ACCIDENT

Aircraft Type and Registration:	Boeing 737-436, G-DOCT
No & Type of Engines:	2 CFM56-3C1 turbofan engines
Year of Manufacture:	1992
Date & Time (UTC):	8 July 2005 at 1006 hrs
Location:	Aberdeen Airport
Type of Flight:	Public Transport (Passenger)
Persons on Board:	Crew - 6 Passengers - 149
Injuries:	Crew - None Passengers - None
Nature of Damage:	Damage to tailplane and elevator
Commander's Licence:	Airline Transport Pilot's Licence
Commander's Age:	35 years
Commander's Flying Experience:	8,500 hours (of which 3,965 were on type) Last 90 days - 185 hours Last 28 days - 67 hours
Information Source:	AAIB Field Investigation

Synopsis

On takeoff, sections of a blast pad positioned at the runway threshold lifted and broke up, causing damage to the aircraft's tailplane and elevator. The crew were unaware of the damage to the aircraft and completed the takeoff and flight to their destination without further incident. The investigation identified issues concerning the construction and marking of the blast pad and other factors concerning the conduct of the takeoff. 10 safety recommendations were made.

History of the flight

The crew were operating their final sector of the day, from Aberdeen to Gatwick, with the commander acting as handling pilot. Prior to start, the flight crew had received the aircraft performance figures for their predicted departure weight. These were calculated for a reduced thrust takeoff at FLAP 15, rather than the more usual FLAP 5, due to performance limitations. The commander stated he briefed the co-pilot that, due to the short runway length, he would hold the aircraft on the brakes whilst setting takeoff power.

The aircraft was pushed back at 0956 hrs and, after engine start, was taxied to Runway 16, via Taxiway W, for departure. ATC cleared the aircraft to line up and take off on Runway 16. The commander taxied onto the runway, ensuring that the aircraft was positioned close to the threshold, to make maximum use of the runway length available. This was witnessed by the crew of a following aircraft, the commander of which stated that

G-DOCT had turned slightly left as it crossed holding point W5 (Figure 1) before turning sharply to the right to line up on the runway centreline. He further stated that this turn was through more than 90° and appeared to be done "gently". This commander also stated that the wheels of the aircraft had remained on the runway throughout the manoeuvre and that, once lined up, G-DOCT was brought to a halt with the tail "just in front of the threshold lights".

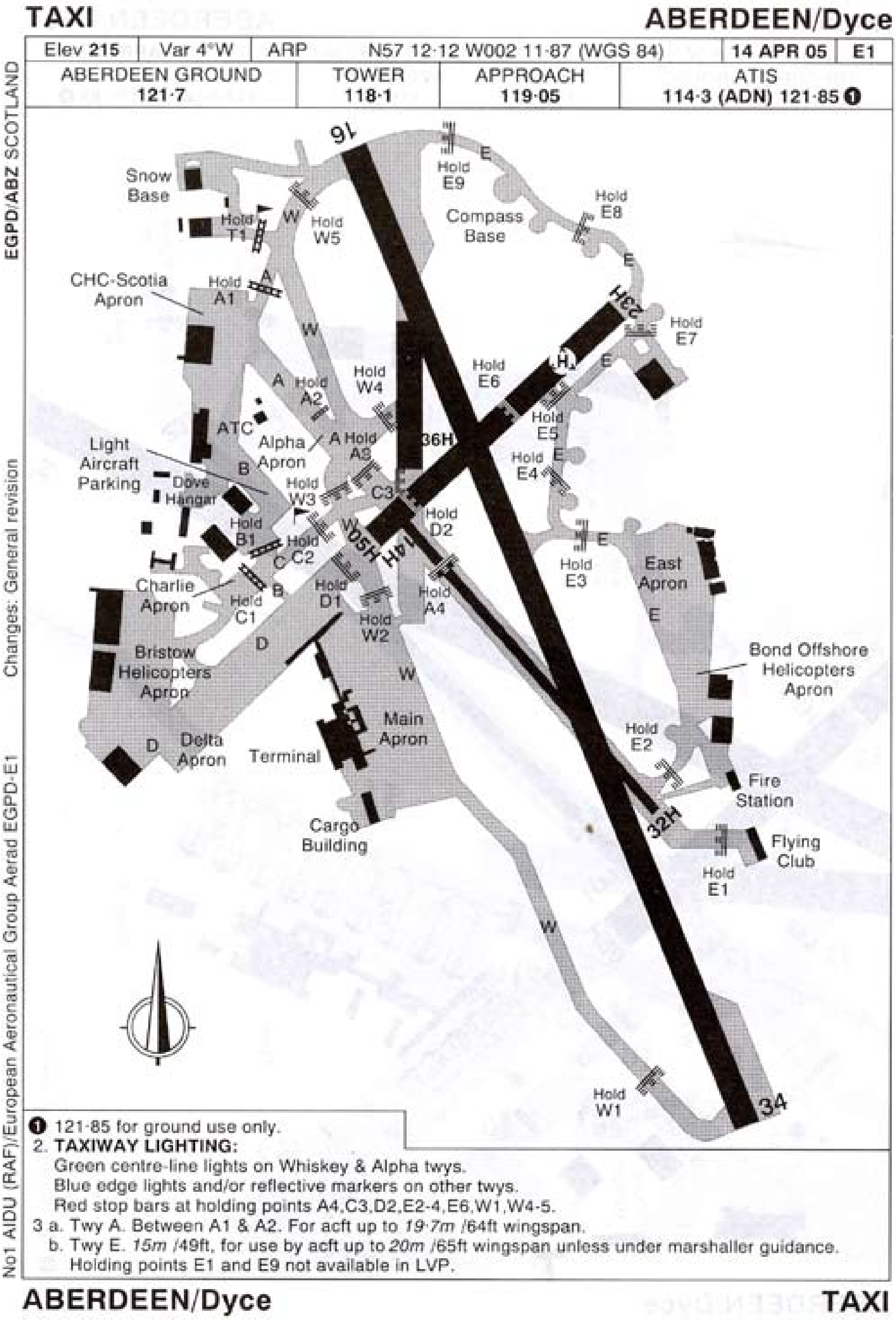

Figure 1

Aberdeen Airport taxi chart

The commander of G-DOCT stated that, on being cleared for takeoff, he had held the aircraft on the brakes as briefed. He stated that he set the thrust levers to 40% N_1[1] and waited for the engines to stabilise at this power before selecting takeoff power by pressing the TO/GA (takeoff or go-around) button. The commander recalls that takeoff power had been about 92% N_1 and that, once the thrust had reached about 90% N_1, he released the brakes. The aircraft began to move forward and almost immediately he felt a jolt as if the nosewheel had run over a small bump. Neither pilot was unduly concerned and the commander continued the takeoff. The takeoff time was 1006 hrs.

The flight crew of the following aircraft had watched G-DOCT take off and saw two large sections of asphalt, the largest section estimated to be 2 m by 3 m, slowly lift and disintegrate as the aircraft started its takeoff roll. They reported what they had seen to ATC, and this was heard by the crew of the aircraft taking off, just as they became airborne. Once they had completed their 'after takeoff' checks the departing commander asked over the radio if the crew who had witnessed the surface break-up had seen any damage to the aircraft. This crew replied that no damage to the aircraft had been seen and, in light of this reply, and the fact that the aircraft appeared to be handling normally, the commander of G-DOCT decided to continue with the flight.

The commander stated that the rest of the flight was uneventful and the aircraft landed at Gatwick at 1114 hrs. After shutdown, believing there had been no damage to the aircraft, the crew returned to the crew room, only to learn shortly afterwards that a routine engineering inspection had revealed considerable damage to the tail of the aircraft.

Footnote

[1] N_1 is the rotational speed of the engine fan, expressed as a percentage of maximum rpm.

Aircraft damage

The aircraft sustained damage to its left tailplane and left elevator. There was a dent 2.4 metres long on the underside of the left tailplane as depicted in Figure 2. The dent contained pieces of black bitumen from the asphalt section that had struck it. Some of the tailplane skin within the dent had torn and some ribs had buckled. A section of the elevator, approximately 0.9 m by 0.6 m, had completely detached, causing a separation between the outboard section of the elevator (containing the balance weights) and the remainder of the elevator – see Figure 3. The elevator underside was peppered with pieces of black bitumen. The damaged sections of elevator were found in the grass area behind the Runway 16 threshold, close to the extended runway centreline. The farthest pieces were found 132 metres behind the threshold.

Blast pad damage

The blast pad (also known as an erosion strip) at the Runway 16 threshold at Aberdeen Airport was a paved area 8.4 m long and 72 m wide, extending beyond both sides of the 45 metre-wide runway (area shown in yellow in Figure 4). The asphalt surface of the central section of this blast pad, approximately 6.5 m either side of the runway centreline, had completely detached. Most sections of asphalt had been blown aft into a grass area – some were found 20 metres behind the end of the blast pad. The remainder of the asphalt sections were piled up in the damaged area of the blast pad (see Figure 5), the largest of which was approximately 1.8 m by 1.5 m and 6 cm thick, weighing approximately 340 kg. The exposed surface below the removed asphalt consisted of stones and dirt with almost no bitumen residue. Some of the stones from this surface were found on the runway. The majority of the bitumen overband sealing (designed to create a flush surface, without cracks, between the runway and blast pad) had detached with the asphalt.

Figure 2

Damage to left tailplane and left elevator on G-DOCT

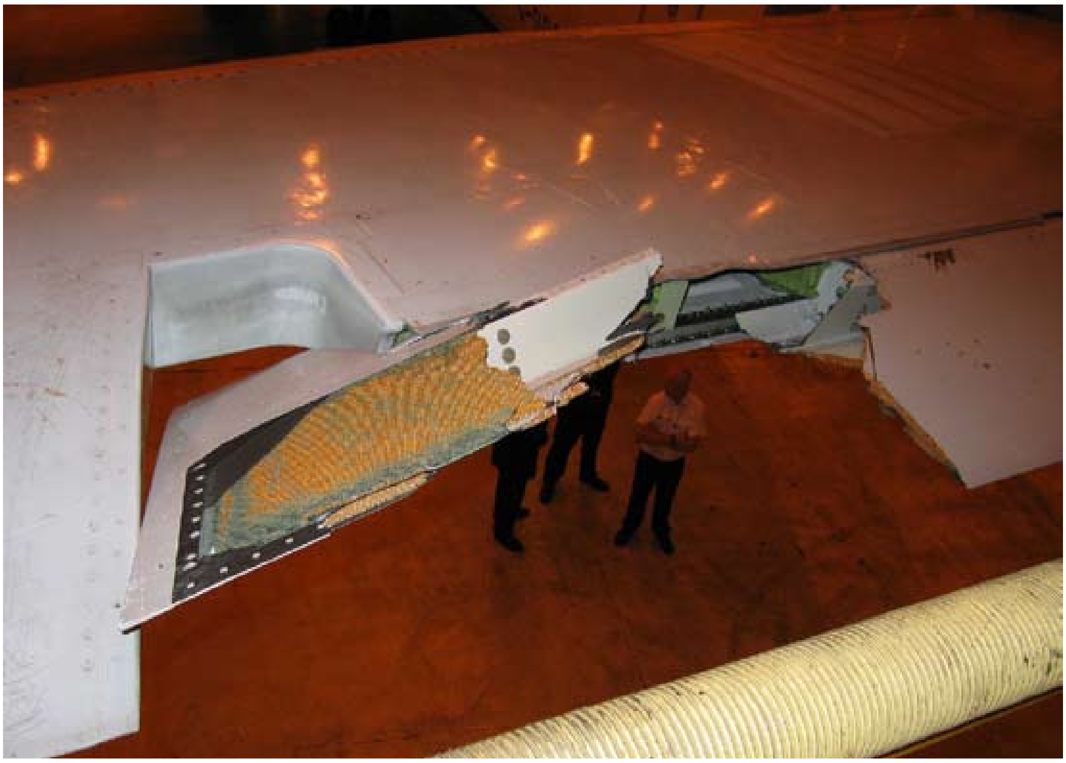

Figure 3

Damage to left elevator of G-DOCT, showing separation of outboard section

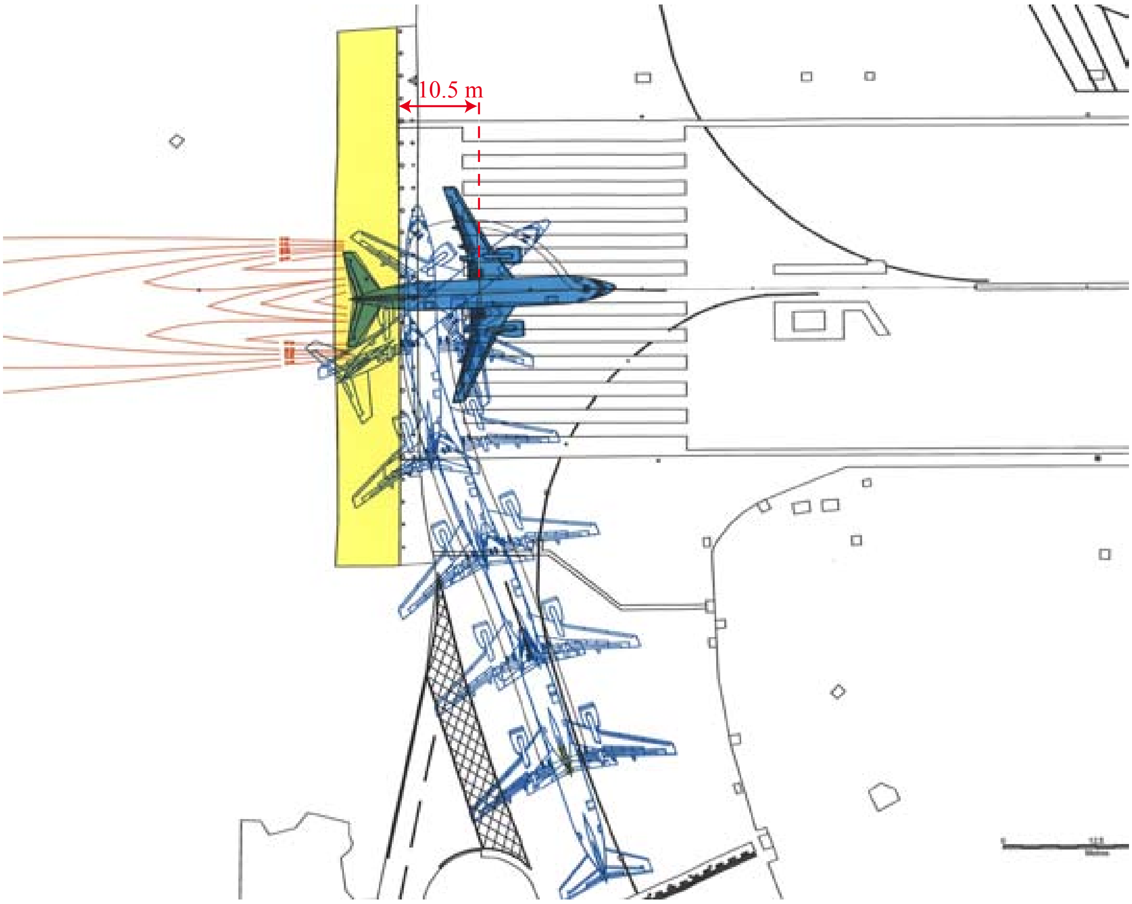

Figure 4

Predicted line-up path for a 737-400 trying to maximize takeoff distance available without running over the blast pad (blast pad shown in yellow)

Flight recorders

The aircraft was fitted with a Flight Data Recorder (FDR) that recorded a range of flight parameters and a Cockpit Voice Recorder (CVR) which recorded 30 minutes of crew speech and area microphone inputs. Both the FDR and CVR were downloaded at the AAIB where 25 hours of data from the FDR, including the accident at Aberdeen and subsequent flight to Gatwick, were recovered. Audio recordings from the CVR for the accident at Aberdeen were overwritten with more recent information.

A time-history plot of the relevant parameters during the accident at Aberdeen is given at Figure 6. The data presented at Figure 6 starts just before G-DOCT came to a halt at holding point W5 for Runway 16, where the aircraft remained for eight seconds with brakes applied.

As the brakes were released, the aircraft began moving, turning through 40º to the right over a period of 40 seconds (at a maximum turn rate of 2º/second), on to a heading of 075º(M). The ground speed peaked at eight knots during this turn. The aircraft remained on this heading for five seconds before turning to the right through a further 85º, over 16 seconds, onto the runway heading of 160º(M). Left-engine thrust, up to 40% N_1, was applied during the turn and the aircraft's turn rate reached a maximum of 8.6º/sec while the ground speed peaked at two knots. Once on the runway heading, the brakes were applied and the aircraft came to a stop.

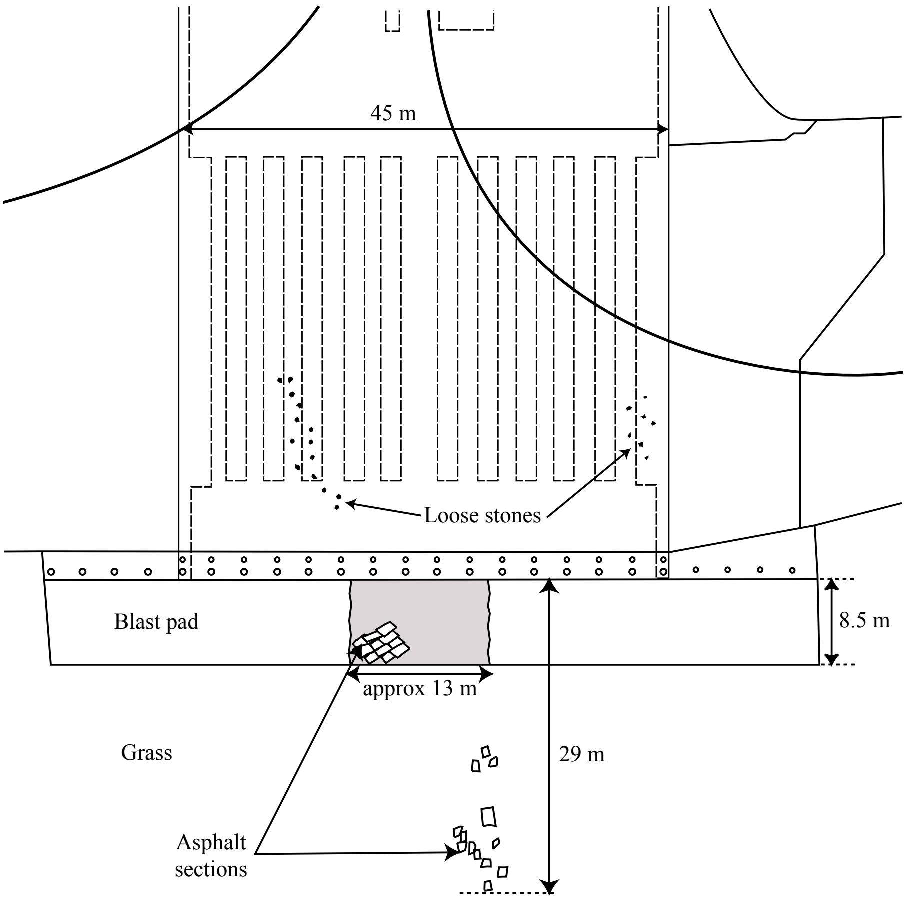

Figure 5

Blast pad debris following accident to G-DOCT.
Grey area denotes delaminated portion of blast pad

The aircraft remained lined up on the runway with brakes applied for one minute. After 38 seconds (ie 22 seconds before brake release), the thrust on both engines started to increase from 25% N_1 to 45% on the left engine, and to 49% on the right engine, where they remained for three seconds. The thrust then continued to increase, at a slightly faster rate, reaching 95% N_1 five seconds before the brakes were released. The thrust remained at 95% N_1 for about two seconds before again increasing, reaching 100% N_1 two seconds before brake release. From brake release, it took a further two seconds for the brake pressure to drop to zero by which time the aircraft was already moving forward and accelerating through seven knots.

During the flight to Gatwick no anomalies in the flight data were found to indicate an asymmetric flight configuration that might have been a result of damage to the aircraft.

Aberdeen Airport

Aberdeen Airport has three short runways for helicopter use and one main long runway for fixed-wing aircraft. The main Runway 16/34 has a declared Takeoff Run Available (TORA) of 1,829 m in both directions and a declared Accelerate Stop Distance Available (ASDA), also of 1,829 m, in both directions. The largest aircraft that operate out of Aberdeen are Boeing 767 aircraft.

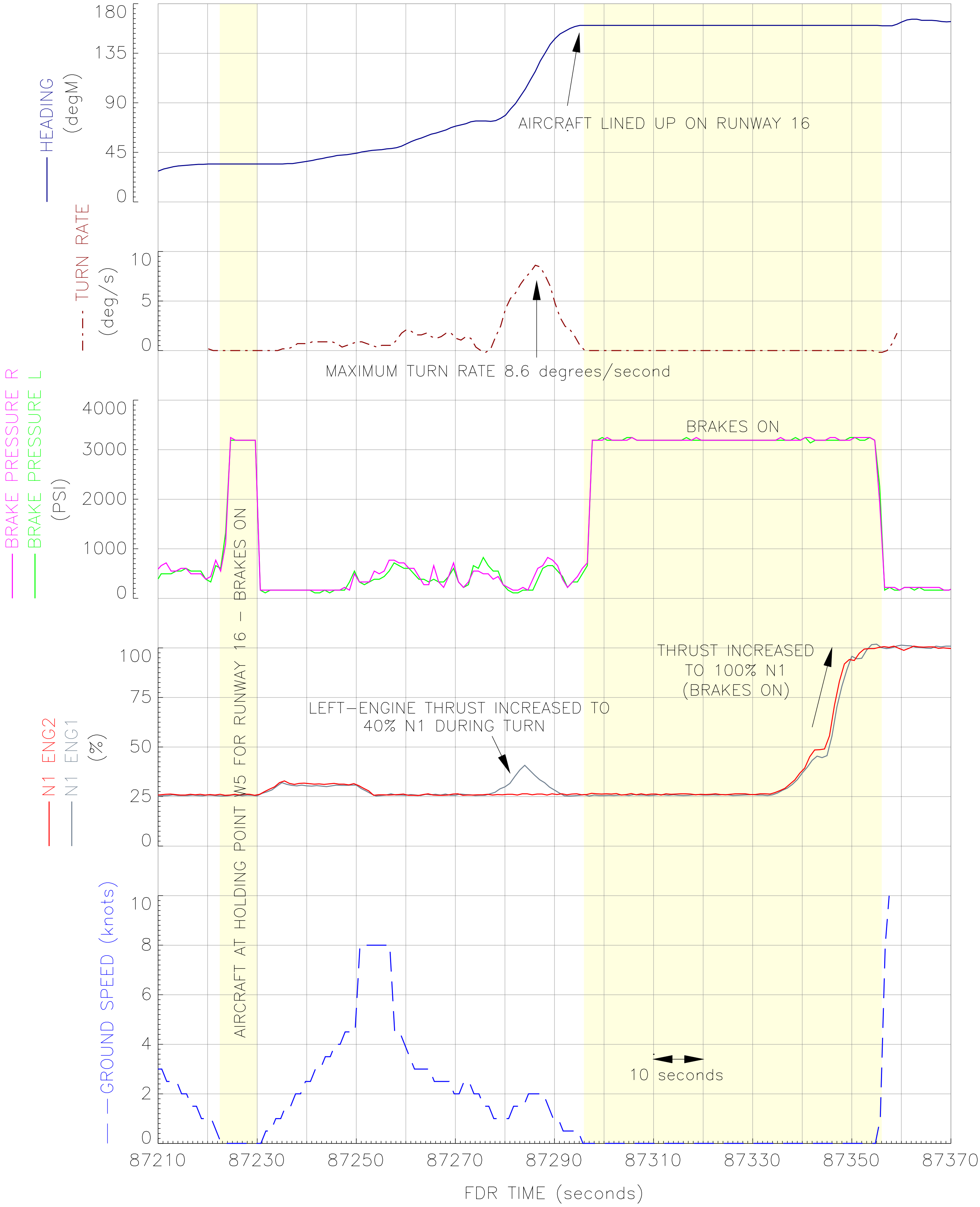

Figure 6

Salient FDR parameters

Blast pad history and construction

Runway 16/34 at Aberdeen Airport was originally constructed in 1952 to its current length without blast pads at the runway ends. The runway has since been re-surfaced many times. The airport authority did not have records detailing when the blast pads at both runway ends were constructed nor did they have records detailing the specification of the blast pads. No blast pads were shown in drawings of the runway created in 1986. The first time the blast pads were noted in documentation was following a survey carried out in January 1996. The airport authority believes the blast pads were probably constructed during the early 1990s to prevent erosion from the existing areas of grass at the runway ends. The central section of the blast pad, approximately 30 m wide, had been re-surfaced some time after the blast pad's original construction. On 31 March 1992 a BAe 146 aircraft (G-UKHP)[2] over-ran the end of Runway 34 (ie went into the grass off the Runway 16 end) and airport staff believe that the central section of the blast pad may have been repaired after that occurrence.

Following the accident to G-DOCT it was determined that the damaged blast pad surface probably consisted of Hot Rolled Asphalt (HRA) laid on a Type 1 Sub base (a mix of stone material which aids load distribution). The sections of damaged asphalt had varying thicknesses of between 4.5 cm and 6.5 cm. The depth of the asphalt where the blast pad joined the runway surface was measured at 6.5 cm. It was not possible to determine if there were any defects in the construction of the central section of the blast pad but the airport authority believed that it was possible that this repair was not up to the same standard as the surrounding blast pad. In any case, the blast pad was not designed to take the weight of the large airliners operating out of Aberdeen Airport, and although it was behind the runway threshold lights it was not marked as being unusable.

Design standards for blast pad construction

The CAA's design guidelines for runways are laid out in Civil Air Publication (CAP) 168 *Licensing of Aerodromes* but, this publication does not contain any guidelines or references to blast pads or erosion strips. It includes requirements regarding stopways which can serve as blast pads but stopways are different from blast pads in that they form part of the runway's ASDA and can be used for performance calculations. Stopways are therefore required to accommodate the occasional passage of the heaviest aircraft in the event of an aborted takeoff.

The international requirements and guidelines for runways are set out in the International Civil Aviation Organisation (ICAO) document '*Annex 14*'. This document does not include any references to blast pads or erosion strips. However, ICAO also publishes an *Aerodrome Design Manual* which states:

> *'The thickness of runway shoulders, taxiway shoulders and blast pads should be able to accommodate an occasional passage of the critical aircraft for runway pavement design, and the critical axle load of emergency or maintenance vehicles which may pass over the area.'*

It further recommends that for aircraft such as the Boeing 707, or smaller, the minimum surface thickness of the asphalt on blast pads should be 7.5 cm. For aircraft such as the Boeing 747, a 10 cm layer should be used. The manual also recommends that blast pads should be as wide as the runway plus shoulders and should be at least 60 m long. It cautions that:

Footnote

2 This occurrence was reported in AAIB Formal Report 4/93 but it was not possible to determine from the report whether the blast pad had been in place.

> *'high-energy jet exhaust from turbine-engined aircraft, at 10.5 m behind the exhaust nozzle of an engine operating at maximum thrust, can raise boulders 0.6 m in diameter completely off the ground.'*

The US Federal Aviation Administration (FAA) published an Advisory Circular on Airport Design (AC 150/5300-13) which stated that:

> *'blast pad pavement needs to support the occasional passage of the most demanding airplane'.*

It also stated that the minimum asphalt surface thickness should be 7.6 cm for blast pads designed to handle aircraft in Design Groups III and IV. The Design Groups are based on wing span and the 737-400 is a Group III aircraft.

The airports authority responsible for Aberdeen Airport had its own guidelines for runway design published in their *Airside Planning Standards* document. It stated that:

> *'For runways used extensively by jet aircraft, runway end blast pads shall be provided as an anti-erosion measure… A minimum length of 30 m shall be provided'.*

Furthermore, the document stated the following regarding runway end blast pads:

> *'For its primary anti-erosion purpose there are no particular strength requirements, only that the surface be sealed to prevent flying debris. However, for practical purposes it needs to be able to support the passage of airport vehicles, including snow clearing and rescue and fire fighting vehicles.'*

Temporary blast pad repair

Following the accident to G-DOCT the remaining asphalt from the central section of the blast pad was dug up and the sub base was compacted. Then a 4.5 cm to 6.5 cm thick layer of stone mastic asphalt (SMA) was laid down to serve as a temporary repair. This repair was completed at 0130 hrs on 9 July 2005, the day after the accident. Between 15 and 16 July 2005 yellow diagonal line markings were painted on the surfaces of both the Runway 16 end blast pad and the Runway 34 end blast pad to warn pilots that the surfaces were not suitable for taxiing.

Permanent blast pad repair

Some time after the accident the decision was taken by the airport authority, in consultation with the CAA, to remove completely both the Runway 16 end blast pad and the Runway 34 end blast pad, and replace each with a new thicker surface that could accommodate the occasional passage of a Boeing 767. The new blast pads consisted of four layers. The bottom layer was a thin geotextile material. Above this was a 35 cm thick Granular Sub Base (GSB) Type 1 stone material. The next layer was a 5 cm thick section of Heavy Duty McAdam (HDM) and the top layer was a 5 cm thick section of SMA. The total asphalt thickness was therefore 10 cm. To reduce further the possibility of jet blast penetrating beneath the blast pad the final surface was finished at a level 2.5 cm below the runway level. However, this 2.5 cm vertical step caused problems when the runway edge surface began to break off as a result of airport vehicle traffic. Subsequently a small asphalt filler ramp was added to protect the vertical surface.

Following the new blast pad construction a new paint marking scheme was applied to alert pilots that the surface was not part of the runway. The paint marks consisted of diagonal yellow lines, joining at the centre to form small chevrons as depicted in Figure 7.

Taxiway and runway markings

ICAO Annex 14 Chapter 5 refers to taxiway and runway markings. Civil Aviation Authority document CAP 637, '*A compendium of Visual Aids intended for the guidance of Pilots and Personnel engaged in the handling of aircraft*', is derived from this document.

The centreline of Taxiway W was marked as a single continuous yellow line. This line continued beyond the end of the taxiway, curving in the direction of takeoff on Runway 16 to meet the nearside of the centreline marking. This line is variously described colloquially as the 'lead on' or 'lead off' line depending on whether an aircraft is entering or vacating a runway.

CAP 637, Section 2.1.2 states:

> *'Taxiway centrelines are located so as to provide safe clearance between the largest aircraft that the taxiway is designed to accommodate and fixed objects such as buildings, aircraft stands etc., provided that the pilot of the taxiing aircraft keeps the **'Cockpit'** of the aircraft on the centreline and that aircraft on stand are properly parked.'*

Note 1 of the same section states the following:

> *'At runway/taxiway intersections, where the taxiway centreline is curved onto the nearside of the runway centreline pilots should take account, where appropriate, of any loss of Runway Declared Distances incurred in following the lead-on line whilst lining up for take-off.'*

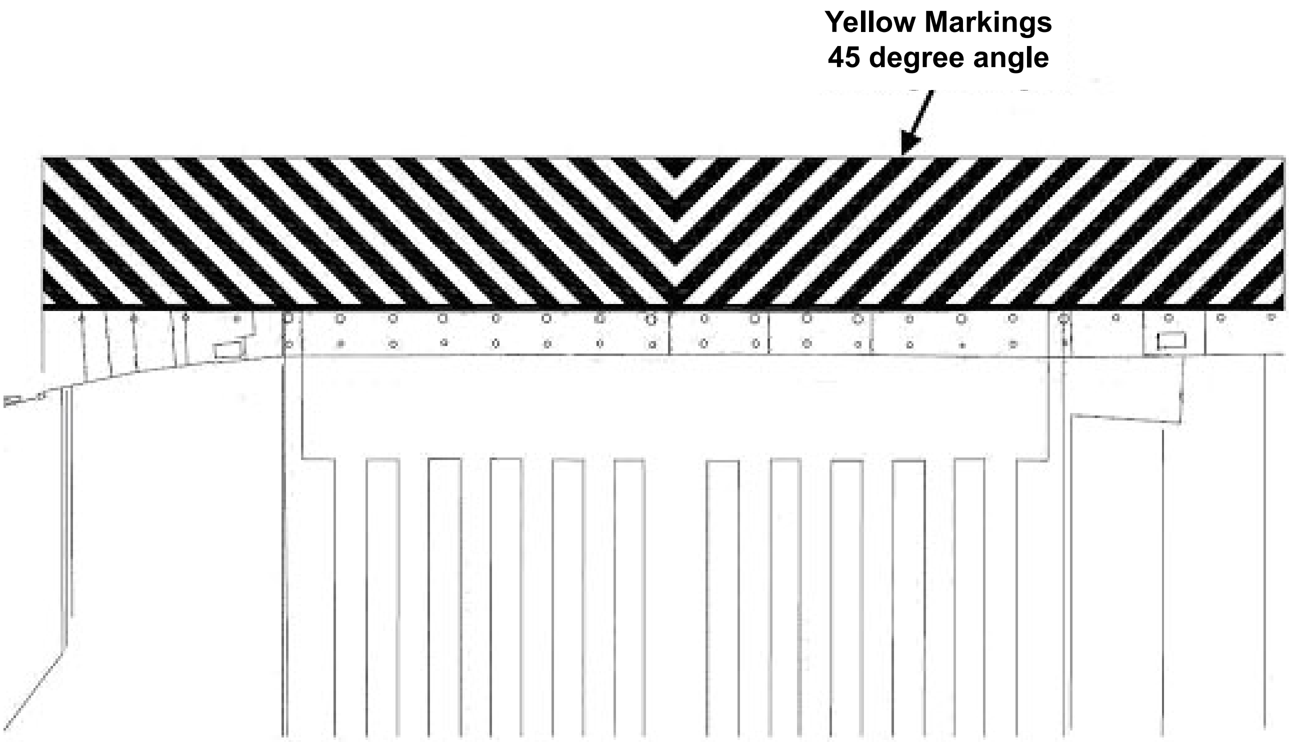

Figure 7

Paint marking scheme applied to the 'permanent repair' blast pads at both ends of Aberdeen Runway 16/34, after the accident to G-DOCT

No mention is made of any requirement for pilots actually to follow the centreline marking although it states that they are:

> *'responsible for taking all possible measures to avoid collisions with other aircraft and vehicles'.*

Section 2 of CAP 637 (Figure 8) describes runway threshold markings and, where a threshold is displaced, the bearing strength of the pre-threshold markings is indicated. The marking described for a pre-threshold area unfit for the movement of aircraft is in the shape of a white 'X'.

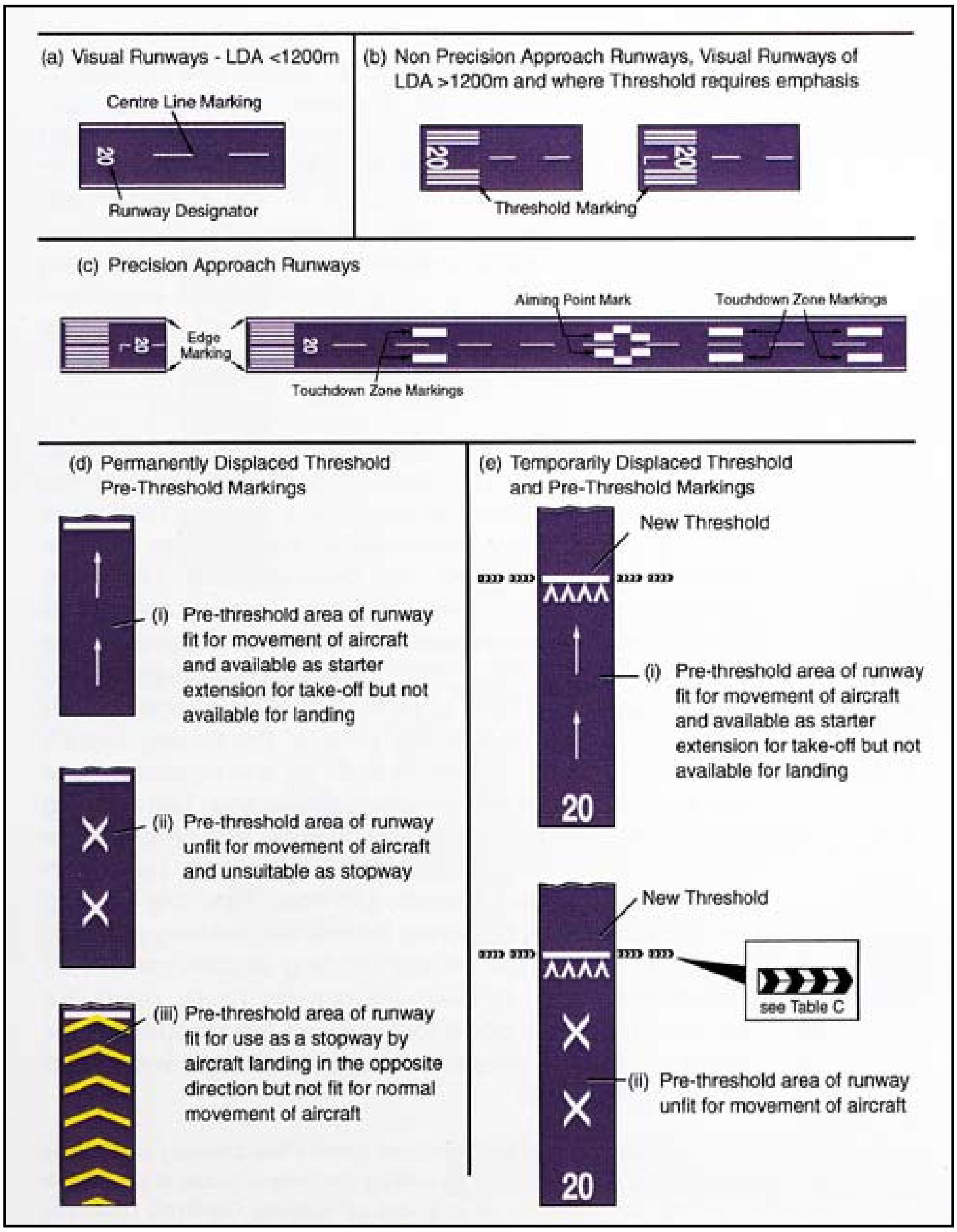

Figure 8

CAP 637 Paved runway markings

The threshold markings of Runway 16 did not extend onto the blast pad, nor was the threshold marked as being displaced. A runway threshold is normally located 6 m behind the 'piano key' markings but at Aberdeen the Runway 16 threshold is located 8.5 m behind the piano keys, behind two rows of runway lights fitted into the surface. There were no markings on the blast pad denoting its bearing strength.

Runway inspections

The Aberdeen Airport authority had a runway inspection process involving the following three levels:

- Level 1: routine daily inspections of the runway surface, carried out by airfield operations staff in vehicles
- Level 2: monthly detailed inspections of the Movement Area, carried out by airfield operations staff on foot
- Level 3: biannual detailed inspections of the Movement Area, carried out by the management team on foot (the last level 3 inspection before the accident was carried out in April 2005)

The Level 1 inspections consisted of 'Full Runway Inspections' and 'FOD[3]/Bird Runs'. During a 'Full Runway Inspection' a detailed inspection of the runway surface was carried out by one vehicle making two slow runs down the runway (once each side) or by two vehicles making a single run (each vehicle doing one side). Four of these inspections were required to be carried out each day and the last 'Full Runway Inspection' before the accident was carried out between the hours of 0300 and 0415 hrs with no anomalies noted. The 'FOD/Bird Runs' were carried out more regularly and at a higher speed in order simply to check for birds and FOD on the runway. The last 'FOD/Bird Run' was completed just two minutes before G-DOCT's departure. According to the officer who carried out this last inspection he did not see any damage to the blast pad surface or notice any damage to the overband sealing at the threshold of Runway 16.

Takeoff performance requirements

Aircraft takeoff performance requirements are calculated taking into account various limiting factors, included in which are runway measurements such as the takeoff run available (TORA), the takeoff distance available (TODA) and the accelerate-stop distance available (ASDA). Whilst the runway dimensions are fixed, allowance must be made for the distance taken by an aircraft to line up with the centreline. This distance depends on the aircraft geometry, the alignment of the access taxiway with the runway centreline and the steering angle used. As the aircraft geometry is known, manufacturers often supply alignment distances for common types of runway access, such as taxiways at 90° to the runway. Where these figures are not published they may be calculated using the method given in JAR-OPS 1 Subpart G, Section 2. This relies on any wheel passing no closer than 3.0 metres (for a B737) to the end of the runway (the 'edge safety margin').

Taxiway W at Aberdeen Airport required a turn through slightly more than 90º to line up with the centreline of Runway 16. The operator's performance calculations for the Boeing 737-400 were based on alignment distances provided by the manufacturer of 10 metres for a 90º turn onto the runway and of 18 metres for a turn on through 180º (these distances incorporate the 3 metre 'edge safety margin'). These figures relate to the distance from the edge of the threshold to the aircraft's main wheels, when the aircraft is aligned with the runway, and conformed to the JAR-OPS method of calculation.

Footnote

[3] FOD refers to foreign object debris.

Modelling used by the AAIB (Figure 4) indicated the minimum alignment distance attainable would leave the aircraft's main wheels about 10.5 metres from the threshold. To achieve this the aircraft would have to enter the runway and run its left main wheel along the edge of the threshold before turning around the right main wheel onto the runway centreline. Once lined up in this manner the aircraft's main wheels are positioned 10.5 m in from the runway threshold and the aircraft's tailplane is directly over the blast pad. The modelling further indicated that, if the aircraft had followed the 'lead on' lines onto the runway, its main wheels would have been about 66 metres from the threshold when aligned with the centreline.

The operator published information to its crews on the takeoff run available and that alignment distances are incorporated into the takeoff performance calculation. However, it did not make clear the exact point from which the aircraft is assumed to start its takeoff run.

Line-up technique

Observations of aircraft operating from Runway 16 indicated that other aircraft were also lined up using a similar technique to that described in this accident: the aircraft were taxied close to the edge of the threshold, without following the 'lead on' line, before braking the inner set of mainwheels and increasing the thrust on the outer engine to turn the aircraft in the shortest possible distance. This resulted in the outer engine passing over the blast pad with above-idle power applied. Evidence from ground marks on the temporary repair to the blast pad indicated that, on occasion, this resulted in aircraft wheels passing over the surface of the blast pad.

Jet-blast pressure study

The aircraft manufacturer publishes velocity profiles for the jet blast behind the tailplane of a 737-400. However, for this accident it was considered important to know the velocity profile and the pressure profile of the jet blast directly below the tailplane at ground level, so the engine manufacturer was contacted to carry out a study using their computational fluid dynamics (CFD) tools. The study revealed that with the engines set to 90% N_1 the jet blast velocity on the ground, aft of the engines and directly below the tailplane, would have been approximately 190 kt. The difference in velocity between the position directly below the leading edge of the tailplane and the trailing edge was minimal. At 100% N_1 the velocity at ground level was slightly lower than at 90% N_1, due to the jet exhaust's slightly narrower profile. The jet-blast pressure study also revealed that the static pressure of the air within the jet exhaust directly below the tailplane at ground level was equal to the ambient static pressure. Thus, the jet blast was not generating suction above the ground.

A further study was then conducted to examine the suction effects from the engine inlet. As G-DOCT made its tight final right turn, to line up with the runway, its left engine was spooled up to 40% N_1 and the path of the left engine probably passed over the blast pad surface. The study was therefore carried out at 40% N_1. The results indicated that in 'nil wind' conditions the static pressure on the ground, in front of the engine inlet, was equal to ambient pressure. However, when a 5 kt cross-wind was introduced into the model, a vortex was generated in front of the engine inlet which applied a suction force of 0.2 psi to the ground. The cross-wind induced flow asymmetry and this triggered the vortex formation. Figure 9 shows the vortex and the pressure contours for a power setting of 40% N_1.

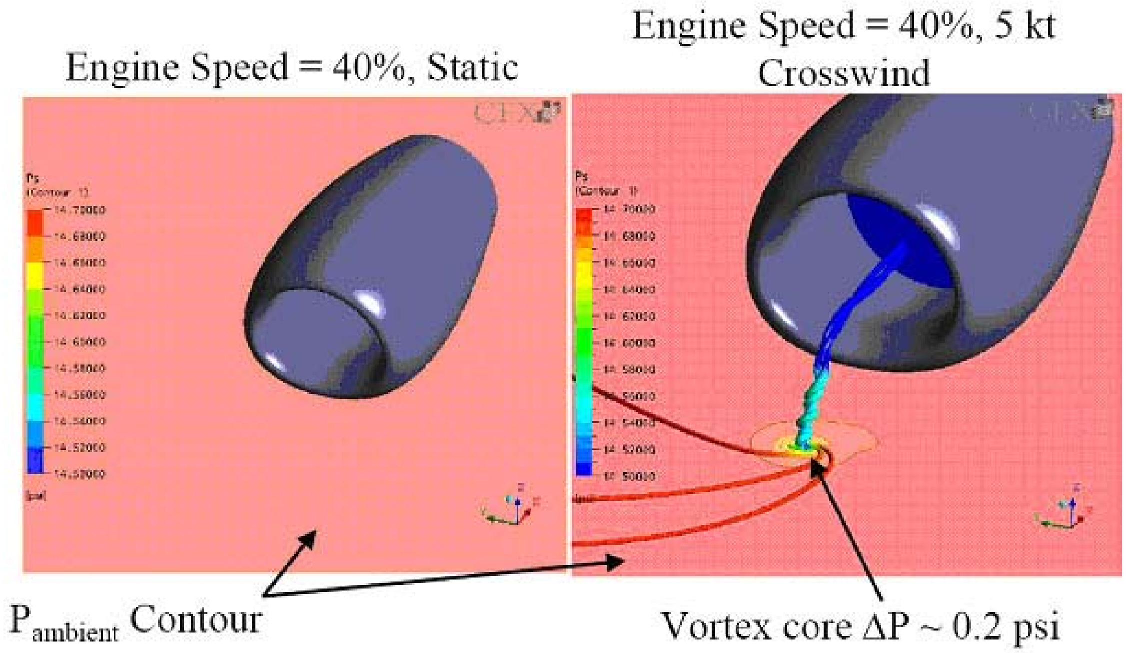

Figure 9

Results from the engine manufacturer's engine inlet study which revealed a 0.2 psi suction force at ground level with a power setting of 40% N_1 and a 5 kt cross-wind

The wind at the time of the accident was 7 kt from 140°(M). Therefore, as the aircraft began its final 85° turn to the right to line up on Runway 16, the aircraft would have been exposed to a cross-wind of approximately 6 kt.

The density of the asphalt from the blast pad was 2,100 kg/m³ (or 0.0759 lb/in³). A section of this asphalt, 6 cm thick, would have a weight per surface area of 126 kg/m² (or 0.18 psi). Therefore, if any adhesive force between the asphalt and the sub base is ignored, this simple calculation suggests that a suction force of 0.2 psi might be sufficient to start to lift a layer of asphalt 6 cm thick.

Normal takeoff technique

The operator's Operations Manual and Training Manual describe the same normal takeoff technique. This requires releasing the brakes before setting approximately 40% N_1, allowing the engines to stabilise at that power setting momentarily and then pressing the TO/GA switch. Pressing this switch when the autothrust is engaged automatically sets the remainder of the takeoff thrust. Should the autothrust be disengaged, the increase in thrust to takeoff power is achieved by manually setting the thrust levers.

In addition the Operations Manual states:

> *'02-NP-40-6*
> *The rolling take off procedure is recommended for setting takeoff thrust. This expedites takeoff and reduces risk of foreign object damage.'*

No other takeoff technique is described in either the Operations or Training Manual. The commander stated, however, that during his 'in-house' type conversion training on the Boeing 737 he had been taught that on limiting runways the correct technique was to hold the aircraft on the brakes whilst setting takeoff power, in order to ensure maximum takeoff performance was achieved. When asked, the commander described a limiting runway as a runway where, due to its length, the aircraft's maximum achievable takeoff weight was below its normal certified maximum and that the aircraft was at, or close to, this reduced maximum weight.

The commander had previously flown the Boeing 757/767 and Boeing 747-100/200 as a co-pilot with the same company and had seen this technique used on both fleets, although he could not recall it being included as part of the training on these types.

The Boeing Flight Crew Training Manual expands on the guidance offered in the operator's own manuals as follows:

'High thrust settings from jet engine blast over unpaved surfaces or thin asphalt pavement can cause structural blast damage from dislodged asphalt pieces and other foreign objects. Ensure run ups and take-offs are only conducted over well maintained paved surfaces and runways.

A rolling take-off procedure is recommended for setting take-off thrust. It expedites take-off and reduces the risk of foreign object damage. Flight test and analysis prove that the change in take-off roll distance due to the rolling take-off procedure is negligible when compared to a standing take-off.

Brakes are not normally held with thrust above idle unless a static run-up is required in icing conditions. A standing take-off procedure may be accomplished by holding the brakes until the engines are stabilised, then release the brakes and promptly advance the thrust levers to take-off thrust (autothrottle TO/GA).'

Previous accidents involving jet-blast damage to runway surfaces and aircraft

A review of the CAA's Mandatory Occurrence Report (MOR) database revealed records of nine previous accidents involving jet airliners that had been damaged by blown sections of runway or taxiway, dating back to 1986. A review of the ICAO's accident database revealed an additional six accidents involving jet airliners that had been damaged by blown sections of runway or taxiway, dating back to 2001. Out of the 15 accidents, 11 occurred during the takeoff phase and at least eight involved aircraft becoming airborne after the damage had occurred. Most of the damage in these accidents was to the tailplane, elevator and flaps. Three of the aircraft that became airborne suffered from vibration or a control problem, as follows:

On *8 April 1988* a Boeing 737 on approach to Berlin airport experienced an immediate right roll when the first level of flap was selected at 2,300 ft. Control was maintained with 2º left rudder trim and a normal landing was carried out. The investigation revealed that the right inboard flap mechanism clutch had disengaged and a lump of tar was found jammed between the aft and mid flap surfaces. No further information could be found on the source of the tar.

On *7 February 1991* an Airbus A320 in France experienced vibration at 237 kt and 4,000 ft during the climb so the aircraft returned to land. The investigation revealed that large sections of asphalt had been thrown up by the jet blast and struck the tailplane and elevators. Part of the right tailplane and parts of the right and left elevators were missing.

On *10 September 2002* a Boeing 737 departing Warsaw experienced a slight left roll after liftoff. Right rudder trim was used to maintain wings level. After landing it was found that sections of asphalt had struck the left tailplane causing damage to its leading edge and three dents on its underside.

Very little information is available about what caused the asphalt surfaces to delaminate in these accidents because no formal investigation by an accident investigation body was undertaken. The AAIB investigated an accident to a Boeing 737 that occurred at Luton Airport on 22 September 1992 (AAIB Bulletin 12/92) where paving blocks from the turnpad area were blown up by the 737's jet blast, causing damage to its tailplane (see Figure 10). The paving blocks had not been bonded to the sand bedding beneath and the paved area was not marked. The aircraft departed normally and the damage was only revealed during a turnaround inspection.

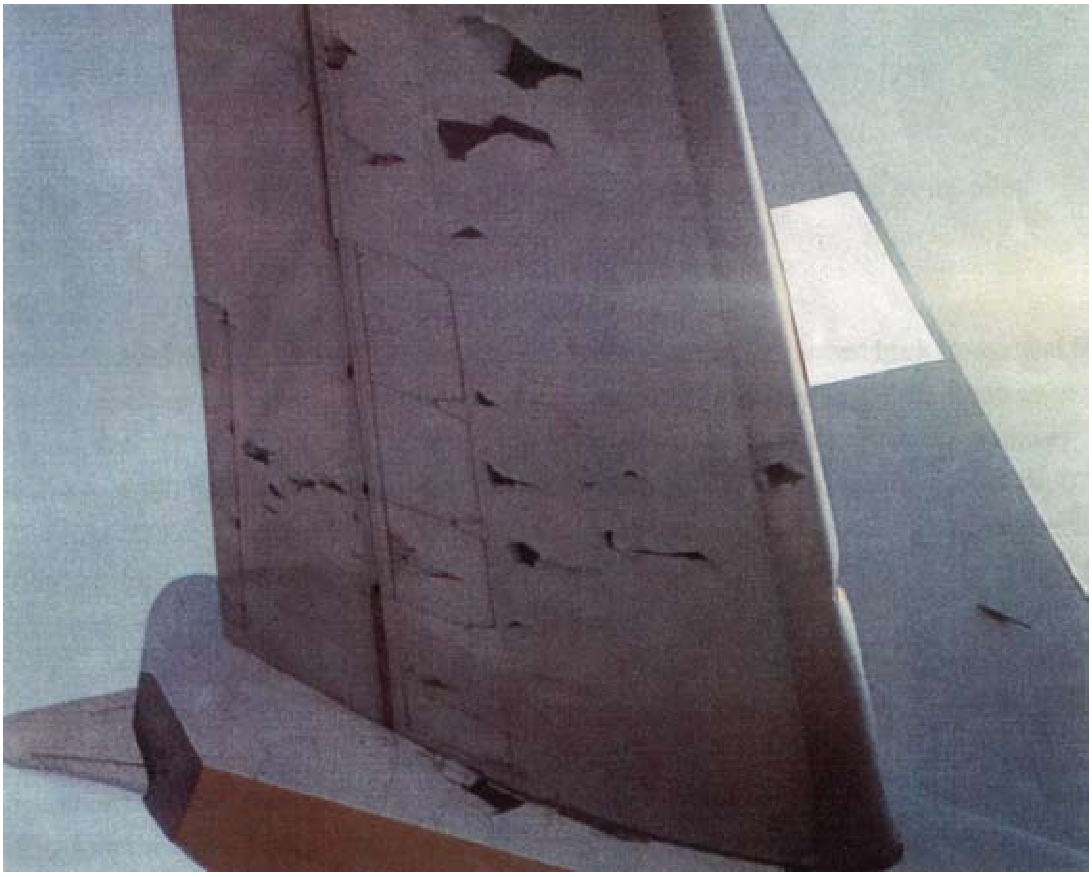

Figure 10

Damage to right tailplane underside of Boeing 737, G-MONM, at Luton Airport on 22 September 1992, following strikes by paving blocks from the turnpad area

The Italian air safety agency, ANSV[4], published a report on an accident very similar to that of G-DOCT, which involved an Airbus A320 at Treviso S. Angelo airport in Italy on 6 August 2002. After backtracking along Runway 07/25 the aircraft turned to line up for a takeoff from Runway 07. When takeoff power was applied the commander felt a jolt and noticed a blue hydraulic system loss so he aborted the takeoff run. Sections of asphalt from the stopway aft of the 07 threshold had been blown up by the jet blast and struck the aircraft's tailplane – the damage is shown in Figure 11. The stopway had been painted with a white arrow rather than with yellow chevrons and the ANSV report questioned the surface's ability to meet the structural requirements of a stopway.

Footnote

4 Agenzia Nazionale Per La Sicurezza Del Volo.

Figure 11

Damage to left tailplane leading edge of Airbus A320
at Treviso S. Angelo airport in Italy on 6 August 2002,
following a strike by a large section of asphalt from the stopway

Analysis

Aircraft damage and potential consequences

The damage to G-DOCT's left tailplane and left elevator was caused by one or more strikes from large sections of asphalt that had been lifted from the blast pad by the force of the aircraft's jet blast. The largest section of dislodged asphalt found was approximately 1.8 m by 1.5 m, but the 2.4 m dent on the underside of the tailplane indicated that it had been struck by a larger section which had then split. The flight crew of the following aircraft, who had observed the lifting of the asphalt sections, estimated the largest to be 2 m by 3 m, and such a section, 6 cm thick, would have weighed approximately 756 kg. It was not possible to determine accurately where the tailplane was located relative to the blast pad at the time of the strikes, but it would have been positioned approximately where it is depicted in Figure 4.

The damage to the tailplane would have had minimal aerodynamic effect, but the elevator was missing a section almost 1 metre long and this would have reduced the elevator's effectiveness. In the event, the flight crew did not have any difficulty rotating the aircraft to takeoff attitude and did not report any control difficulties during the flight. However, further elevator surface loss could have prevented rotation and resulted in an aborted takeoff beyond V_1[5] speed and a potential runway over-run. A more severe outcome could have resulted if the elevator's structure had been compromised to the point where the aerodynamic loads in flight caused further elevator damage and possible separation. The change in the elevator's aerodynamic and mass properties could also have made the elevator more susceptible to flutter.

The review of previous accidents and incidents involving jet airliners damaged by blown sections of asphalt revealed instances of in-flight control problems and vibrations. The lifting of paved runway surfaces and surrounding areas as a result of jet blast therefore presents a clear hazard to the safety of flight.

Cause of the blast pad break-up

The jet-blast pressure study revealed that the aircraft's jet blast, even at takeoff power, would not have generated any suction at ground level below the tailplane. However, if the jet blast had been able to penetrate between the asphalt surface and the Type 1 Sub base, the dynamic pressure of the jet blast, at a speed of approximately 190 kt, would have been capable of peeling the surface away. In the case of G-DOCT it appears that such penetration and peeling by the jet blast occurred. Once the asphalt started to peel away, the exposed surface would have deflected the jet blast around it and created sufficient lift for the detached asphalt to rise 14 ft and strike the tailplane.

The important question, therefore, is what enabled the jet blast to penetrate between the asphalt surface and the sub base. A bitumen overband sealing was laid along the length of the joint between the blast pad surface and the runway surface and this sealing is designed to create a flush surface, without cracks, between the runway and blast pad. A deterioration of this seal would have made it easier for the jet blast to penetrate. However, no deterioration of the overband sealing was noted during the runway inspections that were carried out on the morning of the accident and just prior to the aircraft's departure.

It is possible that, while the flight crew were trying to position the aircraft, the left main gear wheels passed over the blast pad surface and caused some surface

Footnote

[5] V_1 is the decision speed below which a takeoff can be safely aborted with sufficient runway remaining to stop. The rotation speed (V_R) is always greater than or equal to V_1.

damage because the pad was not designed to withstand the taxiing loads of aircraft. From the modelling shown in Figure 4 it was determined that the left gear would have passed very close to, and possibly directly over, the blast pad in order to place the tailplane in a position to be struck by blown sections of the pad. On this occasion, both the flight crew of G-DOCT and that of the following aircraft stated that no wheel passed over the blast pad. It is probable, however, that in the past other aircraft had taxied over the blast pad surface because aircraft had been observed manoeuvring close to the runway end and an aircraft tyre mark was seen on the re-surfaced blast pad. The cumulative effect of these occasional aircraft taxiing loads could have weakened the blast pad surface.

Another possible cause of blast pad damage is as a result of suction from the engine inlet. While manoeuvring to position a Boeing 737 close to the end of the runway, the engine inlet from one of the engines may pass over the blast pad even without the main gear passing over it. There is no prohibition against allowing an engine to pass over a non-load-bearing surface. The pressure study carried out by the engine manufacturer revealed that, in conditions of light cross-wind, a vortex can form forward of the engine inlet. In the case of G-DOCT, with 40% N_1 power set on the left engine and a cross-wind of approximately 6 kt, a suction force of approximately 0.2 psi would have been applied at ground level. Based on the density of the asphalt surface, this suction force might have been sufficient to start to lift the asphalt surface and cause blistering or cracks. However, this would have been dependent upon the strength of the bond between the asphalt surface and the sub base and the adhesive strength between the asphalt surface and the surrounding material. The results are not conclusive but suggest that further research should be carried out to examine the effects of engine inlet suction on paved surfaces.

The damaged blast pad surface was quickly dug up after the accident and resurfaced overnight. It was, therefore, not possible to determine the strength of the bond between the asphalt surface and the sub base. However, the lack of residual bitumen residue on the stone sub base indicated that the bond may have been inadequate and contributed to the jet blast's ability to peel the surface away. The asphalt's surface thickness, of between 4.5 and 6.5 cm, was significantly less than the 7.5 cm recommended by ICAO's *Aerodrome Design Manual* and the 7.6 cm recommended by the FAA's Advisory Circular. If the asphalt surface had been thicker it would have been more difficult for the jet blast to penetrate beneath it. Neither the CAA nor the airport authority had published any guidelines on the surface thickness of paved blast pads.

In order to prevent future recurrences of these types of accidents, blast pads need to be designed so that they are of sufficient strength, sufficient thickness and have adequate bonding and sealing to ensure that they cannot be damaged or uplifted by the engine inlet suction or engine jet blast of the most critical aircraft. Furthermore, since aircraft are permitted to use the full length of the runway, right to the edge of a blast pad, it must be expected that occasionally an aircraft will accidentally taxi over a blast pad. Therefore, blast pads should also be designed to accommodate the occasional passage of the most critical aircraft.

In light of these findings, the AAIB recommends that:

Safety Recommendation 2007-023

The International Civil Aviation Organisation (ICAO) should consider amending Annex 14 to include requirements for paved blast pads that will ensure that they cannot be damaged by the engine inlet suction, the engine jet blast or the taxiing loads of the most critical aircraft.

Safety Recommendation 2007-024

The International Civil Aviation Organisation (ICAO) should review the requirements of Annex 14 to ensure that runway surfaces, stopways and other adjacent areas susceptible to high-power jet blast cannot be damaged by the engine inlet suction or the engine jet blast of the most critical aircraft.

Safety Recommendation 2007-025

The Civil Aviation Authority (CAA) should consider amending Civil Air Publication (CAP) 168 to include design requirements for paved blast pads that will ensure that they cannot be damaged by the engine inlet suction, the engine jet blast or the taxiing loads of the most critical aircraft.

Safety Recommendation 2007-026

The Civil Aviation Authority (CAA) should ensure that paved blast pad surfaces, stopways and turnpads at all licensed UK airports are constructed such that they cannot be damaged by the engine inlet suction, the engine jet blast or the taxiing loads of the most critical aircraft.

Blast pad markings

At the time of the accident there were no markings on the blast pads at either end of the runway. The only delineation between the runway surface and the blast pad surface was the strip of runway threshold and runway end lights. By international convention, in the absence of a line across the runway denoting a displaced threshold, the known load-carrying extent of the runway would have extended back 6.5 metres from the 'piano key' markings. Performance calculations are based on the aircraft wheels not passing closer than 4.5 metres to the end of the runway surface. Therefore, a pilot should aim to keep the aircraft wheels close to the edge of the 'piano key' markings irrespective of the extent of any surface beyond it. The short extent of the blast pad, together with an absence of any markings, meant that it may not have been apparent to all flight crew that the surface did not form part of the runway and was not designed to withstand taxiing loads.

Following the accident, a temporary asphalt surface was laid down and a row of parallel yellow diagonal lines was painted on it. These markings did not conform to any national or international standard. After the permanent repair was installed, a different paint scheme was developed by the airport authority in consultation with the CAA. This new paint scheme, consisting of yellow diagonal lines and mini chevrons (see Figure 7), shared a degree of similarity with the internationally standardised marking for a stopway (yellow chevrons). However, a stopway is designed to be used as an overrun area in the event of an aborted takeoff and is therefore strong enough to cater for the taxiing loads of the most critical aircraft. Blast pads should be similarly designed but if they are not as strong as stopways then a different marking scheme should be used to avoid confusion. The AAIB therefore recommends that:

Safety Recommendation 2007-027

The International Civil Aviation Organisation (ICAO) should establish standardised markings for paved blast pads and amend Annex 14 accordingly.

Safety Recommendation 2007-028

The Civil Aviation Authority (CAA) should, in consultation with the International Civil Aviation Organisation (ICAO), establish standardised markings for paved blast pads and amend Civil Air Publications (CAPs) 168 and 637 accordingly.

BAA and CAA safety action

As a result of this accident the airport operator, BAA, installed a new blast pad at both ends of the runway at Aberdeen Airport. The new blast pads are 10 cm thick and are designed to accommodate the occasional passage of a Boeing 767 (the most critical aircraft). This safety action should prevent a recurrence at Aberdeen. BAA also determined that no action needed to be taken at their other airports because similar issues did not exist.

The CAA Aerodrome Standards Department took some safety action shortly after the accident by publishing information about the accident in its *Reference Point* leaflet (Issue 8 – August 2005). The publication stated that all Licensees should ensure that all hard surfaces are in good condition and should determine where surfaces are not capable of bearing the weight of the largest aircraft. The leaflet states:

> *'If it cannot* [bear the weight of the largest aircraft]*, or if there is any doubt, a suitable marking should be placed on the surface to warn crews of this possibility.'*

It also stated that if Licensees decided to replace blast pads they should take into account the recommended design thickness in ICAO's *Aerodrome Design Manual.* The CAA also tasked all CAA aerodrome inspectors to establish the integrity of all known blast pads at UK airports.

In 2006 the CAA carried out a more detailed survey of blast pads, turn pads and other similar surfaces. It has identified eight UK airports at which closer attention is going to be paid and potential redesigns considered.

Commander's actions

It is apparent that the commander believed, in the absence of any information to the contrary, that the performance restrictions imposed on the aircraft's takeoff were due to runway length. In the event, the restriction was actually due to obstacle clearance requirements during the climb out. Regardless of the cause of the performance limitation, any restrictions are reflected in the maximum weight allowed for takeoff. Therefore, as long as the aircraft remains at or below this weight, there is no requirement to alter the takeoff technique in order to achieve a safe departure.

The commander employed a technique which did not comply with the standard technique laid down in either the manufacturer's or the operator's manuals. Whilst there was nothing in the operator's manuals specifically prohibiting the technique, the manufacturer had published warnings advising against it. These warnings were, however, not readily accessible to the operator's line pilots. Having witnessed others employing the same or similar technique within the company, and having been trained to do so on his type conversion course, it appeared to the commander a legitimate procedure to use on this occasion. It ensured, in his mind, an adequate margin over the performance limitations imposed, he believed, by the length of the runway.

In addition to holding the aircraft on the brakes whilst setting the calculated takeoff power the commander also continued to increase the power above this level until the maximum power available was set. The aircraft remained stationary with high power set whilst this was achieved for some five seconds and it is possible that this contributed to the surface of the blast pad breaking up. It is also possible that, had the commander carried out a rolling takeoff, the tail would have been clear of the affected area of blast pad before sufficient power had been achieved to lift the surface.

As a result of this accident, the operator's 737 Fleet Management issued a Fleet Technical News entitled '*Rolling Take-off Procedure*', outlining the recommended takeoff procedures from the Boeing Flight Crew Training Manual. The commander stated that the takeoff technique he had used on G-DOCT was the same technique he had used on other fleets within the same company: this suggests that the issue would benefit from wider promulgation than the Boeing 737 fleet alone. The AAIB therefore recommends that:

Safety Recommendation 2007-029

British Airways should review the training of takeoff techniques across all fleets to ensure that it is consistent with the operator's intended procedures.

Safety Recommendation 2007-030

British Airways should incorporate information on appropriate takeoff techniques in relevant flight crew documentation for all fleets.

Aircraft performance

The performance figures were correctly calculated for the aircraft, runway and ambient conditions at the time of takeoff. The performance figures relied, however, upon the aircraft lining up 10 metres from the runway threshold in order to be valid. This was slightly less than the minimum line-up allowance in the computer modelling used by the AAIB and 56 metres less than the line-up allowance had the commander chosen to follow the line linking the taxiway centre line to the runway centre line. On this occasion, in order to maximise performance, the crew had ignored the taxi guidance provided. This potentially presents a problem when operating at night or under low visibility conditions.

In order to calculate performance data for airports used by its aircraft, an operator needs to be able to rely on known runway parameters. As these do not normally include the position of 'lead on' lines, they cannot be taken into account when defining the start of the takeoff run in calculating performance. This results in a possible conflict between maximising performance whilst ensuring aircraft safety is not compromised by ignoring runway markings designed to ensure appropriate guidance to aircraft whilst lining up. As the extent of this problem is not fully understood the AAIB makes the following recommendation:

Safety Recommendation 2007-031

The Civil Aviation Authority should review the implementation of current performance requirements for 'Performance A' aeroplanes, to ensure that they adequately reflect desired line-up techniques, in particular following ground markings provided for taxi guidance.

In order for the flight crew to be able to comply with the calculated performance requirements, they must be informed of the reference point used and be able to identify its position so that the aircraft does not commence its takeoff beyond that point. Prior to this accident the operator did not provide this information to its crews. This has now been reviewed and, as a result, additional guidance notes have been provided for use with the operator's computerised performance system on all fleets. The investigation did not extend to analysing how other operators ensure the actual takeoff point complies with that used in the performance calculations. In view of this the AAIB recommends that:

Safety Recommendation 2007-032

The Civil Aviation Authority should, during routine audits of operators of 'Performance A' aeroplanes, ensure that operators' takeoff performance calculations are consistent with the operation of their aircraft, specifically with respect to the line-up position.