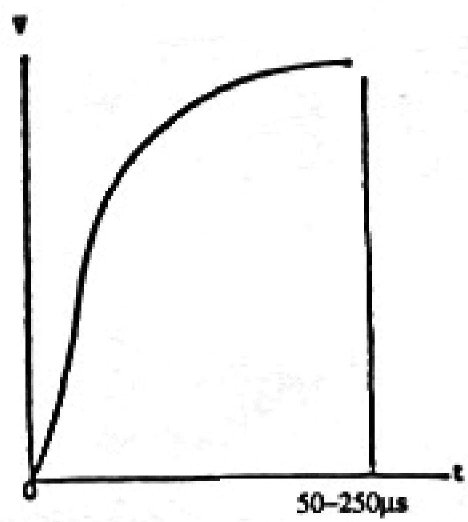


FIGURE 6 VOLTAGE WAVEFORM 'D'

APPLICATION OF WAVEFORMS FOR LIGHTNING TESTS

Test	Zone	Waveforms: Voltage A	Voltage B	Voltage D	Current Components A	Current Components B	Current Components C	Current Components D	Current Components E
Full Size Hardware Attachment Point	1A, 1B	X		X[1]					
Direct Effects Structural	1A				X	X			
	1B				X	X	X	X	
	2A					X[2]	X[2]	X	
	2B					X	X	X	
	3				X		X		
Direct Effects Combustible Vapor Ignition	1A				X	X			
	1B				X	X	X	X	
	2A					X[2]	X[2]	X	
	2B					X	X	X	
	3				X		X		
Direct Effects Corona and Streamers			X						
Indirect Effects Related to Spark Generation Within Fuel Vapor Areas									X[3]

NOTE 1: Voltage waveform "D" may be applied to identify lower probability strike points.

NOTE 2: Use an average current of 2kA ± 10 percent for a period equal to the dwell time up to a maximum of 5ms. If the dwell time is more than 5ms, apply an average current of 400A for the remaining dwell time. The dwell time shall have been determined previously through a swept-stroke attachment test or by analysis. If such determination has not been made, the dwell time shall be taken to be 50ms.

NOTE 3: Indirect effects should also be measured with current components A, B, C, or D as appropriate.

Extracts from LTT report AEA-TSD-0562

7 TEST WAVEFORMS

7.1 Requirement

The blades were to be tested at levels up to, including and in excess of the Zone 1A lightning certification test level specified in Reference 3, and summarised below.

COMPONENT A (Initial Attachment):	Peak Current = 200kA ±10% Action Integral = $2 \times 10^6 A^2s$ ±20% Duration = ≤500μs.
COMPONENT B (Intermediate Current):	Average Current = 2kA ±10% Charge Transfer = 10C Duration 5ms.
COMPONENT C_1 (Continuing Current): *Also known as Short C*	Current Amplitude = 400A Charge Transfer = 18C Duration 45ms.

The three components defined above were applied as a single composite pulse in the order A + B + C_1. The C_1 employed will represent a severe case at the initial attachment point to one TRB, the following TRBs will sweep through the lightning arc every 12ms. The total charge transfer to a single blade could be up to one fifth (5 blades) of the charge transfer available in Zone 1B ($^1/_5$ of 200C = 40C), but it is unlikely to have all the charge transferred through the same attachment point.

7.2 Generators

Component A was generated by the LTT A/D Bank, which comprises a two stage 387.5μF capacitor bank that can be charged to a maximum of 40kV/stage.

The current output waveform of the A/D bank is a unidirectional double exponential whose characteristics are modified by varying the inductance and resistance in the generator/load circuit.

Components B + C_1 (also known as Short C) were produced as a single composite pulse from the LTT Slow Bank. This facility comprises three separate capacitor banks (1000μF, 1000μF and 840μF) which can be connected in any parallel combination and charged to a maximum of 18kV. As ignitrons are used in the discharge circuit, the natural current output waveform of the slow bank is a single half cycle. The shape of the slow bank output waveform is modified by introducing external resistors and air cored inductors. Ignitrons were also used to clamp the waveform producing an extended pulse giving a higher charge transfer.

7.3 Diagnostics

The output waveform of the A/D Bank was monitored by a Rogowski coil looped around the output return (low potential) transmission line. The output waveform of the Slow Bank was monitored by a coaxial shunt mounted in the return (low potential) transmission line.

Screened balanced twin cable was used to transmit the output from the Rogowski coil and the shunt to a screened diagnostic room where the signals were processed, stored and digitally displayed. Further digital processing produced the values of peak current, action integral and charge transfer associated with each test.

Typical test current waveforms associated with these tests are reproduced in Appendix II of this report, where waveform analysis methods are also discussed.

7.4 Calibration Status

The current diagnostic measurement systems associated with the A/D and slow capacitor banks are calibrated in accordance with LTT QA procedures.

7.5 Additional Current Measurements

In addition to the bank discharge current measurements described above, two additional Rogowski current measurement coils were used to monitor the current distribution in the blade root/sleeve region. Primarily the aim was to establish the proportion of current flowing off the TRB via the bonding braid. This measurement could only be made at low current levels, as at high current levels the bonding braid was destroyed and there would have been a risk of direct arc attachments to the Rogowski coils.

Both coils and their associated data transmission, processing and display channels were calibrated against the A/D bank system in advance of the test series. The location of these coils and their corresponding measurements are included in the test results presented in Section 14 of this document.

8 THE TEST ASSEMBLY

8.1 General

The parallel plate return conductor assembly shown in Plate 1* was used for these tests. This configuration simulates the free space conditions encountered in flight and therefore gives a representative current distribution in the test blade.

The test blade was mechanically supported by an insulating cradle at a point approximately 150mm in from the outboard tip, and at the blade root by the sleeve and spindle assembly which was bolted to the return conductor assembly.

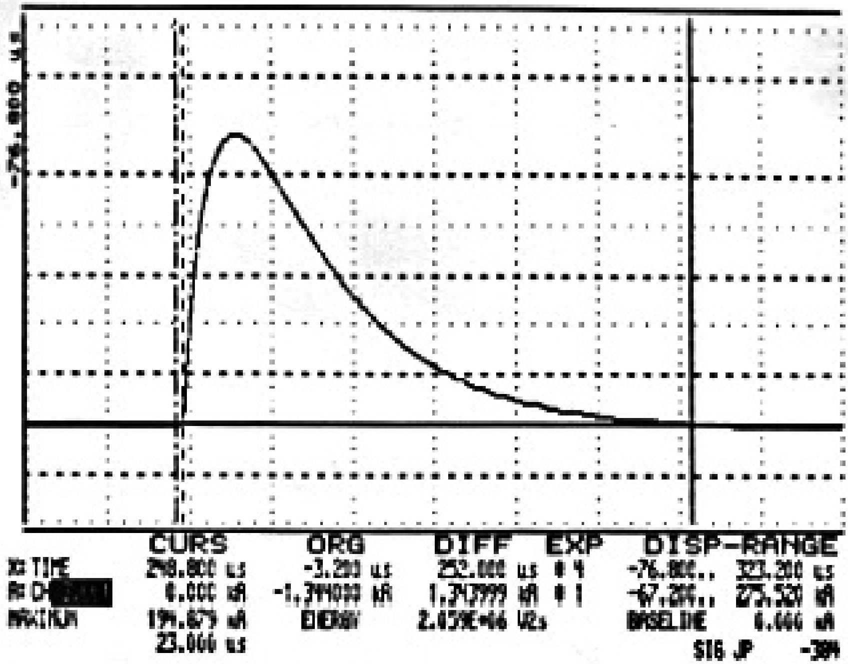
The return conductor assembly was connected to the low potential (earthy) output terminations of the generators.

An adapter plate was fitted to the high potential output termination of the generator and positioned between the parallel plates in line with the blade. This plate allowed both solid and open arc current injection techniques to be used.

In order to minimise the possibility of any liberated carbon fibre or other conductive debris from compromising the high voltage operation of the test facility, polythene sheets were used to shroud the open sides of the test assembly.

* Figure 1A in this Appendix(C)

Component A Waveform

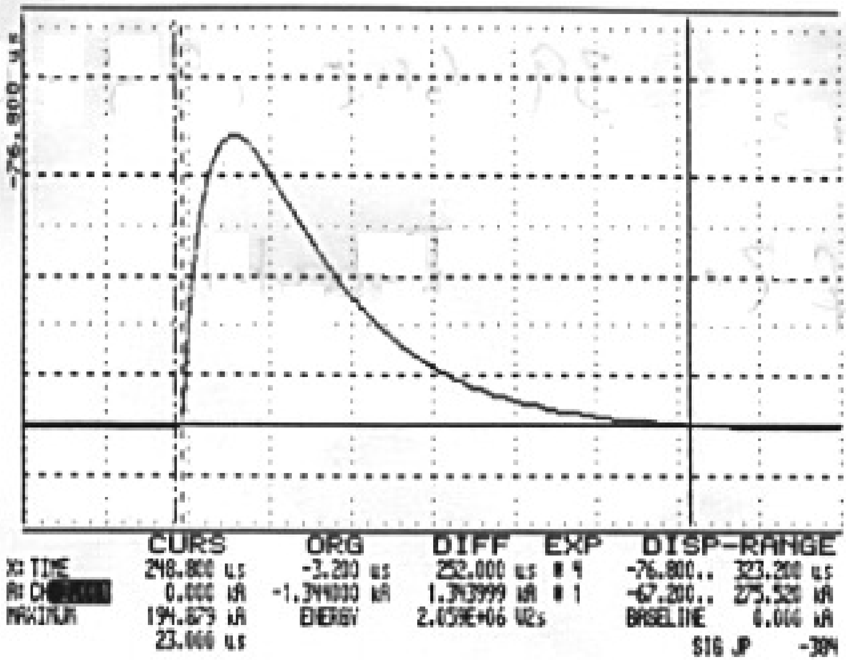


Peak Current is the current amplitude of the positive peak of the waveform.

Action Integral is the integral of the instantaneous current squared (with respect to time) for the duration of the pulse.

NOTE: The bottom line of printed information below the waveform gives the values of Peak Current in kA (MAXIMUM) and the Action Integral in V^2s (ENERGY). The numerical value for the action integral is correct, however the dimensions should be read as A^2s.

Component A Waveform



Peak Current is the current amplitude of the positive peak of the waveform.

Action Integral is the integral of the instantaneous current squared (with respect to time) for the duration of the pulse.

NOTE: The bottom line of printed information below the waveform gives the values of Peak Current in kA (MAXIMUM) and the Action Integral in V²s (ENERGY). The numerical value for the action integral is correct, however the dimensions should be read as A²s.

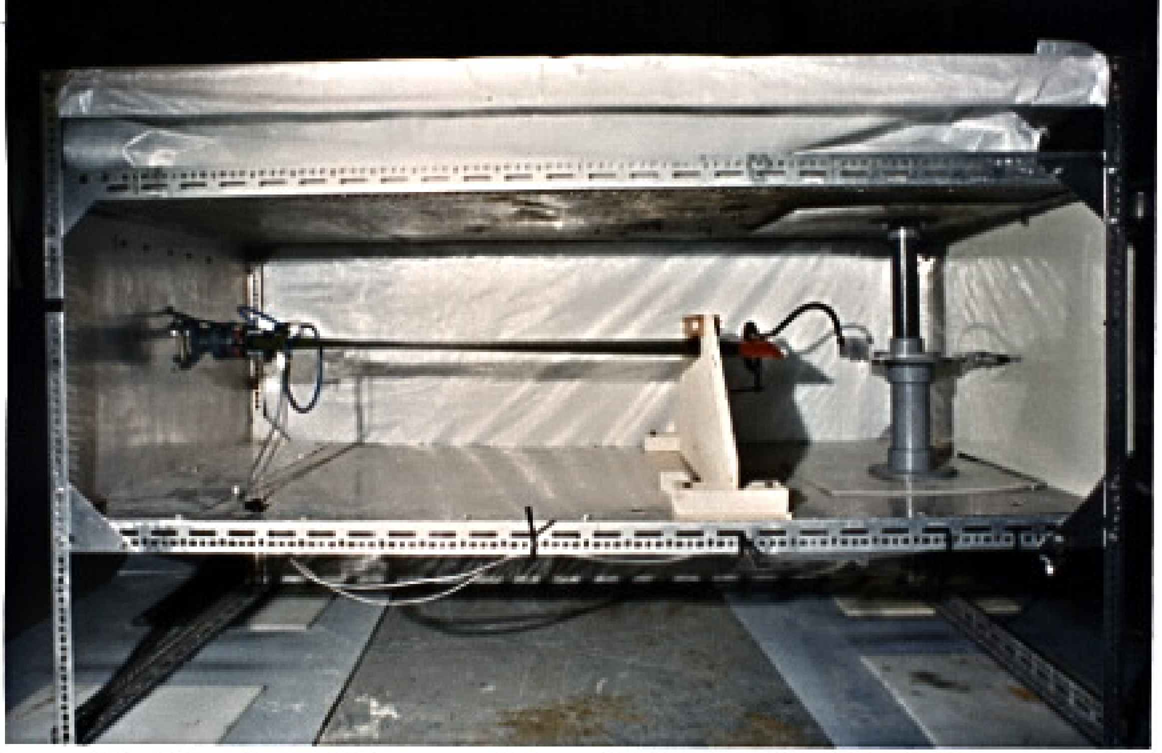


Figure 1A: Showing LTT test cell used for simulated lightning strikes on sample tail rotor blades, as described earlier in Enclosure 2, section 8.1.

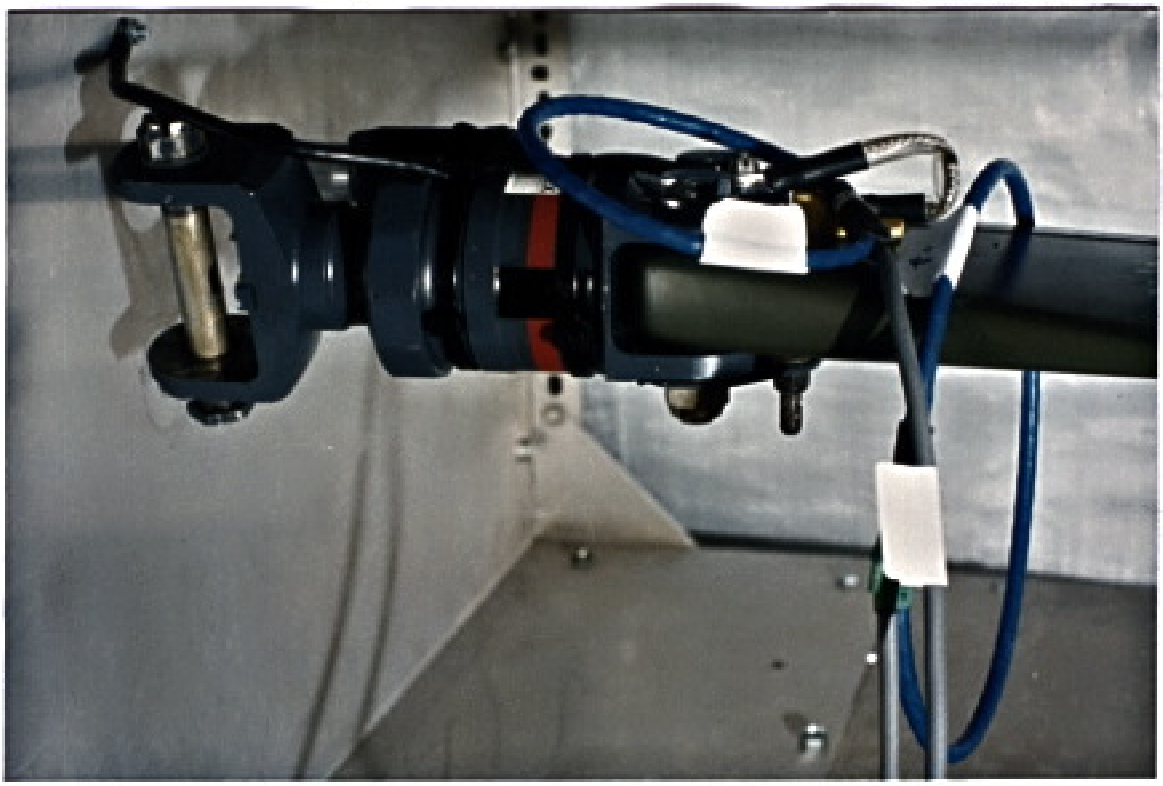


Figure 1B: Showing first test blade with inboard bonding strap and sleeve bolted to metal end plate, and Rogowski coils in position around root area.

Figure 2: Showing 'peel-back' of inboard end of anti-erosion shield from brass conducting strip after 12.7kA low energy test (shield tip input).

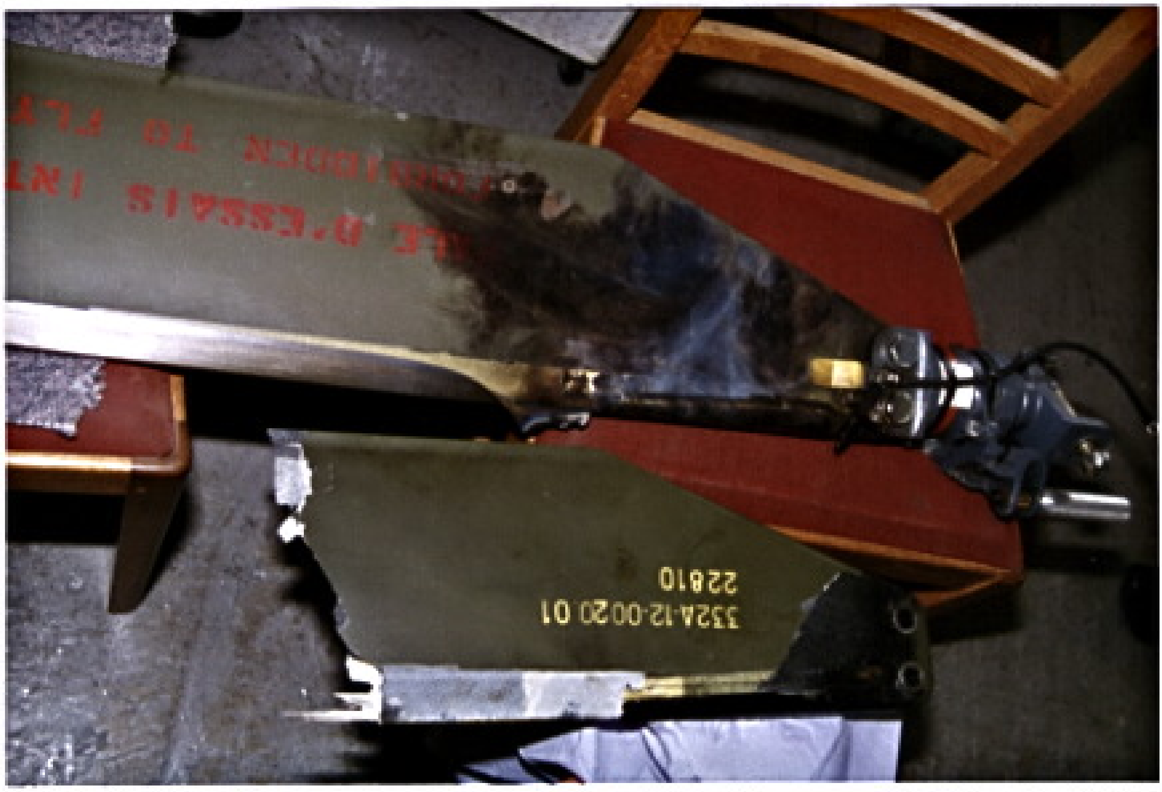


Figure 3: Showing post-test damage to inboard span of TRB s/n 22200 after 190.9kA input to shield tip, with White TRB section for comparison.

Figure 4: Showing tip damage to TRB s/n 20667 after 180.1kA input to trailing edge tip, with peel-back and general debonding of erosion shield.

Figure 5: Showing tip damage to TRB s/n 21667 after 253.7kA input to trailing edge tip, with debonding of erosion shield and 'burn-holes'.

Figure 6A: Showing TRB s/n 20636 after 198.9kA input to aft tip bolt with minor damage around bolt, but almost complete separation of shield.

Figure 6B: Showing thermal delamination damage to root area of above TRB.

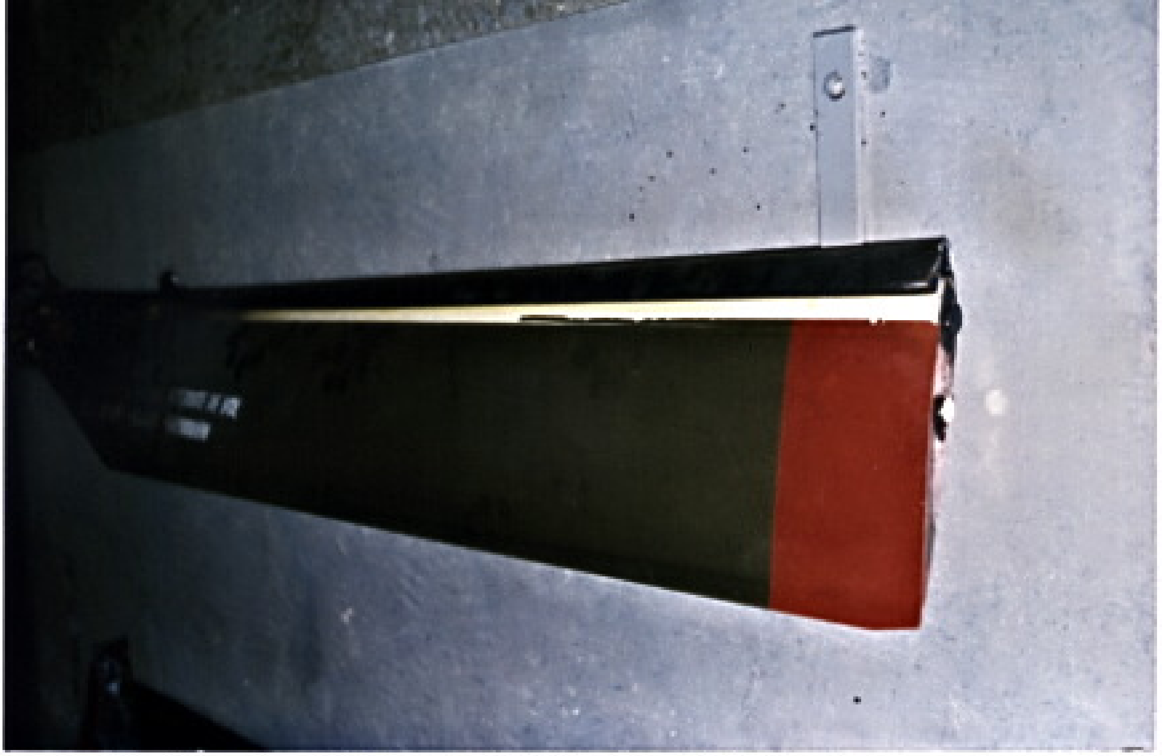


Figure 7A: Showing TRB s/n 20625 after 194.9kA input to forward tip bolt with minor damage around bolt and to erosion shield tip, but almost complete separation of shield.

Figure 7B: Showing damage to inboard area of above TRB.

Figure 8A: Showing general marked damage to TRB s/n 20646 after 188.2kA input to trailing edge, 0.5 metre from tip.

Figure 8B: Showing gross disruption of mid-aerofoil on above TRB and spanwise cracking of skins just aft of erosion shield.

Figure 9A: Showing damage to TRB s/n 20732 after 206.9kA input to inboard end of erosion shield, with local peel-back of shield.

Figure 9B: Showing skin delamination and disbonding outboard of both steel bushes in root area (inboard side) of above TRB.

Figure 10A: Showing detached and badly deformed erosion shield after 275.5kA input to aft tip bolt on TRB s/n 20662.

Figure 10B: Showing longitudinal 'fissure'(arrowed) within blade substrate uncovered by loss of brass bonding strip, and root damage on above TRB.

Figure 10C: Showing marked delamination and disbonding of inboard(left) surface of the root of TRB s/n 20662 after 275.5kA input to aft tip bolt.

Figure 11A: Showing gross damage to aerofoil of TRB s/n 22313 after 253.3kA input to trailing edge, 34cm from tip.

Figure 11B: Showing localised damage to leading edge composite and detached inboard length of shield, with 'burn-holes', on above blade.

Figure 11C Showing marked thermal affects on outboard side of root on TRB s/n 22313 with carbon fibre damage adjacent attachment bolts.

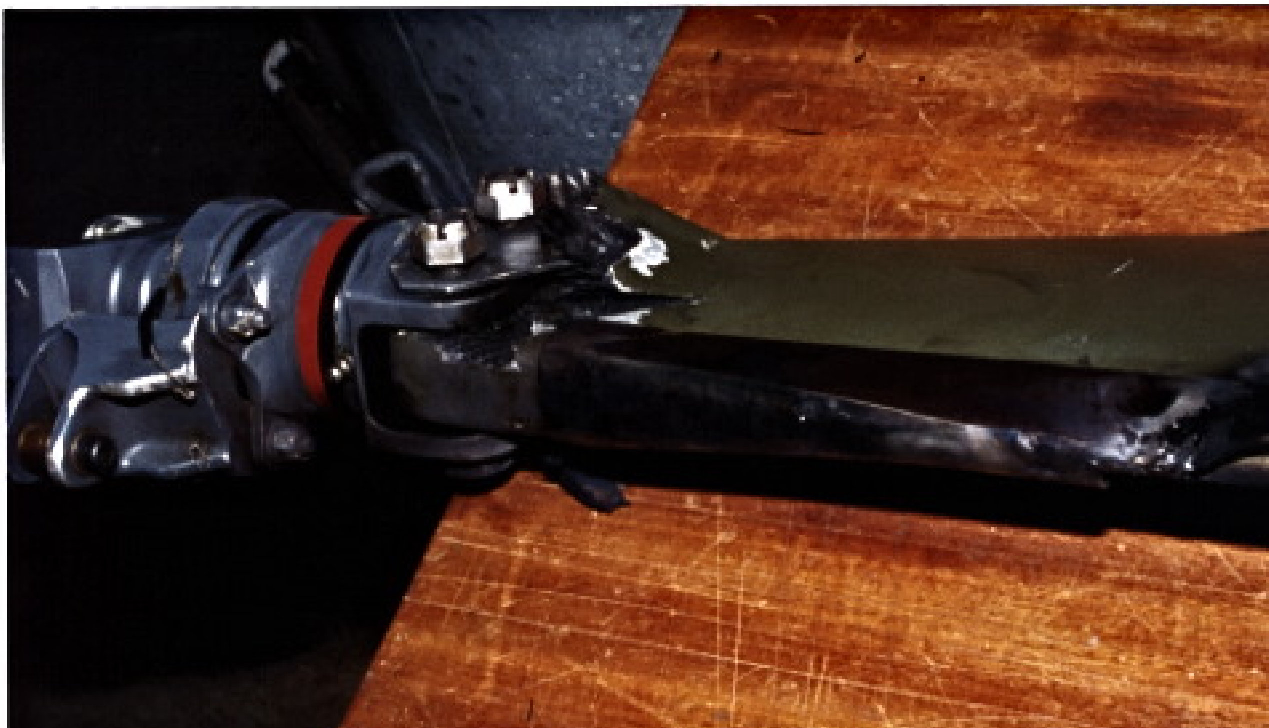


Figure 11D: Showing very marked carbon fibre disbonding and delamination adjacent attachment bolts on inboard side of above blade.

Figure 12A

Figure 12B

Showing (Figure 12A) gross damage to aerofoil with (Figure 12B) 'split' in leading edge and detached erosion shield lying alongside TRB s/n 20697 after 253.8kA input to trailing edge, 20cm from tip.

Figure 12C: Showing almost full length 'fissure'(between arrows) within substrate uncovered by loss of brass conducting strip, and root damage adjacent attachment bolt bushes on TRB s/n 20697.

Figure 12D: Showing thermal disbonding and delamination damage to inboard side of root adjacent bushes on TRB s/n 20697.

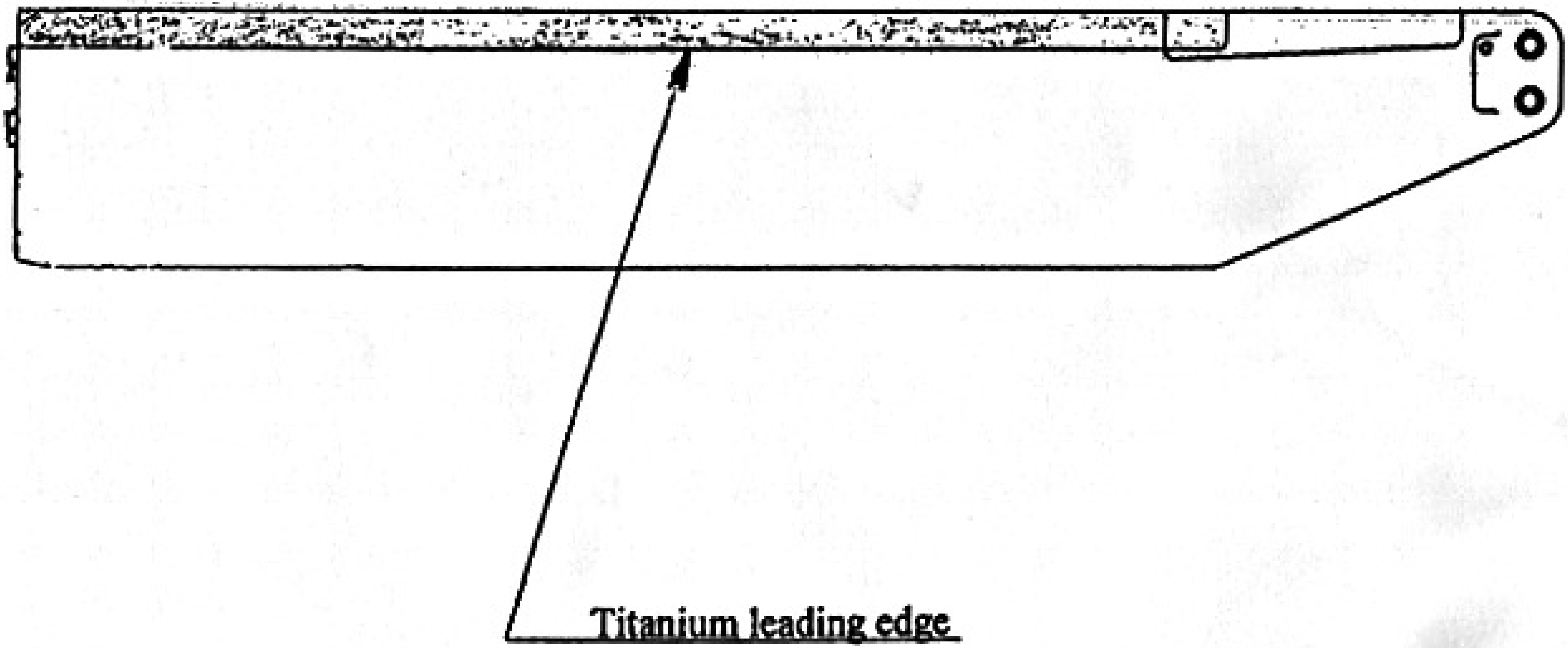


Figure 13A: Showing leading edge anti-erosion shield/conductor design on TRB p/n 332A.12.0020 before modification to improve lightning protection.

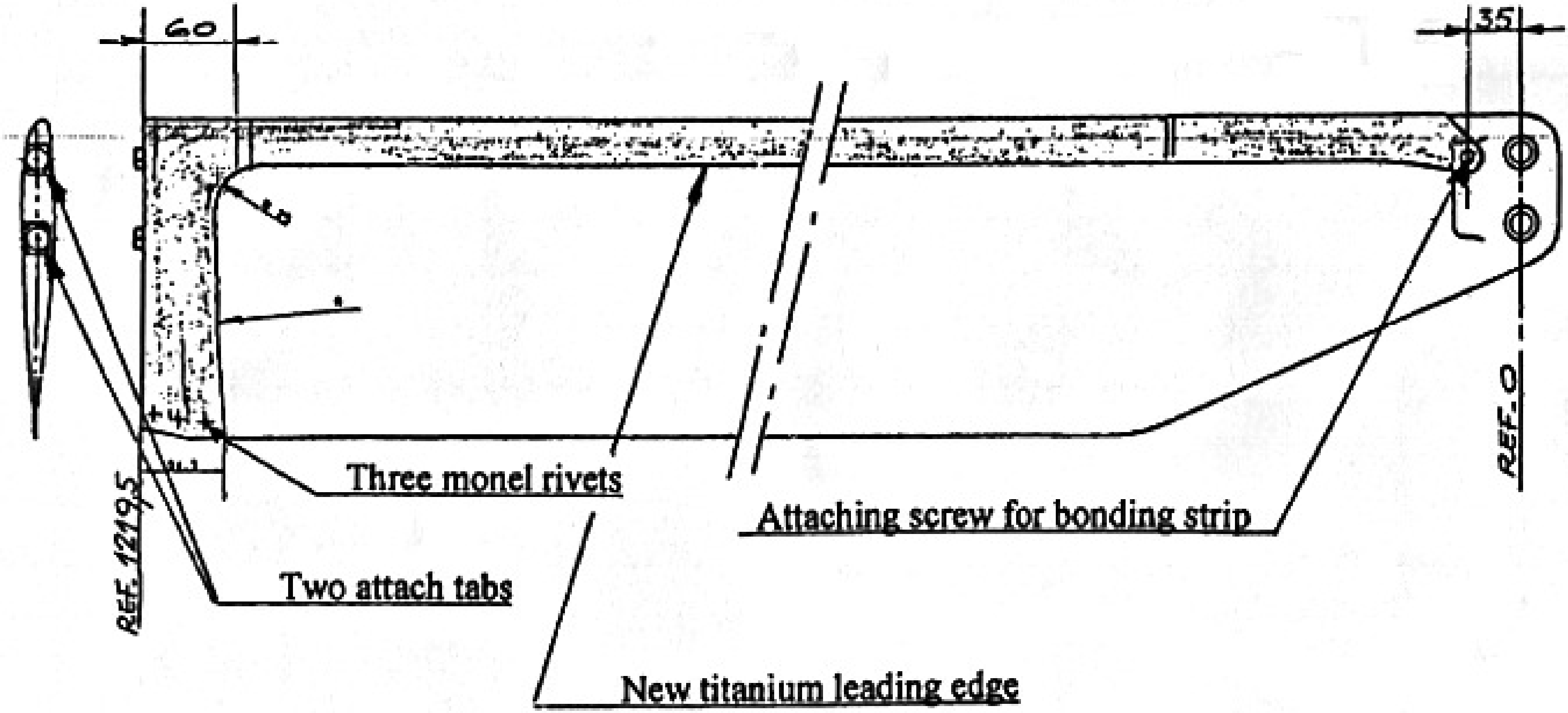
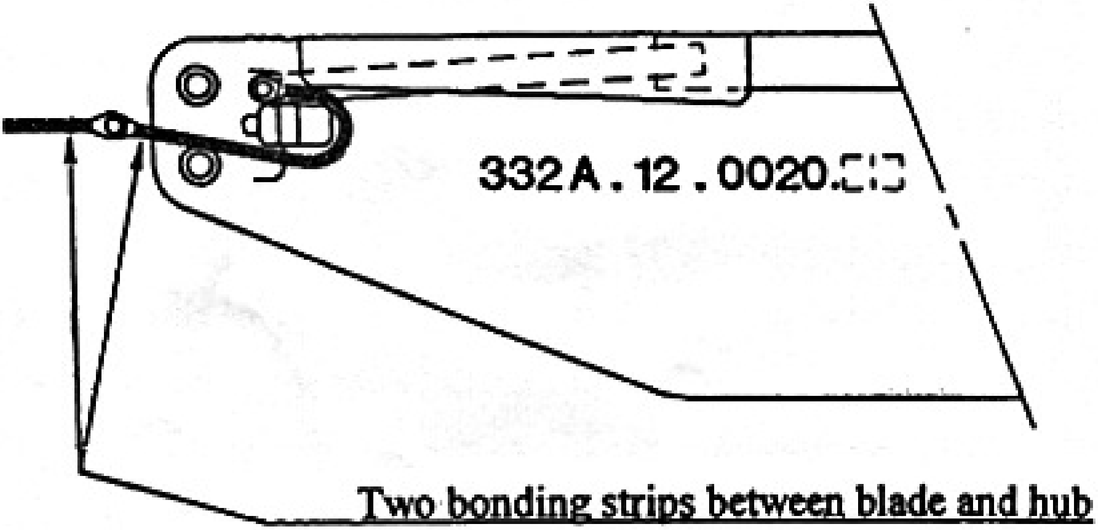


Figure 13B: Showing modified blade p/n 332A.12.0050 design with anti-erosion shield/conductor extended inboard to root and aft to provide improved blade tip conduction, with titanium 'tab' continuity to both tip weight bolts and rivetted attachment to trailing edge.



AFTER

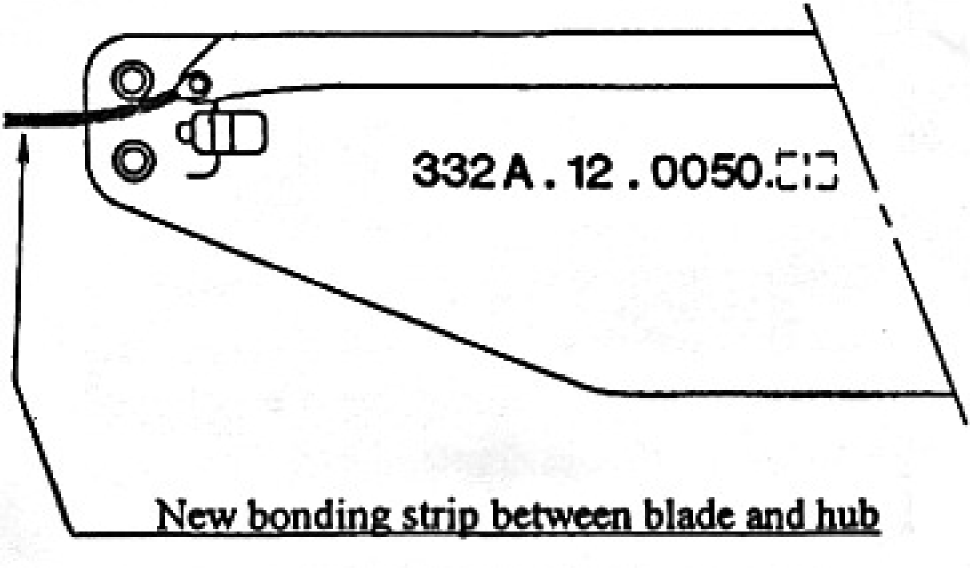
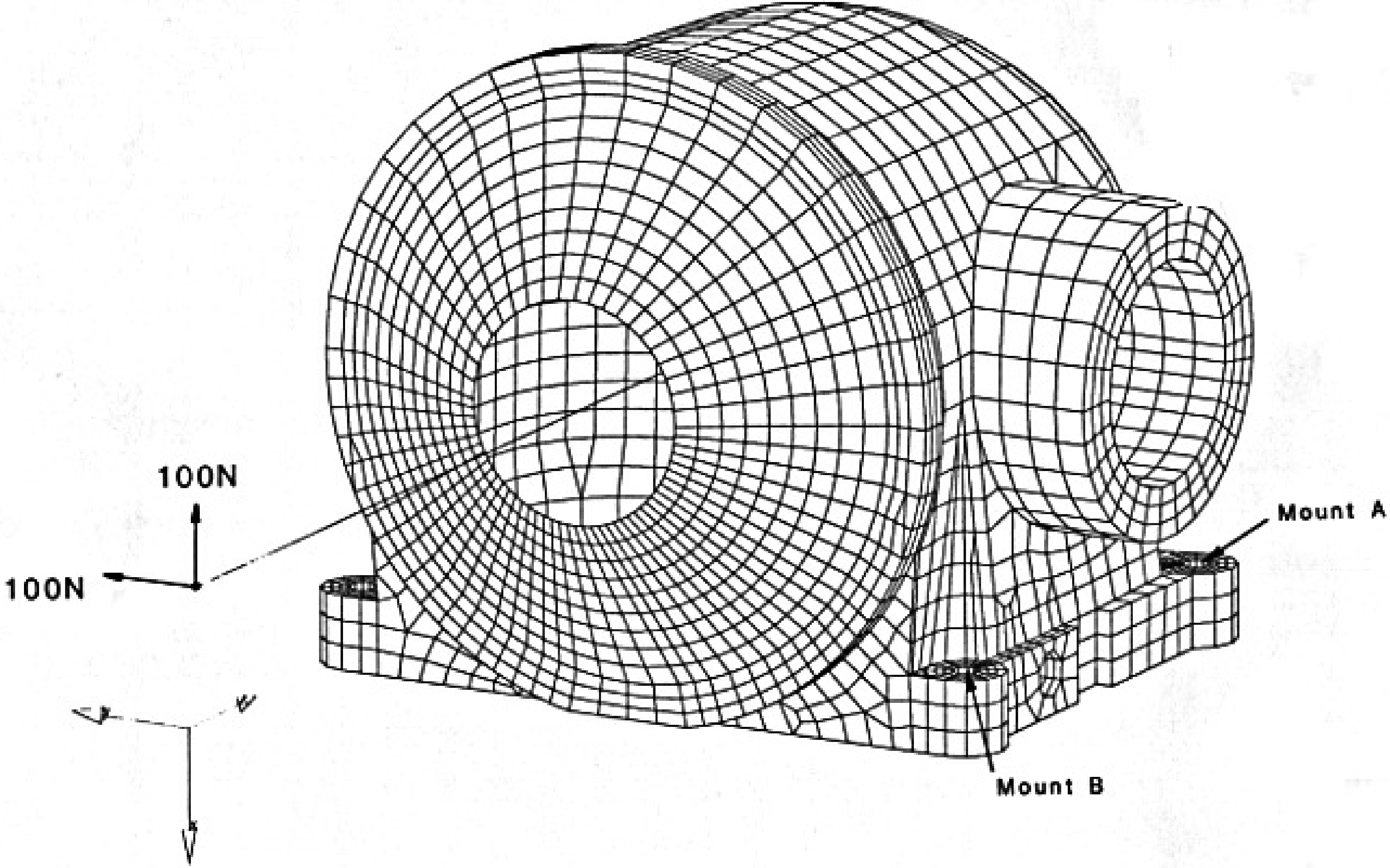
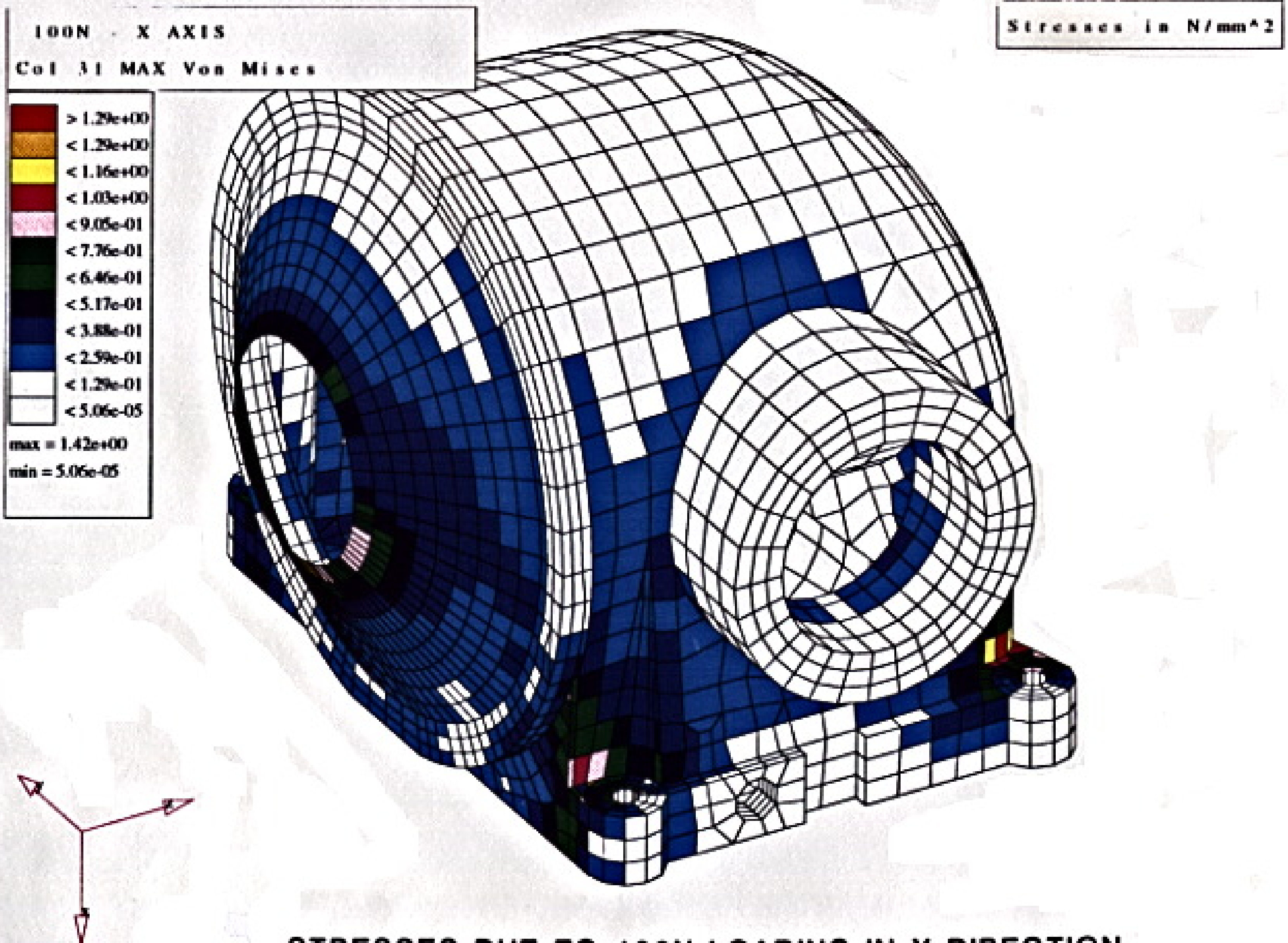


Figure 13C: Showing modified inboard conduction design with replacement of brass strip, which linked erosion shield to root bolt, by extended titanium shield, and fitment of single bonding strap.



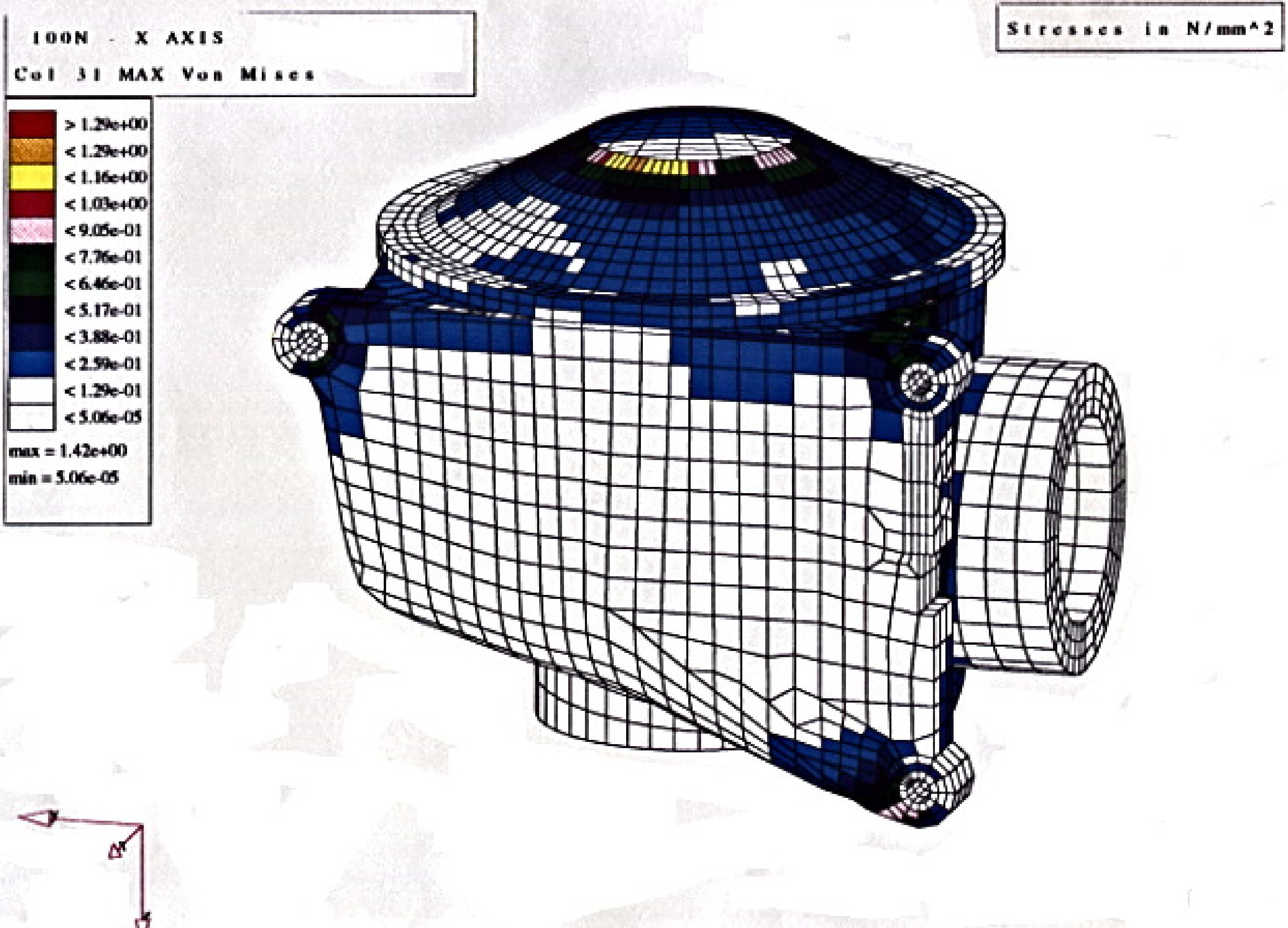
FINITE ELEMENT MODEL SHOWING LOADING LOCATIONS

APPENDIX D
(FIGURE 1)



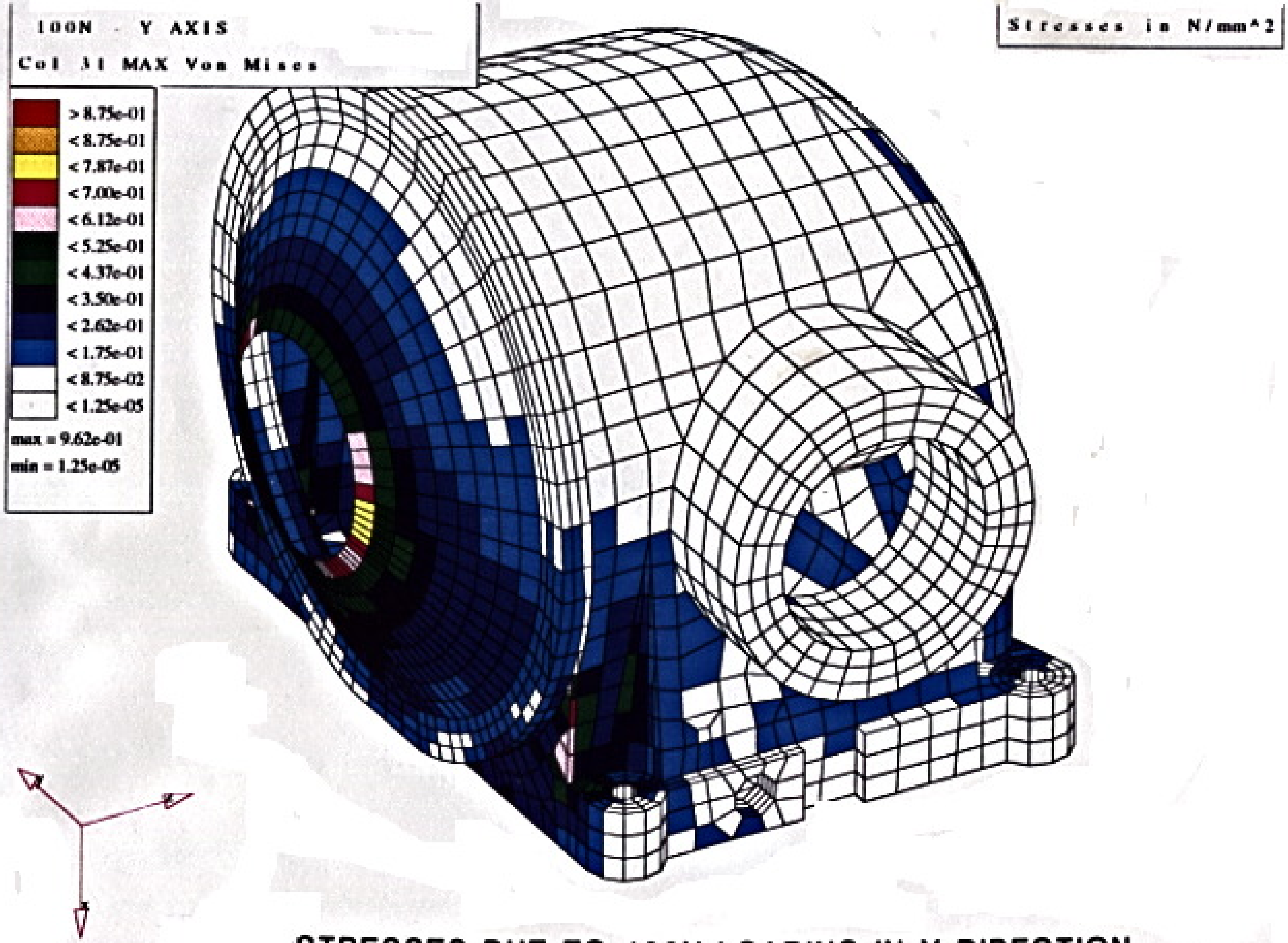
STRESSES DUE TO 100N LOADING IN X-DIRECTION

(FIGURE 2)



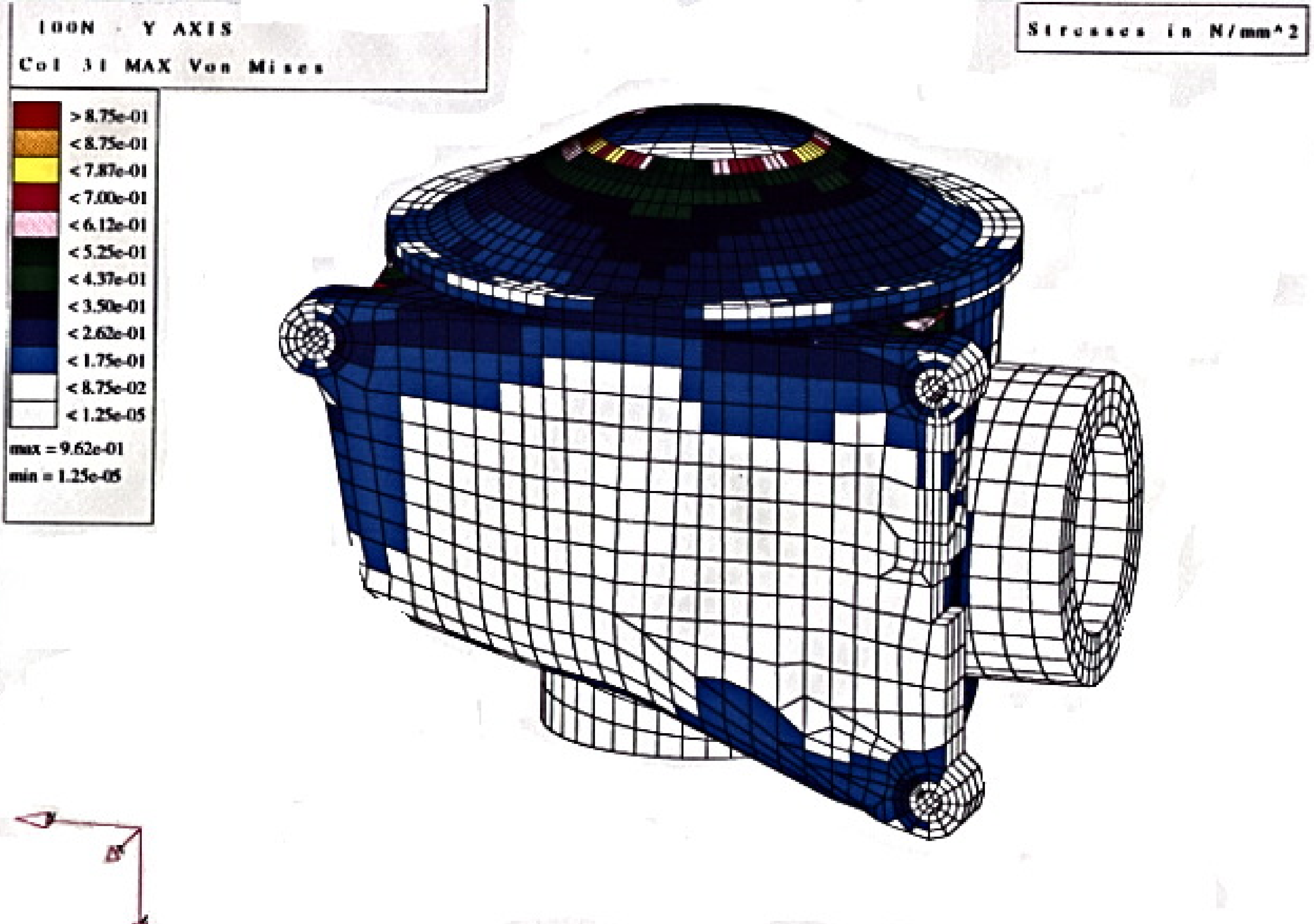
STRESSES DUE TO 100N LOADING IN X-DIRECTION

(FIGURE 3)



STRESSES DUE TO 100N LOADING IN Y-DIRECTION

(FIGURE 4)



STRESSES DUE TO 100N LOADING IN Y-DIRECTION

(FIGURE 5)

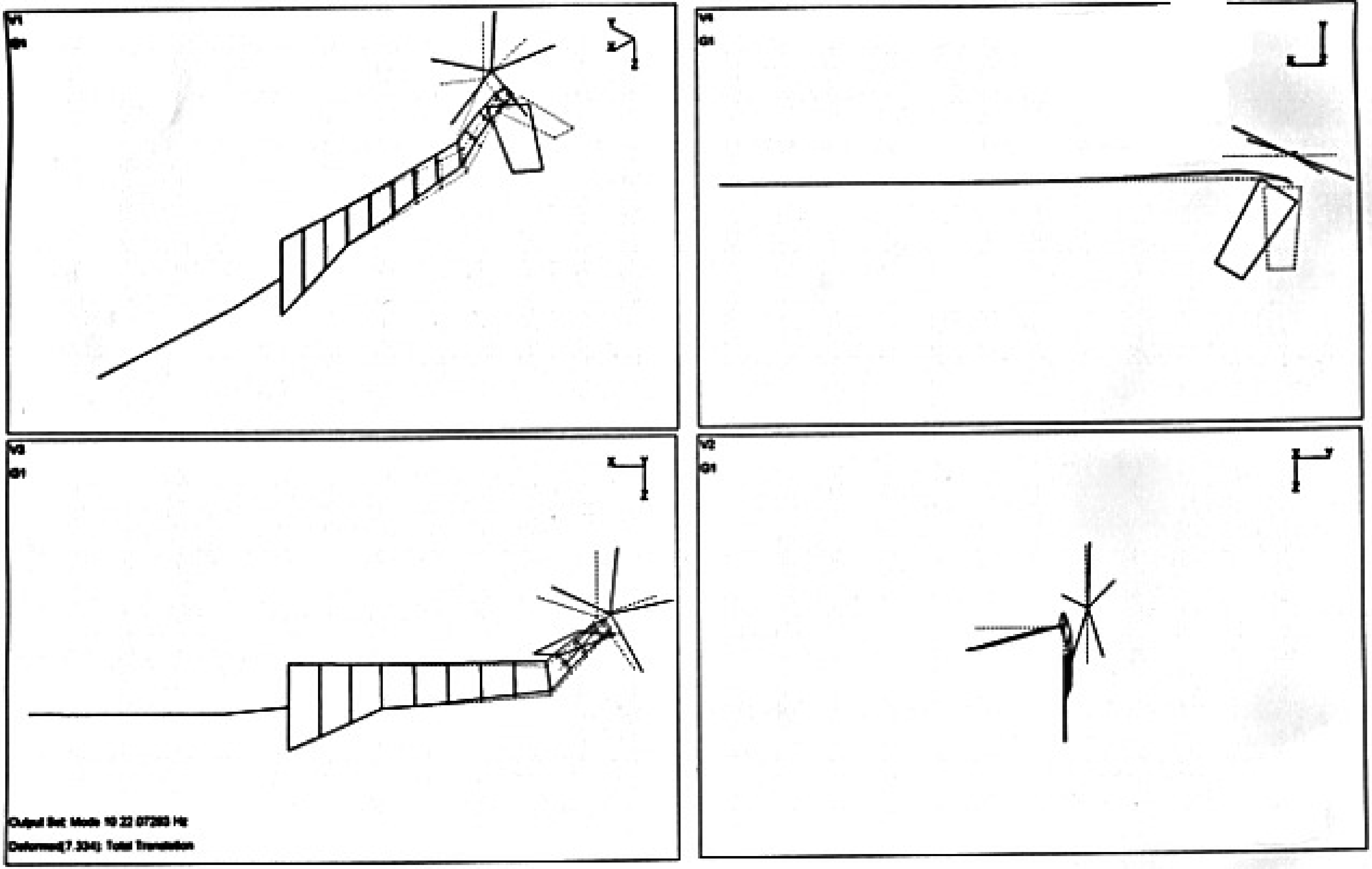


Figure 1: Showing predicted overtone vertical/lateral bending mode at 22.07Hz

APPENDIX E

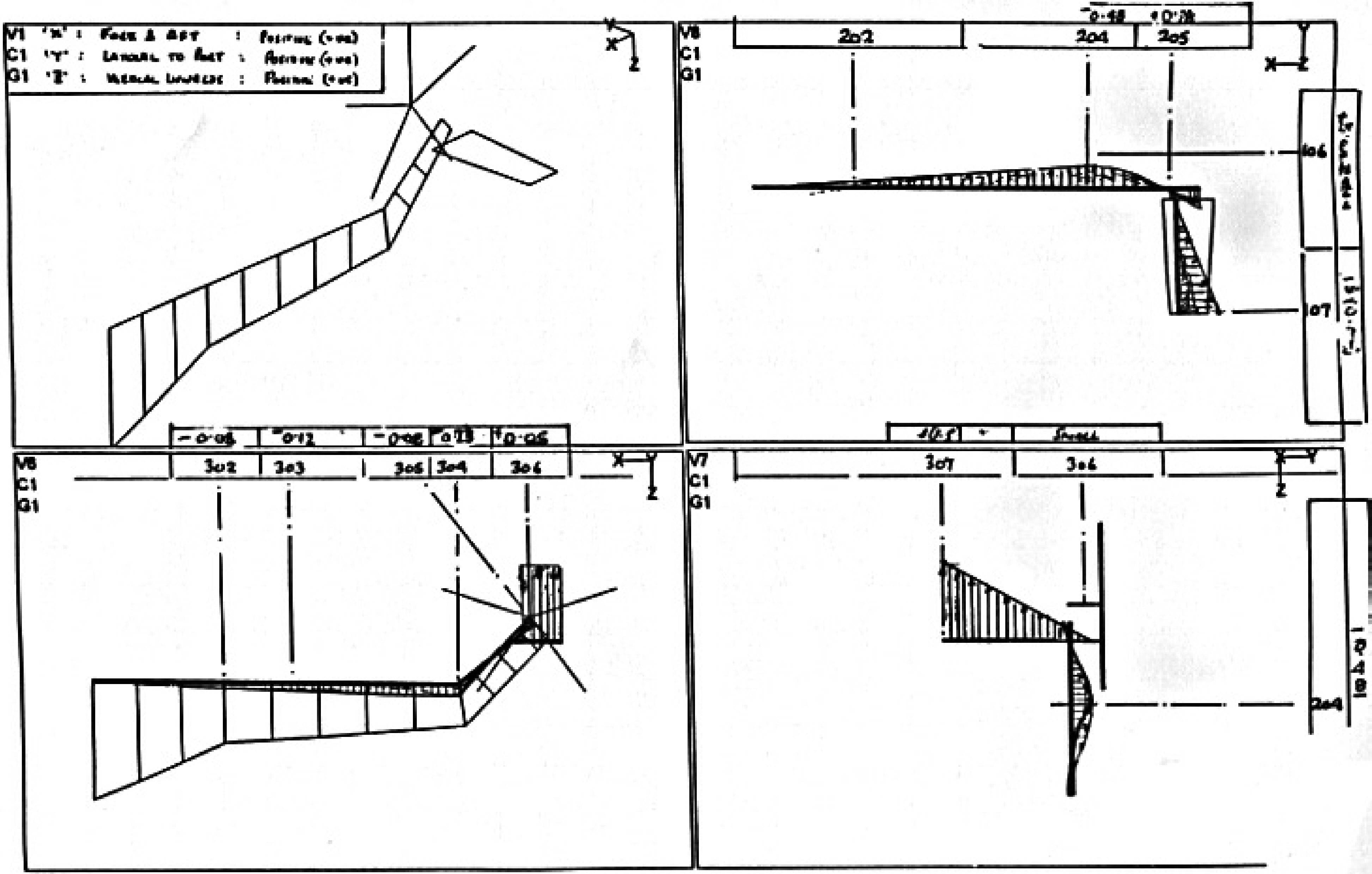


Figure 2: Showing measured overtone vertical/lateral bending and tail roll mode at 22.80Hz

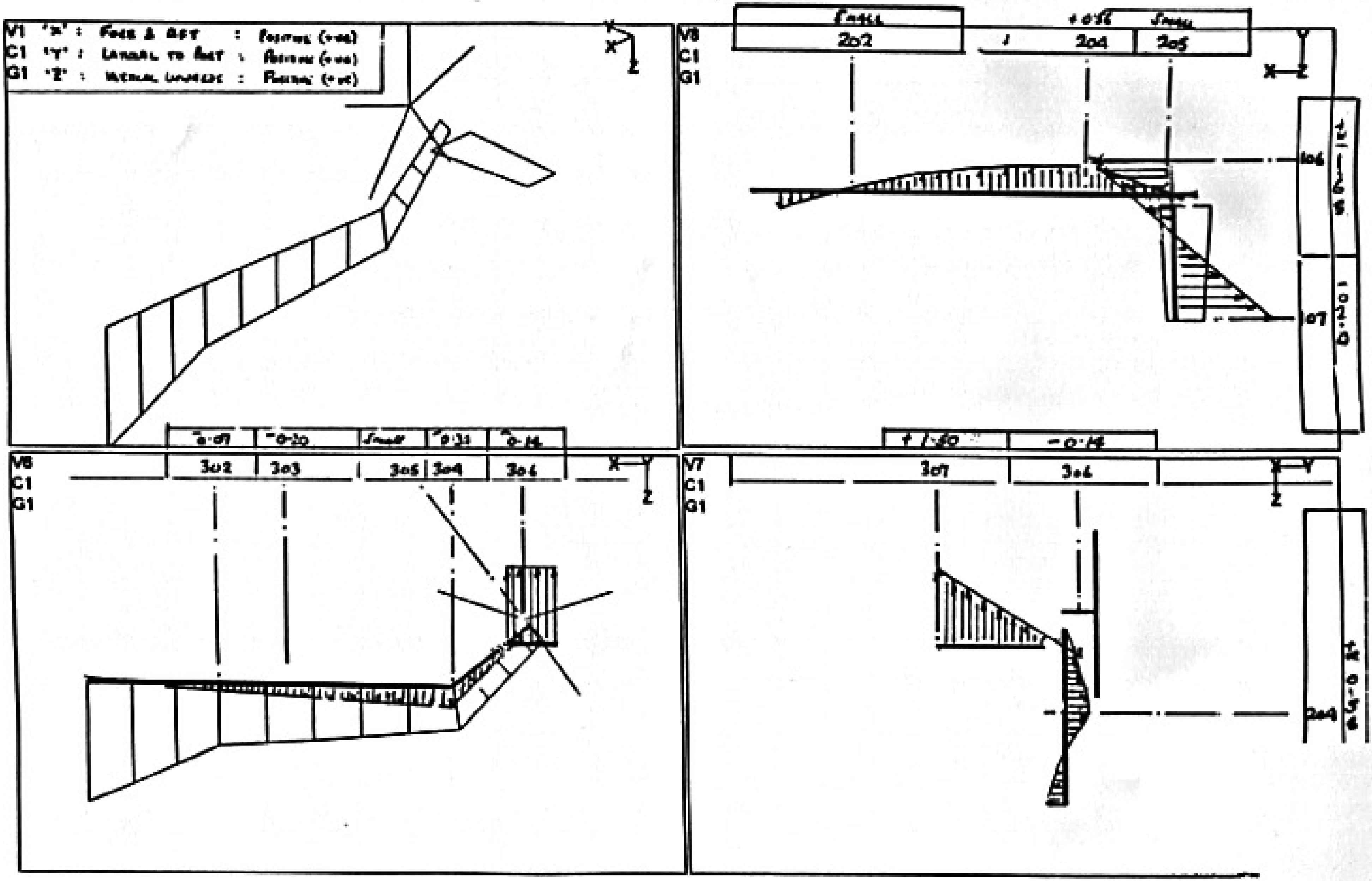


Figure 3: Showing measured overtone vertical/lateral bending with torsion/tailplane yaw mode at 20.80Hz

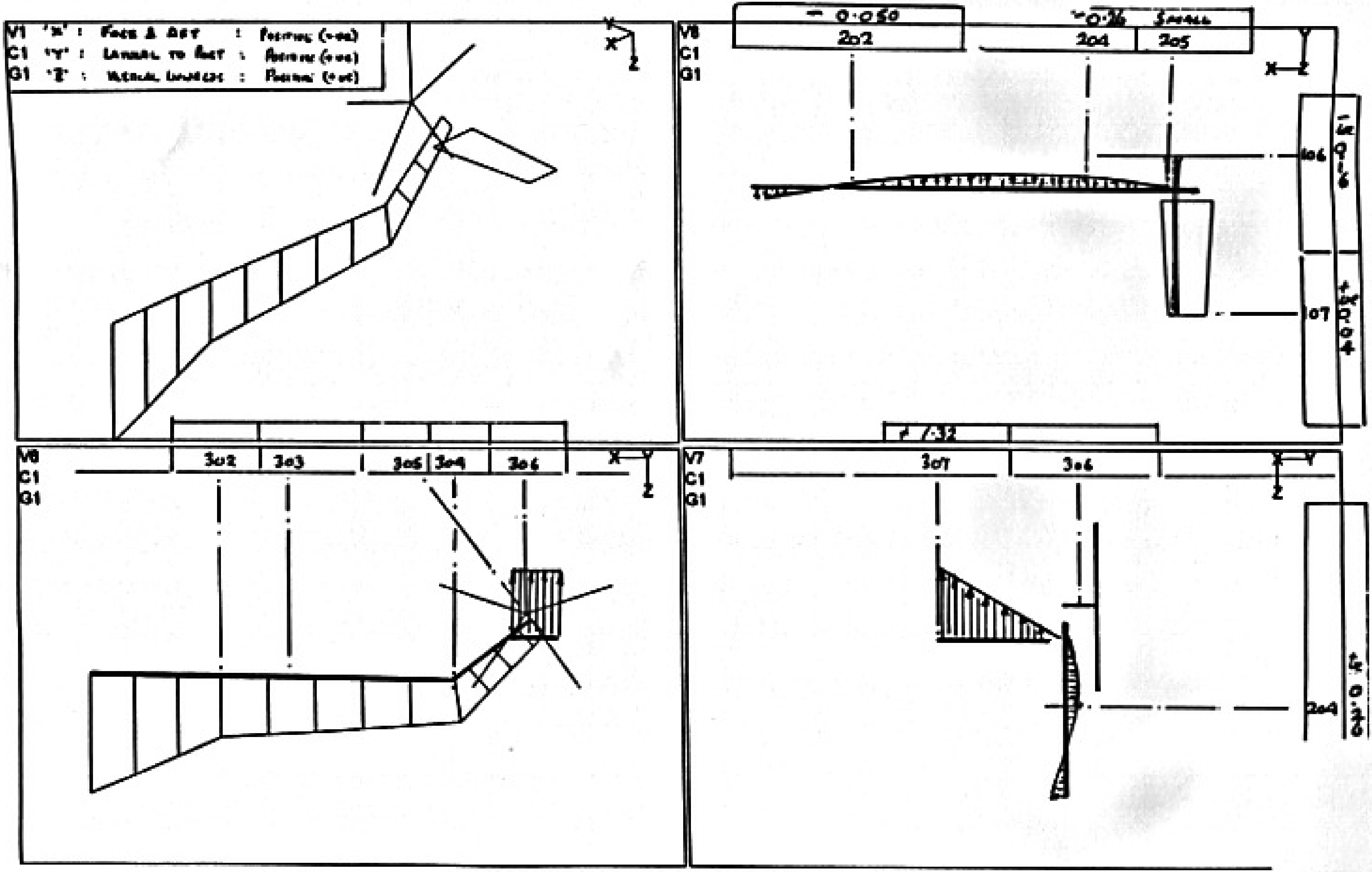


Figure 4: Showing measured overtone lateral bending/tail roll mode at 22.35Hz

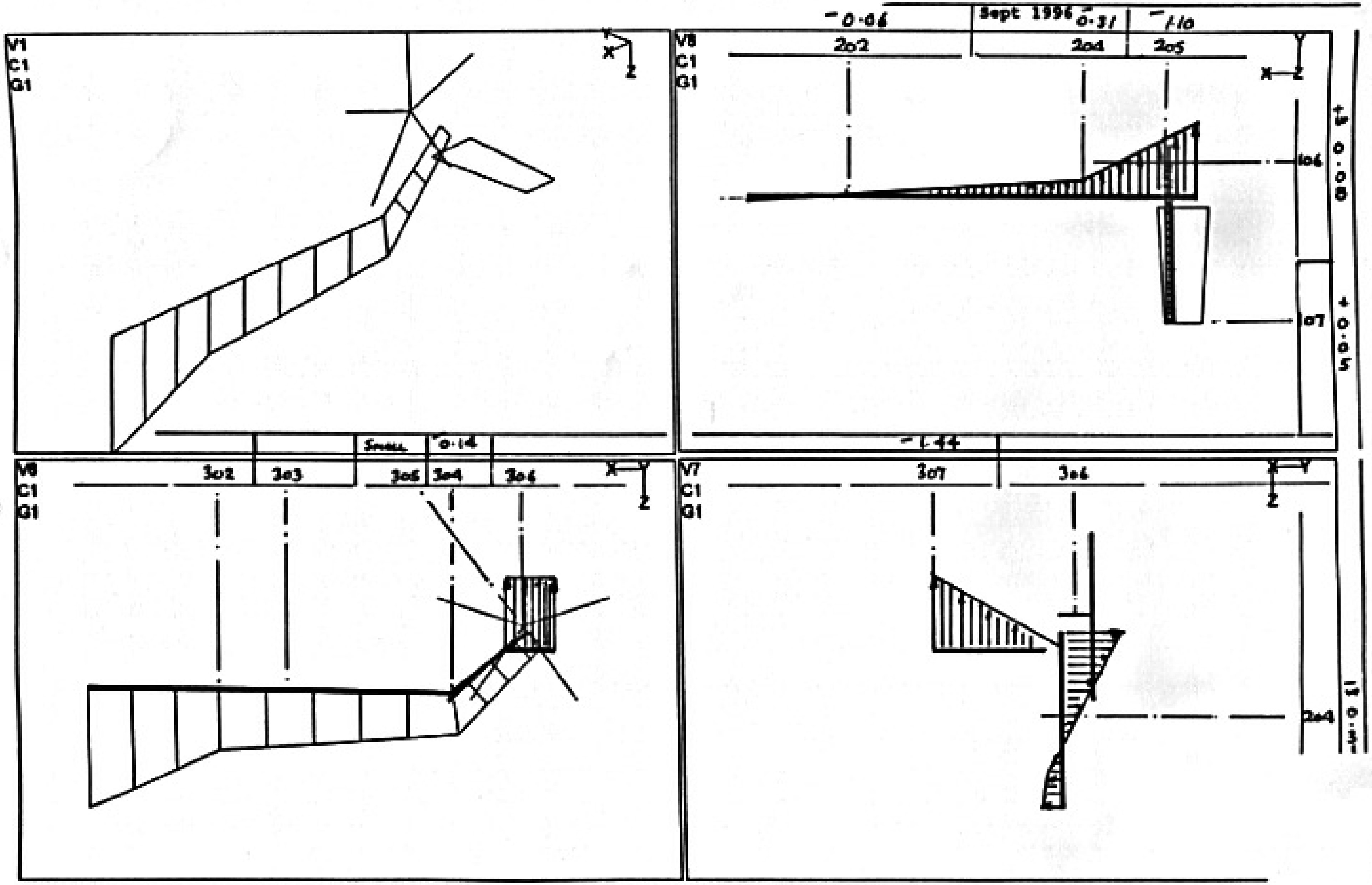


Figure 5: Showing measured lateral bending/tail roll mode at 23.35Hz

MEASURED			PREDICTED		
Mode 7:	20.80 Hz:	Overtone Vert/Lat/ Torsion/Tail Yaw			Aircraft Mode (not represented)
21.56 HZ TAIL ROTOR EXCITATION FREQUENCY IN THIS POSITION					
Mode 8:	22.35 Hz:	Backend Lateral Overtone			Aircraft Mode (not represented)
Mode 9:	22.80 Hz	:Overtone Vert/Lat/Tail Roll	Mode 4:	22.07 Hz:	Overtone Vert'l/Lateral
Mode 10:	23.35 Hz	Aircraft Mode Backend			Aircraft Mode (not represented)

Table 1: Showing summary of measured and predicted tail boom/pylon responses

	RIGHT LUG X-AXIS	RIGHT LUG Y-AXIS	RIGHT LUG Z-AXIS	LEFT LUG Z-AXIS	UPPER LUG Y-AXIS	UPPER LUG Z-AXIS	AVIONICS BAY ACCN.
NEWTONS	36,650	40,000	14,300	17,100	39,700	30,500	6.4G
lbf	8,239	8,992	3,215	3,844	8,925	6,857	

Table 2: Showing calculated dynamic forces on the tail rotor gearbox attachment lugs and G-switch due to out-of-balance effects induced by loss of the anti-erosion shield from one tail rotor blade (X-axis normal to gearbox mounting plane, Y-axis parallel/longitudinal to mounting plane and Z-axis parallel/lateral to mounting plane).