AIRCRAFT ACCIDENT REPORT 2/87

Accidents Investigation Branch

Department of Transport

Report on the accident to Lockheed TriStar G-BBAI at Leeds Bradford Airport on 27 May 1985

LONDON
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Department of Transport
Accidents Investigation Branch
Royal Aircraft Establishment
Farnborough
Hants GU14 6TD

7 July 1987

The Rt Honourable Paul Channon
Secretary of State for Transport

Sir,

I have the honour to submit the report by Mr M M Charles, Inspector of Accidents on the circumstances of the accident to Lockheed TriStar G–BBAI which occurred at Leeds Bradford Airport on 27 May 1985.

I have the honour to be
Sir
Your obedient servant

D A COOPER
Chief Inspector of Accidents

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Accidents Investigation Branch

Aircraft Accident Report No. 2/87
(EW/C917)

Registered Owner:		British Airways
Operator:		British Airtours
Aircraft:	*Type:*	Lockheed TriStar–1
	Model:	L–1011–385–1
	Nationality:	British
	Registration:	G–BBAI
Place of Accident:		Leeds Bradford Airport
		Latitude: 53° 52′ 00″ N
		Longitude: 001° 39′ 10″ W
Date and Time:		27 May 1985 at 1227 hrs
		All times in this report are UTC

Synopsis

The accident was notified to the Accidents Investigation Branch at 1255 hrs on 27 May 1985 and the investigation commenced that day.

The accident occurred when the aircraft overran the end of the runway whilst landing after a rain shower. The aircraft brakes produced less than the expected retardation on the wet runway surface. The passengers were evacuated through the emergency exits and a few minor injuries were sustained. The aircraft was substantially damaged.

The report concludes that the accident was caused by the inability of the aircraft to achieve the level of braking effectiveness on which its wet runway performance is scheduled.

The main recommendations of the report are that the scheduled wet runway performance of the TriStar and the condition of the surface of runway 14 at Leeds Bradford Airport should be re-examined.

1. Factual Information

1.1 History of the flight

On the day of the accident the crew operated flight KT60Y from Gatwick to Palma, Majorca, and flight KT101 from Palma to Leeds Bradford. They took off from Gatwick at 0703 hrs and from Palma for the return flight at 1021 hrs. There were no significant technical defects on the aircraft.

The aircraft established radio contact with Leeds Bradford air traffic control (ATC) at 1216 hrs when it was 15 nautical miles (nm) south-west of the airport in descent to flight level 50. ATC advised the aircraft that the landing runway was 14, there had been a recent moderate rain shower and the runway was wet. The surface wind was reported as 190°/5 knots (kt), with 6 kilometres (km) visibility, one okta of cloud at 1000 feet and 3 oktas at 2000 feet. ATC then cleared the aircraft to descend to 3000 feet above mean sea level (amsl). The rain had temporarily ceased.

None of the flight crew had previously landed at Leeds Bradford and the commander was handling the aircraft for the landing. Although advised by ATC that his aircraft was in sight at 7 miles range from the airport, he elected to fly a radar surveillance approach with his altimeter set to the QNH*. He had previously briefed his crew that he would use 42° flap for the landing, and the co-pilot (P2) was to select nominal 90% N1 reverse thrust ** immediately after touchdown.

The aircraft approached the airport on a radar heading of 350°. When the radar controller turned the aircraft right to intercept the final approach path, he advised that this would position the aircraft on a right-hand base leg at about 8 nm from touchdown. He also at this time cleared the aircraft to descend to 2500 feet and the commander selected 10° flap. When the final turn onto the runway centreline was complete, he lowered the landing gear and disconnected the autopilot but left the autothrottle engaged to control the aircraft's speed. At 5 nm from touchdown, level at 2500 feet and 185 kt indicated airspeed (IAS), the aircraft was cleared to descend on a 3½° glidepath. At this point, the commander called for 22° flap and manually closed the throttles to assist deceleration. The flight data recorder (FDR) showed a reduction of engine power at this time from an engine pressure ratio (EPR) *** of 1.19 to 1.02 on the No 1 engine. As the speed reduced, he called for flap to be lowered to 27°, 33° and finally 42°. When he called for 33° flap, he allowed the autothrottle to resume control of the power, and the EPR on the No 1 engine increased slowly to 1.13. Flap was selected to 42° when the aircraft was 564 feet above the landing threshold at 157 kt IAS and was fully down at 466 feet above the threshold at 158 kt IAS. Power on

* QNH is the corrected mean sea level pressure at an airfield or for a specific area. When set on an aircraft altimeter it causes the altimeter to read the height of the aircraft above mean sea level.

** N1 is a measure of engine speed and thus power. 90% N1 is a higher than normal reverse thrust setting used for short runways.

*** EPR is a measure of engine power.

the No 1 engine at this point, which was 1.14 EPR, increased to 1.18 EPR when the aircraft was 200 feet above the elevation of the threshold and to 1.21 EPR at 36 feet before reducing to 1.02 EPR as the commander closed the throttles for touchdown. Throughout the approach the commander confirmed that he was on the correct glidepath from the target heights passed by the radar controller and by observation of the Precision Approach Path Indicators (PAPI's), which were showing 2 white and 2 red lights, the "on glidepath" indication.

For the last 200 feet of the approach, aware that the runway was wet, he descended into a PAPI indication of one white and three reds. At this stage the P2 called "1000 FEET PER MINUTE DESCENT". The third pilot (P3), who was occupying the flight engineer's station, called "100 FEET", "50 FEET" and "30 FEET" from the radio altimeter as the aircraft descended. All of these calls were heard on the cockpit voice recorder (CVR). The FDR recorded autothrottle disengagement at 36 feet above the runway surface. The commander stated that, on the P3's "30 FEET" call, he closed the throttles and touched down firmly after a short flare. A cinefilm of the landing taken by a witness on the roof of the airport terminal building showed the left mainwheels contacting the runway approximately 450 metres from the landing threshold, followed by the right mainwheels some 500 metres from the threshold. Because of the difficulty of determining from the film the precise points at which the wheels first touched the ground, the accuracy of these two distances can be no better than + or – 20 metres. However, a still photograph taken by another witness shows both sets of mainwheels on the runway at a point 520 metres from the threshold. From this point there were 1282 metres of runway plus a paved overrun of 137 metres remaining for the ground roll.* The cinefilm shows that the nosewheel was lowered onto the runway about 2 seconds after the right mainwheel touchdown.

Analysis of the FDR showed that the aircraft crossed the landing threshold at an IAS of 151 kt with the mainwheels between 24 and 27 feet above the runway and touched down at 144 kt IAS, that the ground spoilers deployed when the left mainwheels contacted the runway 433 metres from the threshold, and that the right mainwheels touched down 510 metres from the threshold. (The accuracy of these figures is + or – 15 metres.)

As soon as the mainwheels were on the ground the P2 selected reverse thrust as briefed. The commander later stated that he applied full braking as soon as he saw the red centreline lights approaching (see para 1.10.2); he was heard by both the other pilots to say at this time "GOSH, THE RED LIGHTS COME QUICKLY DON'T THEY." He felt no positive brake deceleration and applied all the force he could on the brake pedals. The CVR showed that the commander's comment about the red lights was made 4 seconds after right mainwheel touchdown, when the aircraft was 809 metres beyond the landing threshold with 993 metres of the landing distance available remaining plus the 137 metres of additional paved surface ie, a point 1130 metres from the runway end. At 380 metres from the runway

* Throughout this report the words "runway end" refer to the end of the paved concrete surface. The additional 15 metres of asphalt beyond the concrete are not treated as a usable part of the runway for the purposes of this report.

end, the commander said "I'VE GOT MY FEET ON THE BRAKES AS FAR AS I CAN", whereupon the P2 increased reverse thrust to maximum. The FDR showed no significant contribution to retardation from the brakes until the aircraft was 930 metres from the runway end at a groundspeed of 125 kt, some 3 seconds after the commander commented on the red lights. At this point, the braking coefficient of friction (see paragraph 1.17.3 and Appendix 1) was .015. Over the next 470 metres the braking coefficient increased steadily up to .09 approximately 460 metres from the runway end at a groundspeed of 90 kt. The rate of rise braking effectiveness then reduced markedly. It did not begin to rise normally again until the aircraft decelerated below 75 kt at a point 300 metres from the end when, in this last 300 metres, it rose from .11 to .24. The data in this paragraph is shown diagrammatically in Appendix 2.

When he saw the end of the runway approaching, the commander applied full left nosewheel steering to swing the aircraft away from the runway 32 approach light stanchions. The nosewheel of the aircraft left the end of the runway at a speed estimated from the FDR to have been 30 kt, and the aircraft came to rest on a downslope with the mainwheel bogies half buried in soft ground approximately 10 metres beyond the end of the paved surface. The nosewheel drag strut was torn from its forward trunnion mounting and the nosewheel struck the fuselage aft of the nosewheel bay.

When the aircraft came to rest, in a 14° nose-down attitude, the commander ordered the unpremeditated evacuation drill to be carried out. During the engine shut-down sequence the P2 inadvertently knocked the flap lever, causing the flaps to partially retract as the engines ran down. He later restored the flap lever to the 42° flap position. All emergency doors and escape slides functioned correctly, and all passengers were evacuated without serious injury in approximately 90 seconds.

1.2 Injuries to persons

Injuries	Crew	Passengers	Others
Fatal	–	–	–
Serious	–	–	–
Minor/None	14	398	

1.3 Damage to aircraft

The nose landing gear strut folded backwards and the wheels impacted the structure aft of the nosewheel bay. The underside of the forward fuselage and the lower freight floor in this area suffered severe damage. The undersides of the cowlings of both wing-mounted engines were flattened and both engines suffered ingestion damage.

1.4 Other damage

Deep troughs were dug by the mainwheel bogies in the graded area beyond the end of the runway and there was some damage to buried airfield lighting cables. Further minor damage was caused in the same area during the recovery of the aircraft.

1.5 Personnel information

1.5.1 Commander: Male, aged 41 years

Licence:	Airline Transport Pilot's Licence valid until 25 June 1987
Aircraft ratings:	Vanguard, Comet variants, Trident HS121, Viscount, Boeing 737, Lockheed L–1011 TriStar
Last medical examination:	17 May 1985, Class 1, no limitations, valid until 30 November 1985
Instrument rating:	13 July 1984, valid until 12 August 1985
Last company base check:	15 February 1985

Flying experience:

Total flying hours:	10,292
Total hours on type:	1,170
Hours in preceding 28 days:	64
Hours in preceding 24 hours:	4½
Rest period before duty on day of accident flight:	3 days

1.5.2 Co-pilot: Male, aged 43 years

Licence:	Airline Transport Pilot's Licence valid until 17 June 1986
Aircraft ratings:	PA28 and 32, Vanguard, Boeing 707/720, Boeing 747, Lockheed L–1011 TriStar
Last medical examination:	25 January 1985, Class 1, no limitations, valid until 31 July 1985
Instrument rating:	4 March 1985, valid until 3 April 1986
Last company base check:	5 March 1985

Flying experience:

Total flying hours:	9,370
Total hours on type:	600
Hours in preceding 28 days:	35
Hours in preceding 24 hours:	4½
Rest period before duty on day of accident flight:	19 hours

1.5.3 Third pilot: Male, aged 34 years

Licence:	Airline Transport Pilot's Licence, valid until 28 October 1991
Aircraft ratings:	Beechcraft 95, Trident HS121, Lockheed L–1011 TriStar
Last medical examination:	12 July 1984, Class 1, no limitations, valid until 31 July 1985
Instrument rating:	12 April 1985, valid until 11 May 1986
Last company base check:	24 April 1985

Flying experience:

Total flying hours:	4,000 (approx)
Total hours on type:	85
Hours in preceding 28 days:	75
Hours in preceding 24 hours:	4½
Rest period before duty on day of accident flight:	14 hours

1.6 Aircraft information

1.6.1 Leading particulars

Type:	Lockheed L–1011–385–1 TriStar
Constructor's number:	1102
Date of manufacture:	1974
Certificate of Registration:	Registered in the name of British Airways plc
Certificate of Airworthiness:	Issued on 10 February 1978 in the Transport Category (Passenger). Last renewed on 13 March 1985 and valid until 12 March 1989
Certificate of Maintenance:	Renewed on 10 May 1985, valid until 7 September 1985
Total airframe hours:	15,876
Engines (3):	Rolls–Royce RB211–22B–02
Maximum weight authorised for take-off:	195,000 kilograms (kg) (429,879 pounds) (lb)

Actual take-off weight:	176,149 kg (388,338 lb)
Maximum weight authorised for landing:	162,400 kg (358,027 lb)
Estimated landing weight:	159,929 kg (352,579 lb)
Estimated fuel remaining at time of accident:	16,630 kg (36,662 lb)
Type of fuel:	Jet A–1

(The estimated landing weight and fuel remaining at the time of the accident were calculated from the fuel tank contents gauges and fuel flow meter reading. The flight plan estimates of both figures were 750 kg (1653 lb) lower.)

Centre of gravity (CG) at time of accident:	27.3% mean aerodynamic chord (MAC). CG limits at estimated accident weight are from 16.8% MAC forward to 33.9% MAC aft
Target threshold speed at accident weight (V_{AT}/V_{ref}):	138 kt
Landing distance requirement at accident weight with 3 kt headwind:	1740 metres (5707 feet)

1.6.2 *Autothrottle system*

The autothrottle system (ATS) is part of the TriStar–1 speed control system (SCS), which, in turn, is a sub-system of the integrated avionic flight control system. When the ATS is engaged the throttles are driven by a servo-controlled electric motor to maintain a selected airspeed, a pre-computed angle of attack or a computed engine power level. In its speed modes, the autothrottle servo responds to signals from the SCS computer, which also provides signals to drive the speed deviation pointers on the pilot's and the co-pilot's attitude director indicators, whether or not the ATS is in use for speed control. The speed deviation pointers are disabled when the ATS is controlling engine power.

During normal cruising flight and initial approach the ATS may be selected to maintain either an airspeed set by the pilot on the thrust panel or the engine power commanded by the flight management system. When the flap handle is selected beyond the 30° flap position (ie, when landing flap is selected), the ATS switches to alpha mode. In the alpha mode, the ATS maintains a pre-computed angle of attack corresponding to a speed marginally above the landing threshold target speed for the current positions of the flaps and wing spoiler panels.

Maximum and minimum limit switches prevent the ATS selecting excessively high or low power, and the system is rate limited to a maximum of 8° of throttle lever movement per second. The ATS can be overridden at any time by manual operation of the throttles but resumes its function as soon as manual pressure is removed. It may be disengaged by the actuation of either of two throttle-mounted disconnect switches or by moving the engage switch on the thrust panel to "OFF". The system also incorporates failure monitoring with failure warning annunciation and automatic disconnection when failure is detected.

In the alpha mode the system is designed to control the speed to V_{ref}* plus 3 kt with the aircraft loaded to its aft CG limit. The commanded speed increases to V_{ref} plus 6 kt with a mid-position CG and to V_{ref} plus 10 kt with the CG at its forward limit. Automatic gust compensation provides for speed increases of 4 kt and 8 kt for short duration airspeed fluctuations of 6 kt and 16 kt respectively. The ATS also compensates for excessive sink rate whenever the flight path angle steepens beyond −3.5°.

1.6.3 *Direct lift control and autoground spoiler systems*

The TriStar–1 has six spoiler panels on each wing numbered 1 to 6 from inboard to outboard. Panels 2 to 6 are used for speed brakes when the flaps are retracted and, when the flaps are extended, operate in conjunction with the ailerons to assist roll control.

When the flap lever is selected beyond the 30° flap position, panels 1 to 4 move to a null position of 7° and then operate through 7° each side of this position to provide direct lift control (DLC) during the final approach. The DLC servo operates in response to control wheel or autopilot demands and gives a degree of control of vertical speed without pitch angle change.

Panels 1 to 4 also function as autoground spoilers (AGS), extending automatically on touchdown to provide aerodynamic drag and to improve wheel brake effectiveness by reducing residual wing lift.

The flight data recorder (FDR) confirmed that both DLC and AGS systems functioned normally during the approach and landing.

1.6.4 *TriStar–1 braking and anti-skid systems*

The TriStar–1 is equipped with a fully adaptive braking system designed to modulate brake pressure as necessary to maintain optimum braking during a stop irrespective of the friction of the runway surface. Pressure is applied individually to each of the eight main wheels from the normal or the alternate hydraulic system. When the anti-skid system is "OFF", the pressure applied to the wheels is proportional to the pressure applied by the pilot to each brake foot pedal. When the anti-skid system is "ON" and the pilot demands a pressure high enough to produce an incipient skid, the system modulates the pressure to maintain that level of pressure at the brakes that

* In this context V_{ref} is the same as the target threshold speed (V_{AT}), which equates to 1.3 times the stalling speed for the given flap setting.

produces the optimum tyre/runway slip ratio and thus the maximum braking effectiveness. If the pressure demanded by the pilot is less than that required to produce a skid, the anti-skid system allows this pressure to be applied without modulation.

The operation of the anti-skid system is controlled by the Electronic Control Unit (ECU), which receives wheel speed information from transducers mounted in each mainwheel axle. After processing this information, the ECU outputs electrical signals to the anti-skid valves (pressure control servo valves), of which there are two for each wheel, one for the normal and one for the alternate hydraulic supply. These valves control pressure to each wheel individually and relieve pressure whenever the pilot's pressure demand exceeds that required to maintain the optimum slip ratio.

There are three control loops in the ECU. The minor control loop is a deep skid detector and provides full brake release at the first incipient skid. It measures the time taken for the wheel to spin down and spin up again and provides a proportional signal to set a datum for the major control loop, which then ensures that pressure is re-applied at the correct level for optimum braking. After the first incipient skid, the major loop operates through a deceleration detector and provides continuous proportional control throughout the rest of the braked stop. This loop also incorporates a pressure recovery control circuit that increases brake pressure whenever incipient skid activity reduces. In this way, the major loop causes brake pressure to cycle about that level which produces the optimum slip ratio and thus the maximum deceleration available on the given runway surface. The auxiliary control loop functions only to prevent the application of brake pressure to the wheels prior to touchdown and during any bounce, and to prevent prolonged locking of wheels in hydroplaning conditions.

The process carried out by the minor loop to set a datum takes about one second but normally occurs only once during a braked stop on a uniform surface. The process will, however, be repeated if the pilot increases pedal pressure or if the wheels encounter variations of friction large enough to cause incipient skids that are beyond the range of control of the major loop. If this occurs, there can be more than one occasion during the stop when brake pressure is momentarily relieved completely whilst the minor loop determines a new datum for the major loop.

The anti-skid system includes built-in test equipment (BITE), which can be operated from the flight deck to establish the serviceability of the system before take-off and landing. The BITE can be operated from the pilot control monitor, which is situated above the windshield and incorporates fault warning lights. The test is a confidence check of the deep skid detector part of the anti-skid logic circuits and the integrity of the wiring from the wheel speed transducers, through the ECU, and down to the anti-skid valves. It does not check the adaptive or locked wheel protection circuits. A bench check using special test equipment is required to prove the integrity of the full circuitry of the ECU.

Maximum brake pedal deflection is 34°, or 85 mm (3.4 inches), measured at the forward edge of the pedal. The relationship between pedal travel and brake pressure is roughly linear and full pressure is available to the brakes with 79 mm (3.1 inches) of pedal travel. The brake valves installed in G–BBAI required 20 lb of foot pressure to provide pressure to the brakes and 67 lb to provide the full 3000 psi.

1.7 Meteorological information

1.7.1 General situation

A warm, moist, unstable southerly airflow covered the area and there was no significant frontal activity in the 12 hour period preceding the accident. The forecast for Leeds Bradford was for broken stratus cloud following the dispersal of early morning fog, with outbreaks of rain, moderate at times, from mid-morning onwards. The forecast wind was variable, mainly between south and west, light. Expected rainfall between 0600 hrs and 1800 hrs was up to 2 mm.

1.7.2 Actual weather conditions

The following weather report for Leeds Bradford was passed to the commander at 1217 hrs:

> Surface wind 190°/5 kt, visibility 6 km, recent moderate rain shower, one okta at 1000 feet, 3 oktas at 2000 feet, QNH 1007, threshold QFE* 983, temperature +17°C, the runway surface is wet.

At 1222 hrs, the radar controller reported the surface wind as 200°/10 kt and at 1224 hrs, when he cleared the aircraft to land, the aerodrome controller reported the surface wind as 210°/10 kt.

1.7.3 Rainfall

Rainfall was not measured at Leeds Bradford Airport. There were, however, 10 rainfall measuring stations within ten miles of the airport, where between 10 mm and 15 mm of rain was measured on the day of the accident but there was no evidence to show how much of this rain fell before the accident. The first of the three-hourly actual weather reports from the airport to mention rain showers was issued at 1217 hrs. Eye witnesses at the airport spoke of a heavy shower that lasted for approximately 30 minutes between 1140 hrs and 1220 hrs. The commander reported that it was not raining when he touched down on the runway but photographs showed spray from the mainwheels on touchdown and a dense trail of spray behind the aircraft during the landing roll. No spray was seen from the nosewheel. The drivers of the fire vehicles, who drove along the runway less than one minute after the accident, reported that there was no standing water on the runway at that time.

Local rainfall records showed 7 mm of rain in the vicinity of the airport on 21 May and between 6 mm and 12 mm on 25 May. Actual weather reports from the airport reported rain on 21, 23 and 24 May.

* QFE is the atmospheric pressure at airfield elevation.

1.8 **Aids to navigation**

En route navigation aids were not relevant. Runway 14 at Leeds Bradford had no radio marker beacons and no instrument landing system (ILS) but surveillance radar approaches were available to ½ nm from touchdown. The surveillance radar was serviceable and was used to pass heading and height information to the aircraft up to 2 nm from touchdown. Additionally, the commander had range information available from the distance measuring equipment (DME) associated with the ILS for runway 32, which gave cockpit indications of range from touchdown.

1.9 **Communications**

VHF communications were satisfactory. Tape recordings were available of transmissions on the Leeds Bradford approach, radar and tower frequencies.

1.10 **Aerodrome information**

1.10.1 *Runway physical characteristics*

The main runway, 14/32, was extended to the north-west in 1984, increasing its length from 1646 to 2250 metres. Because of higher terrain to the north-west of the airfield, only part of the extension was useable by aircraft landing on runway 14. To comply with the requirement for an unobstructed approach slope of 1 in 40 to a point 60 metres before the landing threshold, the threshold of runway 14 was inset 311 metres from the start of the paved surface, and the glideslope for that runway was promulgated as 3½°.

The landing distance available (LDA) on runway 14 was 1802 metres. Beyond the end of the runway there was a further 137 metres of concrete and 15 metres of asphalt. Beyond the asphalt the ground sloped down at an average of 8½° for 96 metres to the aerodrome boundary fence. Along the extended runway centreline, the approach lights for runway 32 were set on tall, frangible, lighting posts. The physical characteristics of the runway conformed to the criteria adopted by the UK Civil Aviation Authority (CAA) in all respects other than runway slope (see paragraph 1.10.3).

1.10.2 *Lighting*

The approach lights for runway 14 consisted of a coded centreline of 872 metres with 5 crossbars. Runway lighting was installed to agreed international standards and recommendations and included high intensity runway edge lights and centreline lights. The centreline lights were white from the threshold to 900 metres from the end of the declared LDA, alternately red and white from 900 metres to 300 metres from the end and red from 300 metres to the end of the LDA. All of these lights were illuminated at the time of the accident.

1.10.3 *Runway slope*

Runway 14 sloped down from a landing threshold elevation of 674 feet to 656 feet before rising to 667 feet and falling again to 659 feet at the end of the LDA. The overall downslope of the runway was .25% but the downslope over the first 572 metres was .83%. The runway profile is shown in

Appendix 3. The relevant International Civil Aviation Organisation (ICAO) recommendation and the criterion adopted by the CAA was that the slope of the first and last quarters of a runway should not exceed .8%. The aerodromes section of the UK Air Pilot showed the elevations of the threshold and the runway end, from which the overall downslope might be calculated. The downslope of the first quarter of the runway could have been calculated by operators from the elevations shown on the aerodrome obstructions chart.

1.10.4 *Precision Approach Path Indicators (PAPIs)*

The PAPIs for runway 14 were sited 409 metres from the landing threshold. Because of the downslope on the first part of the runway, the PAPIs were 10 feet below the elevation of the landing threshold. The centre of the on-glide-path signal was 3° 30′ above the horizontal and crossed the threshold 72 feet above the runway surface but, because of the runway slope, this point was 82 feet above the elevation of the PAPIs. The minimum pilot's eye height over the threshold (MEHT) was calculated at a point 2 minutes of arc below the lower boundary of the on-glide-path signal, in this case 3° 18′, giving an eye height over the threshold of 67 feet. The relevant CAA recommendation was that PAPIs should be sited to give a wheel height over the landing threshold of 30 feet for the most demanding aircraft that used the aerodrome. The setting of the PAPIs of runway 14 thus conformed to the recommendation for an aircraft with an eye-to-wheel height of 37 feet. The eye-to-wheel height of the TriStar–1 in the approach attitude is quoted as 31 feet in the British Airways Operating Manual.

1.10.5 *Runway surface*

The surface of runway 14 was of 3 types. The extension, completed in 1984, was of brushed concrete. The rest, being the original runway before extension, was also of concrete, laid in 1965. Short lengths of the original runway, close to the original landing thresholds, were of brushed concrete and the remainder was scored concrete. The scoring, carried out in 1966, was still evident but had suffered considerable wear, particularly along the centre strip. Water drained from the surface towards the north-east along a 1% crossfall.

The aircraft touched down on the brushed concrete portion of the original runway but most of the landing roll was over scored concrete.

1.10.6 *Surface friction measurements*

In 1980 the friction (Mu) of the runway was measured using a self-wetting Mu–Meter*. There is no record of the depth of the texture of the runway having been measured at this time. The average friction measured was .55.

* The Mu–Meter is the standard machine in use in the UK for measuring runway friction. It is a towed vehicle with 2 wheels splayed out at 7½° each side of the direction of motion and measures friction from the side forces produced by the wheels. It has a self-wetting capability to enable it to measure wet friction on dry runways. With respect to aircraft braking, the friction coefficient of a runway is the ratio between tyre drag and the vertical load on the tyre. It is a figure between 0 and 1. Mu–Meter readings are related to friction coefficients.

An assessment of this result by the Principal Civil Engineer of the Department of the Environment stated:

> "The average value of .55 is within the range of values we have obtained on concrete surfaces. Standard wetted runs at 80 mph on 5 government owned airfields with concrete runways give values ranging from .45 to .65 with an average of .58, although it is emphasised that surface conditions at each location vary due to age, texture and degree of weathering of the concrete. None of these runways has received a surface scoring treatment."

In 1982, as part of a CAA programme to assess the wet friction characteristics of the runways on all major public use airfields in the UK, runway 14 at Leeds Bradford was again measured using a self-wetting Mu–Meter. The friction was found to average .65 along the runway length, with only small variations between the first, middle and last thirds of the runway. The depth of the texture as measured by the Cranfield Institute of Technology (CIT) averaged .55 mm, varying from .34 mm near the threshold of the old runway 14 to .62 mm at the mid-point and .69 mm near the 32 threshold. The significance of runway texture is explained in Appendix 1. The wet runway friction of the 49 runways measured during this programme varied from .47 to .79 and averaged .66.

After the accident, on 17 June 1985, specialists from the CIT again measured the friction of the runway with a self-wetting Mu–Meter. The average reading obtained within 4 metres of the centreline on the first two thirds of the runway was .59 and that of the last third was .53, giving an overall average of .58. The Mu–Meter did not detect any significant transient variations of friction along the runway length. Readings taken along the northern edge gave a friction of .63 indicating that wear has reduced the friction of the centre strip of the runway. The following texture measurements were taken using the grease patch method:

Location	*Texture of Depth*	*Type of Surface*
100 metres from 32 threshold:	.19 mm	Smooth concrete
300 metres from 32 threshold:	.25 mm	Worn scored concrete
450 metres from 14 threshold:	.52 mm	Worn brushed concrete
150 metres from 14 threshold:	.50 mm	New brushed concrete

In the report on these tests the runway was described as follows:

> "The surface is mainly scored (bumpcut) concrete, which in some areas has been worn fairly smooth. At the 32 threshold* there is an area of brushed concrete which is also worn fairly smooth. The extension at the 14 end is surfaced with new coarsely brushed concrete."

* In the CIT report the term "32 threshold" refers to the runway end as defined on page 3 of this report.

Photographs of the area near the 32 threshold described as "worn fairly smooth" are at Appendix 3. They show that the concrete matrix covering much of the aggregate has been worn away exposing pebbles that have been worn by use. The original surface texturing is only just visible.

Commenting on the surface texture measurements, the report stated:

> "The average surface texture depth is 0.37 mm with considerable variation between readings. The smooth surfaced area 100 metres from 32 threshold had a texture depth of 0.19 mm, whilst the new extension had a depth of 0.52 mm. The ICAO minimum recommended for surface texture on a new or resurfaced runway is 1.0 mm.
>
> "It can be seen that the texture depth reduces as 32 threshold is approached. Although there is no evidence that the aircraft under investigation hydroplaned, ie, no reverted rubber tyres or cleaned tracks on the runway, surface textures as low as 0.19 mm should give cause for concern."

On 17 September 1986, at the request of the management of Leeds Bradford Airport, further tests of the runway were carried out by the West Yorkshire Highways Engineering and Technical Services Laboratory using the sand patch method supplemented by laser meter readings. Photographs taken during these tests are at Appendix 4. These tests showed the mean texture of the runway to be .66 mm (sand patch) and .47 mm (laser meter). There is little data available to establish correlation between different methods of surface texture measurement. Delegates at an ICAO conference in 1981 conceded that grease patch and sand patch methods of texture measurement were not interchangeable, were far from exact, and that the sand patch method invariably gave higher values.

1.10.7 *Friction monitoring*

In accordance with CAA recommendations, periodic measurements of wet surface friction were made by airport staff in conditions of natural rainfall. The friction measured on the last third of runway 14 was normally slightly less than the average for the whole runway length. Mu–Meter readings taken on runway 14 between September 1984 and June 1985 were as follows:

Date	*Condition*	*Mu–Meter Readings*	
		Runway Average	*Last Third*
14 Sep 84	wet, some standing water	.60	.51
22 Sep 84	wet, some standing water	.70	.67
30 Oct 84	surface just wet	.66	.61
22 Nov 84	wet, some standing water	.69	.64
11 Apr 85	runway flooded to mean depth of 2 mm, maximum 3 mm	.48	.47
6 Jun 85	continuous moderate rain	.56	.53

Additional measurements were made on 6 June 1985 in conditions that were reported by the airport staff to be similar to but slightly wetter than at the time of the accident. The runway was drying after the recent moderate rain and was described as being wet overall with 30% of the surface covered by standing water less than 1 mm in depth but with isolated patches 2 mm deep. Six test runs were made at various distances from the centreline. The average Mu measured within 8 metres of the centreline was 0.69 and that of the last third was 0.66.

1.11 Flight recorders

1.11.1 Flight data recorder

A comprehensive digital data acquisition and recording system was fitted to the aircraft. A Davall type 1192 crash-protected digital flight data recorder (FDR), with steel wire as the recording medium, recorded 31 parameters and 53 discretes. The recorder retained the last 25 hours of recorded flight data. In addition, a Davall type 1223 quick-access recorder (QAR), with mylar magnetic tape as the recording medium, recorded an extensive list of additional parameters and discretes. Both recorders were removed from the aircraft and replayed.

All the parameters required for analysis on the FDR were functioning but some parameters on the QAR that would have helped the analysis were malfunctioning. The faulty parameters were primarily the Inertial Navigation System (INS) derived parameters of ground speed, wind speed, wind angle, track and latitude and longitude. Brake pressure, which would have been invaluable to the analysis of this accident, is not recorded on the TriStar–1.

1.11.2 A Fairchild A100 cockpit voice recorder (CVR) was fitted to the aircraft and it recorded 4 tracks continuously on mylar magnetic tape in an endless loop with a duration of 30 minutes. The track allocation conformed to an early CAA specification as follows:

(i) Commander's mic/tels

(ii) Area microphone

(iii) All 3 crew members summed hot microphones

(iv) Co-pilot's mic/tels

The speech intelligibility of the summed hot microphones track was so poor that some evidence was lost. Its quality was markedly inferior to that obtained from installations meeting the current CAA specification where the hot microphone signals are fed to the individual crew members' tracks.

1.11.3 Flight recorder analysis

The digital flight data was corrected and analysed to determine the achieved landing performance of the aircraft. Cross-checks of events against time were made by comparison of the digital data with the audio data and the transcript of speech obtained from the CVR. The number of recorded parameters enabled the validity of the derived data to be established with a high degree of confidence. It was found, however, that the groundspeed derived from the recorded airspeed was 5 to 7 kt lower than that obtained by integration of the recorded longitudinal acceleration, suitably corrected for datum error, pitch attitude and runway slope. Accordingly, the derived groundspeed was integrated to provide distance against time, which was then analysed against:

(i) terrain clearance against time on the final approach derived from radio altitude and barometric altitude, matched against the runway ground profile of the approach path and the runway;

(ii) crew statements of the PAPI indications on short finals;

(iii) evidence from measurements of the accident site at the end of the runway;

(iv) still and cinematic photographic evidence.

This analysis clearly showed that the data computed from the longitudinal accelerometer was more accurate than that derived from the recorded airspeed. Using the refined recorded data, standard data reduction techniques were used to compute the instantaneous braking coefficient of friction against time. The results are shown in Appendix 2.

After the accident, a number of TriStar–1 landings were monitored and it was found that on some of these landings, when 42° flap was extended, the groundspeed indicated by the INS control and display unit was higher than that derived from the indicated airspeed. There appears, therefore, to be some form of manometric error in the airspeed indications on the TriStar–1 which may occur during a landing with 42° flap. This apparent discrepancy warrants further investigation.

1.11.4 *Calculations from recorded data*

The recorded data was analysed to compare the landing performance achieved by AI with the scheduled performance. Times and distances for each segment of the landing were calculated together with the braking coefficient of friction during that segment of the landing roll when both braking and full reverse thrust were active. The shape of the speed/friction curve obtained by plotting the braking coefficient of friction against groundspeed was found to conform to that of the family of similar curves determined by the Engineering Sciences Data Unit (ESDU) and published in 1971 in their Item Number 71026.

These calculations of the aircraft's expected performance assumed a level runway and the use of nominal 90% N1 reverse ("full reverse") on all 3 engines. Theoretical landing distances were calculated for the following conditions:

A. Threshold speed V_{ref} + 13 kt with time in the air, time of brake application, time to achieve full reverse and mean braking effectiveness (.2242) as used in scheduling the aircraft's performance. (1620 metres)

B. Accident conditions ie, threshold speed V_{ref} + 13 kt with time in the air, time of brake application, time to achieve full reverse and mean braking effectiveness (.09) as pertained to the accident. (1935 metres)

C. As for B but using the scheduled braking effectiveness. (1561 metres)

D. As for A but using the mean braking effectiveness achieved at Leeds Bradford by AI. (1957 metres)

The total landing distances calculated for conditions A and C showed that the manner in which AI was operated would have reduced its landing distance by 57 metres if the aircraft had experienced the mean braking effectiveness measured for certification purposes. Comparison of conditions B and D showed that the landing distance required by AI was 22 metres shorter than that calculated using the certification criteria with the braking effectiveness measured at Leeds Bradford. The accuracy of these calculations was confirmed by the close agreement between the result from condition C and the actual landing distance of AI.

The penalty of the delayed brake application of AI was incurred during the segments of the landing between touchdown and brake application and brake application and full reverse where a low level of brake effectiveness is assumed in the equations. Further, because full reverse was established on AI earlier than was assumed for performance certification, the segment of the landing for which the equations use the mean braking effectiveness was longer with the result that the earlier achievement of full reverse largely compensated for the penalty of late braking.

An assessment of the influence of threshold speed on landing distance showed that the distance achieved by AI was 108 metres longer than might have been achieved had the threshold speed been V_{ref} + 5 kt and 35 metres shorter than might have been achieved from V_{ref} + 15 kt, the speed on which the scheduled performance was based. When a figure of .09 for mean braking effectiveness was substituted in the equations for scheduled performance (V_{ref} + 15 kt and 2 engines in reverse), the resulting LDR, less the 8% field length factor, was found to be some 117 metres longer than the actual landing distance of AI.

Appendix 5 shows the landing distances calculated for conditions A to D above compared with the actual scheduled performance of A and the theoretical scheduled performance of the aircraft.

1.12 Wreckage and impact information

1.12.1 On site examination

1.12.1.1 Runway and overrun

The runway surface was examined 4 hours after the accident. Light rain was falling and the surface was wet but there was no significant standing water. The aircraft had overrun the runway to the left of the centreline and had sunk into soft ground. The tail empennage overhung the end of the asphalt strip beyond the concrete pavement.

The initial touchdown point could not be identified among the marks made by other aircraft in the touchdown zone but marks were found on the surface over the last 457 metres of the runway. These marks were two parallel lines of slightly paler concrete, and their dimensions corresponded to the inboard and outboard tyres of the aircraft's right main landing gear bogie. They commenced some 7 metres to the right of the centreline and, at 60 metres from the end of the concrete, they veered to the left and departed from the pavement 2.1 metres right of the centreline. At 55 metres from the end of the concrete a similar pale track had been left by the nose landing gear. This mark showed a single broad track and appeared to indicate that the nose-gear had been skidding sideways at this point. At 45 metres from the end of the concrete two parallel tracks were seen from the left main gear bogie. The marks showed that, when 55 metres from the end of the pavement, the nose landing gear had been steered sharply to the left and had left the pavement 3 metres left of the centreline. A deep gouge in the soft overrun area showed that the nose gear had begun to sink immediately and had collaped shortly afterwards. Both main bogies had sunk quickly to their axles, the left having rolled for 8.5 metres through the soft ground and the right for 12.2 metres before coming to rest with mounds of displaced earth in front of the wheels. The wheels had caused some damage to buried airfield lighting cables.

1.12.1.2 *The aircraft*

The aircraft had come to rest on an 8½° downslope and was angled 11° to the left of the runway centreline. The nose gear had collapsed backwards, and the aircraft was resting 14° nosedown on the underside of the forward fuselage and the main landing gear. Some flattening was evident on the undersides of the No 1 and No 3 engine cowlings. All 8 escape slides were deployed and, except for the No 3 slide on the right side, all were fully inflated. It was established later that the deflated slide had been punctured when a cargo door was opened to remove baggage. There was no internal damage to the passenger cabin or flight deck. The thrust reversers were stowed and one fire bottle had been discharged into each engine and one into the auxiliary power unit. There was evidence of severe foreign object damage to the No 3 engine and, although it was not apparent at the time, the No 1 engine had also suffered some foreign object damage. The wing flaps were in the 22° extended position.

With electrical power off, the following cockpit readings and selections were noted:

	No 1	No 2	No 3
Fuel used per engine:	5540 kg	5510 kg	5620 kg
Brake system:	"NORMAL" selected		
Flaps:	42° selected		

Tailplane trim:	5 (within take-off range)
Autothrottle:	"OFF"
Speed selector:	150 kt
Brake pressure:	Normal system 3000 pounds per square inch (psi) Alternate system 3200 psi

With electrical power available the brake pressure readings were:

Normal system 1700 psi

Alternate system 3700 psi

The reservoirs for hydraulic systems A, B and D were full but that for system C was empty. The parking brake was applied and was maintaining brake pressure on all 8 wheels.

1.12.2 *Subsequent detailed examination*

1.12.2.1 *Nose landing gear and fuselage*

When the nose of the aircraft was raised, the nose landing gear was found to be still attached at its main pivots. The drag strut had pulled out of the forward trunnions and the strut had folded backwards. The fuselage had come down on to the left tyre, consistent with the nosewheel having been turned to the left when the strut folded backwards. The left wheel and strut had penetrated the fuselage skin and pushed up the freight bay floor structure. The damage to the fuselage skin, main frames and floor beams was confined to an area between fuselage stations 449 and 600 and stringers 41 and 29.

1.12.2.2 *Main landing gear*

The main landing gear tyres had all been in good condition before the accident, most being approximately half worn but with adequate groove (tread) depth remaining. The treads had been deeply cut during the overrun and subsequent recovery of the aircraft. Brake wear pin extensions with the brakes on were found to be within limits. Tyre pressures could not be checked until the aircraft had been pulled out of the soft ground two days after the accident; pressures were then found to be (in psi):

	1	2	3	4
Front	202	172	195	195
Rear	171	195	195	197

1.12.2.3 *Hydraulic systems*

The pipes carrying C system hydraulic pressure in the nose wheel bay had been fractured, allowing most of the fluid to escape. The hydraulic fuses associated with No 2R and No 3R normal system brakes had tripped but the system had been reset leaving the tell-tales protruding. This was attributed to actions during the recovery of the aircraft when a brake pipe had been severed on the right main landing gear. A full report on tests of the aircraft braking system is at paragraph 1.16.1.

The wing spoiler panels operated by hydraulic systems A, B and D could be raised by manual operation of the speedbrake lever but the automatic ground spoiler system could not be checked with the C hydraulic system inoperative.

1.12.2.4 *Airspeed indicators*

A calibration check was carried out on the pilot's and co-pilot's airspeed indicators (ASIs) in the range 65 kt to 200 kt. The pilot's ASI showed no errors. The co-pilot's ASI was accurate between 100 kt and 120 kt but read one knot high above and below this range.

1.13 Medical and pathological information

Not applicable.

1.14 Fire

There was no fire.

1.15 Survival aspects

When the aircraft left the runway, ATC alerted the airport emergency services. Four fire vehicles reached the aircraft one minute after the accident. When the aircraft came to rest, the commander ordered the unpremeditated evacuation drill. All 8 cabin exits were opened by the cabin crew and all 8 escape slides were deployed successfully. The passengers were evacuated in 1 minute 30 seconds. Because of the high tail attitude, the rear slides were angled at approximately 70° to the horizontal. Twelve passengers suffered minor cuts, bruises and sprains in using these steep rear slides. Although no time was allowed for passengers to remove shoes, the slides were undamaged and remained inflated throughout the evacuation.

Within one minute of the accident, the local ambulance service had been alerted and had despatched 12 ambulances to the airport. These vehicles carried the injured passengers to local hospitals.

1.16 Tests and research

1.16.1 *Tests of the aircraft anti-skid system*

After the accident, BITE checks using the pilot control monitor indicated that the anti-skid braking system was serviceable. (See paragraph 1.6.4.) The BITE check at the ECU itself also indicated that the system was fully serviceable. A functional test of the anti-skid system was then conducted using individual pressure gauges on each wheel brake inlet. For the first part of this test the oleo compression proximity switches were disabled to put the aircraft in the "flight" condition, and brake application prior to landing was simulated. Each gauge showed approximately 100 psi, indicating that the locked wheel protection mode was functioning correctly. The aircraft was then restored to the "ground" condition and the wheel speed transducers were spun sharply and then stopped. As the anti-skid system sensed wheel spin-up, all gauges showed full brake pressure, which released when the system sensed spin-down. The test was successful on all 8 wheels thus proving hydraulic system continuity and the integrity of the anti-skid valves. Finally, the ECU was removed from the aircraft and bench tested several times. It was found to be operating correctly within its design parameters.

1.16.2 *Aircraft tyres*

The tyres were examined by representatives of the Thompson Aircraft Tyre Corporation. They reported that all tyres showed small areas of light chevron cutting, typical of the marks made by braking on a grooved runway. Some tyres had suffered deep cuts from the ground manoeuvring during the recovery of the aircraft. There was no evidence of rubber reversion such as might have been caused by sustained hydroplaning, and the tread condition was such that a water film of approximately 10 mm would have been necessary to obtain any dynamic hydroplaning effect. The light marks observed on the runway were attributed to the scouring action of water abruptly ejected by the high hydrodynamic pressures in the footprint area. Such scouring action is not characteristic of a pure hydroplaning phenomenon and can be caused by braking and sharp cornering on a very wet runway.

The Thompson report describes the phenomenon of lubrication by a thin film of water in the following words:

> "A very important increase in stopping distances on wet runways has also been observed for speeds inferior to the critical speed of pure hydroplaning – particularly in the case of smooth runways (non-grooved). In this case the losses of adherence are due to the lubrication effect (due to water viscosity) which applies to the interface tyre/runway. This phenomenon leads to a very important decrease of the friction coefficient which can fall down to values inferior to 0.2 or even 0.1 for speeds of 80 to 100 knots."

The conclusions of the Thompson report are:

> "Considering only the possible role played by the tyres and based upon the condition of the tyre tread, the most probably hypothesis is that there has been a loss of braking traction during the landing operation provoked by a lubrication phenomenon. Such a phenomenon can be provoked by the presence of a film of water between the tyres and a relatively smooth runway."

1.16.3 *Tests of autothrottle system performance*

In order to determine the mean performance of the ATS on the whole of their TriStar–1 and –200 fleet, the British Airways performance engineers analysed flight data recordings of a sample of 203 TriStar landings with the ATS engaged. A linear relationship was assumed between alpha speed and aircraft weight in the range 128 kt to 168 kt. Differences due to CG position and flap setting (33° or 42°) were ignored as they were deemed to be small. The mean speed maintained by the ATS between radio heights of 95 feet and 65 feet at an aircraft weight of 160,000 kg was 150.38 kt against a V_{ref} of 142 kt, and the standard deviation in the results was 2.97 kt. Because the majority of the landings in this first sample were made using 33° flap, a further sample of 21 landings using 42° flap was taken. This second sample yielded a mean speed of 148 kt at 160,000 kg against a V_{ref} of 138 kt. From these results, British Airways concluded that the ATS in the accident aircraft operated normally and that the aircraft achieved the datum angle of attack before auto-throttle disconnect.

1.17 Additional information

1.17.1 British Airtours standard operating procedures

1.17.1.1 The commander was required to operate the TriStar in accordance with the standard operating procedures and guidance written in the British Airways Operations Manual (OM).

1.17.1.2 The final approach

In describing the normal handling technique to be used for a non-precision approach, the OM stated that landing flap should be selected at or before decision height, when the runway is in sight and the correct visual approach path can be maintained. For a precision instrument approach, however, the OM stated that landing flap should be selected at 1500 feet above aerodrome level (AAL). The preferred technique taught by British Airtours training captains for all approaches leaned towards that described for precision instrument approaches in that pilots were taught to establish landing flap by 1000 feet AAL whenever possible in order to achieve a stabilised approach path.

The ATS should normally be used for all approaches and, for manual landings, should be disengaged at or before the landing flare. If the ATS was not available, pilots were required to maintain the speed commanded by the speed deviation pointer, which is also referenced to alpha speed (see paragraph 1.6.2). The landing threshold should be crossed at a speed between $V_{ref} + 5$ kt and $V_{ref} + 15$ kt.

Included in the OM were two warnings to pilots not to deviate from the indicated approach path. The section describing visual landings included the warning "DO NOT MAKE A LAST MINUTE DIVE AT THE THRESHOLD". The section describing the final approach included the warning "NEVER DUCK BELOW THE GLIDEPATH".

1.17.1.3 Manual landing technique

Between 30 and 20 feet above the ground the flare should be initiated, the ATS disengaged, and the throttles closed progressively. The OM stated that, although the anti-skid system is designed to ensure that brake application cannot occur until the system is effective, it is good practice to keep the feet clear of the brake pedals during touchdown. At the time of the accident the deceleration sequence was described as follows:

"When the weight is on the main landing gear, thrust is automatically reduced to ground idle. Check AGS deployment or select ground spoilers manually in the event of a malfunction. Check throttles completely closed, then apply scheduled reverse thrust and lower the nosewheel gently but without delay . . . ."

The OM continued with 3 paragraphs describing the use of reverse thrust before stating:

"When the wheels are firmly on the ground, apply sufficient steady brake pressure to suit the runway conditions and distance available. . . "

The aircraft flight manual (FM), in describing the technique required to obtain the scheduled landing performance, states:

"When landing with anti-skid operating, apply maximum wheel braking as soon after touchdown as practical, and actuate reverse thrust for landing on all operating engines within approximately 4 seconds of touchdown."

1.17.1.4 *Slippery runways*

The landing performance section of the OM gives maximum weights for landing on both wet and slippery runways. Under the section on "Landing Distance Requirements", the OM states:

"The normal scheduled landing distances allow for a wet runway. If a runway is reported as having poor braking conditions, is covered by ice, snow or slush or has standing water in excess of 3 mm, the appropriate slippery runway landing performance data must be used."

1.17.1.5 *British Airtours data for Leeds Bradford*

The OM classified Leeds Bradford as a Category A airfield (defined as "No special difficulties, self-briefing only". The landing data included the following information:

Aerodrome Elevation 682 feet

Runway 14

Landing distance available:	1802 metres
Maximum landing weight, zero headwind, 42° flap:	162,400 kg*
Maximum landing weight, zero headwind, 33° flap:	151,000 kg
Touchdown zone elevation:	674 feet
Decision height on surveillance radar approach:	980 feet QNH 306 feet QFE

* 162,400 kg was the certified maximum landing weight of the TriStar–1. The generalised landing distance chart in the OM showed the maximum weight at which a TriStar could be landed on a wet runway 1802 metres long with zero headwind was 167,700 kg.

Nominal 90% N1 reverse thrust must be used to achieve the published landing weight.

The British Airways approved instrument approach chart for the surveillance radar approach to runway 14 specified a height of 2530 feet on QNH at the final approach fix 5 nm from touchdown and a glideslope angle of 3½°.

1.17.2 *Landing distance requirements*

The TriStar–1 was certificated as a Performance Group A aircraft on the UK register according to the airworthiness code in British Civil Airworthiness Requirements (BCAR), Section D. BCAR Section D has now largely been incorporated in the internationally agreed Joint Airworthiness Requirement (JAR) but the method of determining landing distance currently specified in JAR 25 does not differ significantly from that in BCAR Section D. Two methods are approved. The first, known as the Arbitrary Method, applies to most countries and requires the aircraft's landing distance to be measured on a dry, hard, paved surface from 50 feet above the landing threshold at a speed not below the target threshold speed (V_{AT}). For turbo-jet powered aircraft this distance is then multiplied by a factor of 1.67 to produce the dry runway landing distance requirement and by 1.92 for the wet runway requirement. If the aircraft is deemed to have reliable and effective reverse thrust, the wet runway factor may be reduced to 1.82. The second method, known as the Reference Method, requires the aircraft's landing distance to be measured on a wet, hard, paved surface of defined friction characteristics. The landing distance is measured from 30 feet above the landing threshold at a speed of V_{AT} + 15 kt. If reverse thrust is available, one engine is deemed to be inoperative in reverse thrust. The achieved landing distance of the aircraft is corrected by a factor determined by comparison between the measured friction of the test runway and that of a specified Reference Wet Hard Surface. The scheduled landing distance is then determined by formula but may not be less than 1.08 times the measured landing distance. The CAA have stated that, in addition to this 8% factor, the main components of the safety margins built into scheduled landing performance are:

a. A screen height of 30 feet.

b. A high speed at the threshold (V_{AT} + 15 kt).

c. An extended flare from 30 feet to touchdown.

A test report issued by the Ministry of Defence (Procurement Executive) in October 1979* showed that the CAA Reference Wet Hard Surface, when measured using a Transport and Road Research Laboratory Trailer (an approved surface friction measuring device commonly known as a "Miles Trailer"), had high friction characteristics similar to those of a porous friction course. A graph from this report is reproduced at Appendix 6. The same report included the results of trials between the Miles Trailer and the Mu–Meter at speeds over a range from 20 to 80 mph which showed that in water depths between .25 and .50 mm (0.01 to 0.02 inches) the readings obtained by the Miles Trailer were lower than those of the Mu–Meter, as shown in the table below:

* S&T–MEMO–1–79 A Means of Specifying a Standard Reference Wet Surface for Military Aircraft.

Miles Trailer Reading	*Mu–Meter Reading*
.20	.32
.40	.46
.60	.69

1.17.3 *UK certification of TriStar–1 landing performance*

The TriStar–1 was flight tested in 1972 for performance certification by the Reference Method. Rejected take-offs and landings were carried out on a runway artificially wetted to match as closely as possible the friction characteristics of the CAA Reference Wet Hard Surface.

The test runway was 3049 metres (10,000 feet) long, having 1677 metres (5500 feet) of brushed concrete surface followed by 610 metres (2000 feet) of asphalt and a further 762 metres (2500 feet) of concrete. It was wetted to an average water depth of approximately .46 mm (.018 inches). For the calculation of landing performance the wet runway anti-skid operative braking coefficient of the aircraft was measured during 5 landings, and the results were averaged. The results were then verified by two complete reference landings. The coefficient of friction of the runway was measured using a Miles Trailer, which took measurements immediately before and after each landing. The spread of the Miles Trailer measurements was as follows:

Speed	*Range of Measurements*
85 kt	.19 to .36
65 kt	.21 to .38
45 kt	.29 to .44
20 kt*	.24 to .59

These measurements were averaged to produce a speed/friction curve, which was then compared with that of the Reference Wet Hard Surface. The friction of the test runway was found to agree closely with that of the Reference at speeds above 50 kt but below this speed, largely as a result of the lower measurements taken on the asphalt portion, the test runway was considered to be more slippery than the Reference.

The braking coefficient of friction experienced by the aircraft averaged over the whole braking distance (hereafter referred to as the braking effectiveness) varied from .1968 to .2124, giving an uncorrected average of .2074. This average was then multiplied by a factor of 1.081 to correct for the difference in friction characteristics between the test runway and the Reference Wet Hard Surface. The final figure of braking effectiveness accepted for landing performance certification was .2242. However, the Lockheed Aircraft Corporation have since confirmed that, of the 7 flights conducted to determine the landing performance of the aircraft, no flight

* Of the measurements taken at 20 kt, the majority were on the asphalt portion of the runway. Those taken on the concrete portion varied between .46 and .59.

was reported as having gone beyond the end of the concrete although visual observation of runway markers implied that one flight overran onto the asphalt by about 100 feet. All of the 6 other flights completed their braked stops on the concrete surface.

The operating technique used to obtain the measured landing performance was for maximum braking to be applied 1.44 seconds after mainwheel touch-down, which, taking account of crosswind effects, must mean both sets of mainwheels, and for maximum reverse thrust to be selected on 2 engines 3 seconds after touchdown and cancelled as the aircraft decelerated through 70 kt.

The measured air distances from threshold to touchdown achieved during the flight tests were not used for scheduling the aircraft's landing performance. This distance was calculated using an equation for the time in the air. This equation is judged by the CAA to give results that are typical for transport aircraft having maximum threshold speeds in the range 100 kt to 165 kt. The time in the air from this equation for the TriStar in the conditions of the accident was 6.025 seconds, relating to an air distance of 482 metres.

1.17.4 *Further TriStar landing trials*

In 1973, during an evaluation of a special condition landing requirement for Concorde, the US Federal Aviation Administration (FAA) carried out a further series of wet runway landing trials using a TriStar and a Boeing 737 at Roswell, New Mexico. The runway surface was concrete but it had less texture and the water depth was slightly greater than during the CAA certification trials. Runway friction was measured using four different types of ground vehicles, including a Mu–Meter and a Miles Trailer. The Miles Trailer readings were averaged between 85 mph and 0 mph and could not therefore be compared directly with the CAA Reference Wet Hard Surface. Twenty two landings by the TriStar were measured, 8 using idle power, 9 using reverse thrust on one engine and 5 using reverse thrust on two engines. The results of the braked stops using reverse thrust on two engines gave the following figures for Mu–Meter readings, water depth and braking effectiveness:

Mu–Meter Reading at 40 mph	*Water Depth (mm (inches))*	*Braking Effectiveness*
.507	.61 (.024)	.0935
.414	.43 (.017)	.1017
.448	.51 (.020)	.0912
.404	.61 (.024)	.0856
.477	.63 (.025)	.1147

The other 17 landings showed similar results with Mu–Meter readings varying between .329 and .527, and braking effectiveness between .0718 and .1284. The texture depth of the runway was stated by the FAA to be .216 mm. Recorded brake pressure showed that the anti-skid valves controlled pressure at the brake cylinders to between 500 and 1000 psi.

In their report on these trials, the Lockheed Aircraft Corporation commented that direct comparison between landings was hampered because runway wetness varied from test to test. Generally, the runway was more slippery than normally required for aircraft certification. Due to the crossfall on the runway, water depth on the right of the centreline was slightly greater than on the left, and wheel speed monitors detected some momentary hydroplaning on individual wheels of the right main landing gear on some tests. It was also found that on many of the landings some wheels took two seconds, and sometimes much more, to spin up to synchronous speed and that brake application often occurred before full spin-up, resulting in brake-induced hydroplaning, which further degraded braking performance.

1.17.5 *UK standards for measuring and reporting wet runways*

The periodic checks of the braking friction available on runways in conditions of natural rainfall which are recommended by the CAA are performed using a Mu–Meter towed at 40 mph. Mu–Meter calibration values are obtained using a towing speed of 80 mph, and the value at and below which a runway should be notified as liable to be slippery when wet is .39. Mu–Meter readings of .45 obtained at 40 mph are considered to be equivalent to a notification calibration value of .39. Aerodrome operators are advised to identify a friction level above .45 at which they will recognise a need for remedial action to preserve an acceptable level of friction.

The condition of a wet runway is determined by the aerodrome operator and notified to pilots by ATC using the following terms and descriptions:

Damp:	The surface shows a change of colour due to moisture.
Wet:	The surface is soaked but no significant patches of standing water are visible.
Water patches:	Significant patches of standing water are visible.
Flooded:	Extensive standing water is visible.

The UK Air Pilot states that, when a runway, other than one notified as liable to be slippery when wet, is reported as damp or wet, pilots may assume that an acceptable level of wet runway friction is available.

1.17.6 *Previous accidents*

Records held by the CAA described 10 previous landing overrun accidents on wet runways in the UK in the previous ten years. Two of these accidents had occurred to Viscount aircraft at Leeds Bradford, and both showed clear evidence of hydroplaning. One of these accidents was attributed to a late touchdown and the other to late selection of ground fine pitch on the aircraft's propellers.

Worldwide during the same period the records described 54 landing overrun accidents, 5 of which were fatal. Only 8 of these accidents were described as having occurred on ice or slush.

2. Analysis

2.1 General

Although the commander and the other two operating pilots had not previously landed at Leeds Bradford, all were properly qualified and adequately experienced for the flight, and the aircraft was free of defects. The aircraft was below the maximum permitted landing weight for the runway length and notified condition, and more reverse thrust was used than was normal, but it failed to complete its landing in the distance available. There was a delay between mainwheel touchdown and brake application, and the brakes when applied produced less than the expected deceleration. This analysis considers the braking effectiveness of the aircraft and the extent to which the handling of the aircraft, the condition of the runway and the performance certification of the aircraft contributed to the accident.

2.2 The final approach and touchdown

The aircraft reached the final descent fix with only 10° flap extended and at a relatively high speed. Because of the 3½° glideslope and small headwind component, the rate of descent, IAS and groundspeed during the first part of the approach remained fairly high with the result that the commander did not select landing flap (42°) until 564 feet above the landing threshold, some 36 seconds before touchdown. Whilst such a late selection of landing flap might have been normal on a surveillance radar approach with the runway not in sight, on this occasion the commander had the runway in sight at or soon after the final approach fix and his approach did not conform to the principle of the company operating procedures, which stresses the importance of a stabilised approach. From the point where the flaps were fully extended at 466 feet above the landing threshold, the aircraft was on the correct indicated glidepath and its IAS could have been reduced to V_{ref} + 5 kt or less by the landing threshold if a lower power setting had been used. The fact that it was not must be attributed to the behaviour of the speed control system (SCS), which commanded the autothrottle to apply more power than was needed from the time of selection of landing flap to the point of autothrottle disconnect. Due to this excess power the aircraft crossed the threshold at an IAS of V_{ref} + 13 kt; the discrepancy revealed by analysis of the FDR between manometric and inertial groundspeed means that the actual airspeed was slightly higher but the commander could not have been aware of this.

The FDR showed that the aircraft was 30 feet above the runway approximately 20 metres before the landing threshold. Time in the flare from 30 feet to left mainwheel touchdown was 5.8 seconds. However, because of the downslope of the runway, the point of touchdown was more than 12 feet below the elevation of the threshold; an additional descent that would have taken .8 seconds even if flown at 900 feet per minute on the indicated glidepath. The commander's flare manoeuvre, therefore, was not prolonged, taking 5.8 seconds compared with the 6.025 seconds calculated from the equation used for scheduling the aircraft's performance, and achieving an additional 12 feet of descent in that time. However, the runway downslope reduced the speed bleed-off between threshold and touchdown.

2.3 The runway slope

Examination of the distance covered in the flare gives rise to concern about the ability of aircraft to achieve their scheduled performance on runways with significant initial downslopes. In this accident, the aircraft passed the screen height (30 feet) some 20 metres before the threshold and then, despite the downslope, the commander achieved touchdown some 453 metres beyond this point. This figure may be compared with the 482 metres calculated from the performance equation for a level runway. If he had carried out a normal flare (ie, a body angle change of 1½° to 2° at a radio altitude of 30 feet), he would have landed long. How long is difficult to define and depends on the nature of the flare manoeuvre. It might be expected that a pilot should see a runway slope and should fly to his required point of touchdown but in many large aircraft, including the TriStar, the mainwheels are so far below and behind the pilot that the point of mainwheel touchdown is between 300 metres and 450 metres before the pilot's visual aiming point, and the aircraft is normally flared on radio altitude. If, however, it is assumed that the pilot can and does adjust his flare manoeuvre to take account of the downslope, unless he deliberately steepens his approach path prior to the flare, an action most pilots would be reluctant to take, he can only either delay his flare or use a lower body angle in the flare. Because a flare initiated at the normal radio altitude (about 30 feet), even to a lower body angle, would cause an immediate reduction in rate of descent, a delayed initiation of the flare would give a lesser distance to touchdown. It is reasonable therefore to calculate the minimum distance penalty of a downslope on the latter basis.

On this basis the effect of the initial downslope of runway 14 at Leeds Bradford can be calculated to increase the distance from 30 feet to touchdown by 71 metres, bringing the total calculated distance to 553 metres. This figure assumes that the pilot does not adjust the body angle in the flare to allow for the downslope. The fact that the commander of G–BBAI achieved left mainwheel touchdown after an air distance of 453 metres indicates that he did make allowance for the downslope and confirms that his flare was not prolonged.

Nevertheless, it should not be assumed that all pilots would be successful in mitigating the effects of an initial runway downslope, even if conditions were such that they could detect it visually. The potential increase in air distance becomes very significant when the runway is short and wet. If, on runway 14 at Leeds Bradford the whole 71 metres is subtracted from the LDA, the remaining effective LDA is only 1731 metres, some 9 metres too short for the landing distance required at the landing weight of AI. There is no requirement, however, for operators to take account of initial runway downslopes. For performance purposes runways are defined as having a uniform slope from threshold to runway end; moreover, when a runway is usable in both directions, operators may ignore slope when despatching aircraft to that runway. There can be no criticism, therefore, of British Airtours for despatching AI to that runway at that weight. It would, however, because of the comparatively short LDA on runway 14, have been prudent for British Airtours to have looked closely at the physical characteristics of that runway, and to have recognised that the downslope could reduce the safety margin on landing, particularly in wet conditions. It is considered, therefore, that British Airtours should not have categorised the airfield as "having no special difficulties" but should have required special briefing for pilots required to land there.

A more general point that arises from the analysis of this accident is that a significant downslope at the landing end of a runway has the potential to erode safety margins and can, by itself, make the difference between a safe landing and an overrun for, within the overall slope of a runway, the much smaller advantage gained from an upslope during the landing ground roll does not compensate for the much greater distance lost during the landing flare over a downslope on a dished runway. If then, as the CAA have stated, an element in the calculation of scheduled aircraft landing performance is the air distance allowed for in the flare, then this margin is significantly reduced by the effect of a downslope. There is a need, therefore, for operators to identify and take account of the effect of significant runway initial downslopes when calculating maximum landing weights at those airfields affected.

2.4 The landing roll

When the aircraft touched down, because its indicated airspeed over the threshold was within the bracket allowed for in its scheduled landing performance, and, despite the downslope, it touched down within the distance allowed for, it should have stopped within the distance available. The fact that it did not may be attributed only to poor deceleration during the landing ground roll.

2.4.1 Reverse thrust

The contributions to deceleration controlled by the aircraft crew were reverse thrust and braking. Considering reverse thrust first, the FDR showed that reverse was selected with no delay, effective reverse thrust being obtained some 3 seconds sooner than allowed for in the scheduling of landing performance. The contribution made by reverse thrust was in the order of 390 metres of landing distance. Had maximum power reverse thrust been selected at the earliest possible time during the landing roll, this contribution would not have been increased by more than about 10 metres. The use of maximum power reverse at an earlier stage of the landing roll would thus have had a relatively minor effect and would not have made up for the lack of brake retardation.

2.4.2 The use of the brakes

The commander stated that he applied full braking as soon as he saw the first red centreline lights approaching, and, from the CVR, it was determined that this was approximately 4 seconds after both sets of mainwheels were on the ground as against the 1.44 seconds allowed for in certification. However, because the level of braking effectiveness measured at the high speed end of the speed/friction curve was so low, the loss of landing distance attributable to late braking was small and was more than compensated for by the early achievement of full reverse thrust. Clearly, therefore, late braking could not have been the primary cause of this accident.

A further possible cause that was under the commander's control must also be examined, and that is the amount of braking he actually applied, for this was not measured by the FDR. Certain facts are relevant:

a. The brake valves installed on the aircraft provided no pressure to the anti-skid valves until a pressure of 20 lb was applied to the brake pedals. A pedal pressure of 67 lb provided the full system pressure of 3000 psi to the anti-skid valves.

b. The captain was familiar with the application of full braking having been required to practice this in the flight simulator on 6-monthly competency checks.

c. The braking system of G–BBAI was shown to be serviceable and operating within correct tolerances.

d. The Roswell trials, where pressure to the brake cylinders was measured, showed that when the runway was slippery the anti-skid valves controlled pressure at the brake cylinders to between 500 psi and 1000 psi.

Although there is no evidence to confirm that the commander applied full braking when he said he did, aware as he was that he had little more than 900 metres of runway remaining, it would be unrealistic to suppose that he applied no brake at all and equally unrealistic to suppose that he applied less than 20 lb force to the pedals. Nevertheless, it cannot be assumed that he used full pedal pressure when he first applied the brakes. However, from a point 380 metres from the end of the paved surface, when he said he had his feet on the brakes as far as he could, it is reasonable to suppose that full braking was applied. Any other conclusion must assume that, with the end of the runway approaching rapidly, he either did not have the skill to apply full braking or he did not try to do so, and neither seems likely. It may be concluded, therefore, that full braking was applied at least over the last 380 metres of the paved surface. Over the landing roll as a whole no step change was found in the rate of deceleration to show that pressure to the brakes was increased at any time. Moreover, the speed/friction curve, although it showed clearly a part of the landing roll when braking effectiveness ceased to rise normally, conformed generally to the expected shape and showed no significant positive change of slope to indicate any point where braking might have been increased. It is also concluded, therefore, that from 4 seconds after both sets of mainwheels were on the ground, sufficient pedal pressure was applied for the anti-skid valves to operate normally.

Unfortunately, in the absence of brake pressure information on the FDR, evidence of when and how the commander applied the brakes is largely circumstantial. Because evidence of braking is so important to the investigation of overrun accidents, it is recommended that this data should be recorded on all existing aircraft exceeding 230,000 kg maximum weight and on all new aircraft exceeding 27,000 kg maximum weight.

2.5 The commander's actions

In assessing the extent to which the commander's actions may have contributed to the accident, it is necessary to examine first the information available to him. He knew the runway length, the maximum permitted weight for landing in wet conditions and the required landing configuration (42° flap and nominal 90% N1 reverse thrust). He also knew from the OM that he could not land safely if the runway was slippery, and that his company classified Leeds Bradford as a Category A airfield presenting no special difficulties. The runway was not notified as liable to be slippery when wet and he could therefore assume that an acceptable level of wet runway friction was available (UK Air Pilot). If he had had to make a judgement himself on whether or not the runway was slippery he could have made this judgement only on the basis of the depth of water on the runway; the slippery runway performance applying in standing water in excess of 3 mm (OM). All the information available to him, therefore, indicated that he could expect to land safely using standard operating techniques.

His actions appear to become relevant from the point of his late selection of landing flap, which has already been discussed. The most significant contribution to threshold speed, however, came from the autothrottle, which increased power after this selection. It must be considered, therefore, whether or not he should have left the autothrottle engaged when it was adding power to maintain a speed some 8 kt above V_{ref} + 5 kt. Perhaps he should have disengaged it but, if he had done so, he would have been required to maintain the speed indicated by the speed deviation pointer, and this pointer is referenced to the same signals as the autothrottle. Whilst, then it might be considered that faced with a short, wet runway he would have shown better airmanship if he had overridden or disengaged the autothrottle and deliberately flown the aircraft at a speed below that indicated by the speed deviation pointer, he cannot be criticised for poor airmanship on these grounds because his conduct of the final stage of the approach conformed to company operating procedures. Nor would it be reasonable to argue that, because the landing distance would have been shorter if the aircraft had crossed the threshold at a lower speed, the pilot should have achieved this lower speed for it must be acknowledged that the speed he achieved was within the bracket specified for the aircraft's scheduled landing performance. Moreover, from the speed actually achieved, the aircraft would have stopped within the scheduled LDR if the actual braking effectiveness had been better than .14.

The only action of the commander's that diverged from the operating procedure required to achieve the scheduled landing performance was the timing of his application of brake. This did not meet the Flight Manual requirement for brakes to be applied as soon as practicable after mainwheel touchdown but it did comply fairly closely with the landing technique described in the OM. (The OM has since been amended to state that the brakes should be applied "when the main gear wheels are firmly on the ground"). In assessing the likely effect of earlier brake application, the very poor brake retardation measured for the first 8 seconds of the landing roll appears to indicate that earlier application would have had little effect on the length of the landing roll. Since the accident it has been suggested that the reason for the poor brake retardation was that the pilot applied the brakes later than he thought he had done and that he failed to apply sufficient pressure to the pedals at any stage of the landing roll. This point has been argued in paragraph 2.4.2 above, and the balance of evidence does not support such a hypothesis. The poor braking effectiveness throughout the landing roll still remains to be explained.

2.6 **The runway surface**

The scheduled landing performance is based on a mean braking coefficient of friction of .2242 over the whole of the full-braked portion of the landing roll. It can be seen from Appendix 2 that this value was reached only after the aircraft speed had reduced to 45 kt, approximately 4 seconds before the nosewheel overran the runway end, and that the average throughout that part of the landing roll where braking effectiveness could be measured was approximately .09, compared with the scheduled value of .2242. Having taken account of any contribution to these low figures that may have been made by the commander's braking technique, it must be concluded that most if not all of this lack of braking effectiveness was due to the condition of the runway surface.

The possibility that at the time of the accident the friction of the runway had been reduced by an accumulation of industrial deposits and dust was considered. Such contamination might have been present after a prolonged dry period but the rainfall records for the Leeds Bradford area showed that there had been sufficient rainfall at and near the airport during the 6 days prior to the accident to make this unlikely.

2.6.1 *Runway surface friction*

Regular Mu–Meter tests have given rise to no concern about the level of friction available on the surface of runway 14 at Leeds Bradford. Although the readings taken in naturally wet conditions show quite wide variations, at no time have they fallen to a level at which the runway would be notified as slippery when wet. The 3 measurements taken by CIT during the previous 5 years using a self-wetting Mu–Meter in standard conditions have also given acceptable readings. (It remains to be explained, however, how this properly calibrated method of measurement could have shown an apparent improvement in readings between the .55 measured in 1980 and the .65 measured in 1982.) The latest readings, taken after the accident, show the friction to be above .45 but somewhat below the average of the UK runways measured in 1982. (.58 against .66, with only 6 out of 49 giving lower readings.)

2.6.2 *The limitations of runway friction measurements*

ICAO recommendations regarding acceptable levels of friction are expressed in terms of the readings of several different types of friction testing vehicles in use by member states, but correlation between different vehicles is poor and no direct correlation has yet been demonstrated between any vehicle currently in use and aircraft braking performance. As far as the Mu–Meter is concerned the current standard is that, if the readings at 40 mph are consistently above .45, the runway will not be notified as liable to be slippery when wet and, according to the UK Air Pilot, "pilots may assume that an acceptable level of wet runway friction is available". This was clearly not the case in this accident. It may be that the figure of .45 is too low to provide a reasonable safety margin on runways of critical length in view of the apparent inconsistencies in the measuring method. At Roswell, for example, several of the Mu–Meter readings were above .45 but the Lockheed Aircraft Corporation considered the runway to be "more slippery than normally required for aircraft certification". It would be difficult, however, on the evidence available for the UK alone to set a higher value as long as many other ICAO member states use the same, or a similar, level of friction to determine whether or not a runway is slippery when wet. The measured friction of the runway at Leeds Bradford, however, cannot be considered in isolation.The depth of water on the runway at the time of the accident is also important.

2.6.3 *The depth of water on the runway*

The airport operations staff assessed the runway as wet but not flooded, an assessment supported by the evidence of the drivers of the fire vehicles who drove along it one minute after the accident. There was, however, enough water to produce visible spray from the mainwheels on touchdown and a dense trail of spray behind the aircraft during the landing roll. None of this evidence really answers the question of whether or not there was enough water on the runway to reduce the braking effectiveness of the aircraft to the low level that was achieved. The condition of the aircraft tyres after the accident showed that neither dynamic nor reverted rubber hydroplaning occurred but this does not exclude the possibility of brake-induced hydroplaning such as occurred during the Roswell trials in water depths of only half a millimetre. Nor does tyre condition exclude the possibility of thin film lubrication, as described in the report by the Thompson Aircraft Tyre Corporation. Perhaps the best indication of the degree of wetness of the runway comes from the Thompson report, which attributed the light marks found on the runway to "the scouring action provoked by the water which is abruptly blown away under the high hydrodynamic pressures effect in the footprint area". It is reasonable to assume that, after all the water that could escape through the tyre treads and runway grooves had escaped, there was still enough water under the tyres to produce "high hydrodynamic pressures". It may therefore be concluded that there was a significant depth of water on at least the last 457 metres of the paved surface, where the light marks were seen.

2.6.4 *The limitations of the reporting of runway states*

The responsibility for assessing the state of a runway rests with the aerodrome operator. The assessment is then passed to pilots by air traffic control but the information available to pilots is limited. The only descriptions that may be used are "damp", "wet", "water patches" or "flooded". In the absence of significant visible patches of standing water, the single description "wet" must serve to cover the wide range of conditions from slightly more than damp to a uniform but shallow covering of water up to a millimetre or more in depth. Because water depth is rarely measured, and it is extremely difficult to measure depths as low as 1 mm anyway, assessments of runway state are purely subjective and depend very much upon the knowledge and experience of the observer. When, therefore, a runway is covered overall by a thin film of water, as it may well be during and after moderate rain, it may be described as merely "wet" because the definition of "flooded" ie, "extensive standing water is visible" may appear to the observer to describe a more severe condition. Yet such a thin film of water on a runway of poor texture can cause a critical reduction in brake effectiveness, as was shown at Roswell.

2.6.5 *The runway texture depth*

Before good tyre to runway contact can be made, any water on the runway surface must escape either through the grooves in the tyres or through the drainage channels in the runway texture. It must be asked, therefore, if the texture of the runway at Leeds Bradford was adequate for the degree of wetness. The texture measurements taken by CIT showed the average texture of the runway to be .37 mm, varying from .52 mm on the new extension to as low as .19 mm close to the end of runway 14. These measurements were taken using the grease patch method which was used during the CAA's survey (carried out by CIT) of UK runways in 1982, and which appeared to show consistent results at that time. The highest texture measured on a concrete runway in 1982 was .55 mm and the lowest was .39 mm. Over a further range of texture measurements taken in previous tests in the UK and the US and published in 1971 by the Engineering Sciences Data Unit (ESDU), 7 concrete runways classified as "typical of most lightly textured concrete" showed a texture depth ranging from .12 to .23 mm, and 4 concrete runways classified as "heavily textured concrete" had texture depths between .29 and .41 mm. These figures lend some credibility to the CIT measurements. On the other hand, the measurements of runway 14 at Leeds Bradford taken by the West Yorkshire Highways Laboratory using the sand patch method supported by laser meter readings show an average texture depth of .66 mm (sand patch), which is higher than the texture measured on any concrete runway in the UK in 1982, and higher than the best figure quoted in the ESDU report for the heavily textured runways measured. Clearly there is a significant difference in the results obtained by these different methods of measurement and, at present, there is very little data available on the correlation between the different methods. No conclusion may be drawn about the real depth of texture of the runway without further investigation.

2.6.6 *The nature of the runway texture*

Whatever the real texture depth of the runway, the microtexture of its surface is of equal or even greater importance. It is the sharpness of this microtexture that must overcome the viscous effects of a thin film of water, break its surface tension and establish tyre to runway contact. The Thompson report described the lubrication phenomenon as being "provoked by the presence of a thin film of water between the tyres and a relatively smooth and wet runway". If runway 14 at Leeds Bradford is "relatively smooth" in this sense then it might be expected that Mu–Meter readings would indicate this, but they do not. It might be expected, however, that after 19 years of use, the original texture had suffered some degree of wear, and the report by CIT refers to and shows photographs of some areas that have been worn fairly smooth. These may be compared with the photographs taken by the West Yorkshire Highways Authority which show areas of the runway where the original texture can be seen. However, no firm conclusion can be drawn about the true nature of the texture of this runway because of the conflict in the evidence and it is recommended that the CAA investigate in detail both its depth and microtexture.

2.7 UK Certification of TriStar landing performance

The validity of the results of the wet runway performance trials conducted in 1972 for UK certification of the TriStar depend to a very large extent on the validity of the assessment of the friction of the artificially wetted runway used for the flight tests. This investigation has brought to light two serious weaknesses in this assessment. Firstly, although the asphalt surface was not used during the braked stops, the low Miles Trailer readings on this surface were allowed to influence the assessment, and this resulted in an upward adjustment of 8.1% in the measured braking effectiveness that was not justified by the evidence. Secondly, the correlation measured by MOD(PE) between Miles Trailer and Mu–Meter readings in water depths less than ½ mm implies that, if a Mu–Meter had been used to measure the friction of the trials runway, it would probably have shown the runway to have had higher friction than the CAA Reference Wet Hard Surface (RWHS), and the measured braking effectiveness would have had to be factored downwards to produce a valid result.

The doubts about the validity of the flight test results are reinforced by the performance of the TriStar at Roswell in 1973, when the aircraft achieved less than half its scheduled braking effectiveness. The CAA have since stated that they considered the Roswell trials did not cast doubt on the UK scheduled performance because the Roswell runway was not representative of operational UK runways either in texture depth or friction characteristics. Yet several of the Mu–Meter readings associated with the poor levels of brake effectiveness were above the "slippery" level of .45, and the average texture of the runway, .216 mm, was not dissimilar from the grease patch measurements taken at Leeds Bradford after the accident. It does not, therefore, seem to be a safe assumption that the Roswell runway was very much worse than some of the runways that might be encountered by the TriStar in UK service. In fact, the very close parallel between the performance of AI at Leeds Bradford and the results of the Roswell trials show that it would be prudent for the CAA to take notice of these results. The available evidence thus clearly indicates that the CAA should re-examine the scheduled wet runway performance of the TriStar as derived from the trials conducted at Boeing Field in 1972.

The 1979 report by MOD(PE) raises the wider question of the suitability of the RWHS as a reference for the measurement of wet runway performance. The report showed that the RWHS was, in fact, a high friction surface. The CAA have stated that they gave little credence to the MOD(PE) results, regarding them as an indication of the unreliability of the readings of friction measuring vehicles. However, the MOD(PE) conclusions were based on Miles Trailer measurements and, if they are not valid, it is difficult to see how the TriStar scheduled wet runway landing performance can be valid, for it also was determined against Miles Trailer measurements. Accordingly, it is considered that there is a risk that the RWHS may have somewhat better friction than the average runway likely to be encountered by aircraft on the UK register, and safety margins on surfaces below this notional standard may be seriously reduced.

However, it is not intended in this report to cast doubt upon the validity of the principle of certifying aircraft performance by the Reference Method. The method attempts to take realistic account of the effect of a wet runway surface on aircraft stopping distance; by penalising aircraft with poor stopping performance it encourages the development and use of effective retarding systems. If there is a weakness in the method, it could be in the definition of the Reference, for there is evidence to suggest that it specifies a higher coefficient of friction than is likely to be available on many older runway surfaces. The RWHS should be re-examined to determine whether or not it represents today a safe level of friction for the certification of aircraft performance. If it does not, then the margins allowed for in the scheduled landing performance of all aircraft operating on the UK register whose performance has been determined by the Reference Method, should be reviewed.

2.8 **Margins in certification**

If, when the landing performance of the TriStar is reviewed it is held to be correct before the field length factor is applied, and if the RWHS is confirmed to be a suitable reference for performance certification, then the safety margins built in to scheduled landing distances must be examined for they proved to be inadequate in the case of this accident. Of the main components of this safety margin given by the CAA (see paragraph 1.17.2) the screen height, threshold speed and time/distance in the flare of AI have already been discussed and shown to have had lesser values than those used when the performance of the aircraft was calculated from the data measured during the certification flight trials. When AI touched down, therefore, an element of the safety margin at least equivalent to the 8% field length factor remained unconsumed and, if the remaining variables that directly affected the aircraft's stopping capability had been at the "average" values assumed for certification purposes, the aircraft should have stopped some 129 metres (8%) short of the LDR of 1740 metres. The combined effects of the later time of brake application and the earlier achievement of full reverse appear to have had the potential to shorten rather than to extend the landing distance (if the inherent artificiality of the theoretical performance equations is accepted), and the actual threshold speed should have produced a shorter landing distance than that scheduled on a threshold speed of V_{ref} + 15 kt. Calculations showed that the potential savings from these factors amounted to 57 metres. The aircraft should have stopped, therefore, some 1544 metres from the landing threshold. In fact it continued for a further 395 metres before overrunning the end of the concrete and, on a level runway, would have continued for approximately 27 metres more before coming to rest, a total extension of 422 metres beyond the theoretical unfactored landing distance.

Of the remaining variables, the state of the tyres, the performance of the anti-skid system and the pressure applied by the commander to the brake pedals have been discussed and cannot be held to account for the poor braking effectiveness achieved by the aircraft. It is concluded, therefore, that the runway surface did not provide an adequate level of friction because of either the nature of its surface or the depth of water on it, or a combination of both. Yet both of these variables appear to have been within acceptable limits, the first from Mu–Meter readings and the second by visual observation. If then all elements of the performance certification are held to be correct, the safety margin was inadequate.

If the margin built in to landing performance is too low it might well be asked why such accidents do not occur more often. The reason may be that nearly all the runways used by the TriStar in UK service are long enough to allow additional margins. Of the 169 runways worldwide for which data was provided in the British Airtours OM only one is shorter than runway 14 at Leeds Bradford, by just 2 metres, but is at sea level and, allowing for the difference in pressure altitude, is therefore effectively some 30 metres longer. Of the rest, not one has an LDA less than the 1966 metres actually used by AI at Leeds Bradford in the conditions prevailing at the time of the accident. There can be little assurance, therefore, from in-service operations that the margins allowed in landing performance are adequate. These margins are expected to cover variations in landing performance that may occur due to runway friction and wetness; a variation that is so wide that it can hardly be covered by the margins currently applied. The situation is aggravated by the variability of Mu–Meter measurements and their lack of correlation with aircraft performance, and the imprecision of subjective assessments of runway wetness. If, then, the TriStar scheduled performance was correct, the safety margin was clearly very much too low to encompass the variation from "average" conditions that occurred at Leeds Bradford and it must be recognised that there is a risk of a similar accident occurring in the future. Moreover, if expected brake effectiveness cannot be achieved on a runway such as Leeds Bradford after a high-speed rejected take-off when safety margins are less favourable the result could be more serious, for the aircraft could be expected to overrun the runway at a higher speed.

It is recommended, therefore, that the CAA review the margins built in to scheduled landing performance of aircraft certificated using the Reference Method to take account of the wide variations of runway friction that occur in wet conditions. Also, unless the doubts raised by MOD(PE) about the validity of the CAA Reference Wet Hard Surface are satisfactorily resolved, the margins allowed for rejected take-off performance should also be reviewed.

2.9 Survival aspects

It is noteworthy that all 8 exits and escape slides functioned correctly and facilitated speedy evacuation of the aircraft, for which the cabin crew deserve to be commended. But for the steep angle of the rear slides, the evacuation might have been completed without even minor injury. It seems sensible, though, that these rear slides should have been used for, although there was no obvious sign of fire when the aircraft came to rest, the cabin crew could not be certain that fire would not start. The prompt reaction of the airport fire service and the local ambulance services also deserves to be commended.

3. Conclusions

(a) *Findings*

(i) The operating crew were properly licensed and adequately experienced to conduct the flight.

(ii) The aircraft had a valid Certificate of Airworthiness and Certificate of Maintenance and there was no evidence of any defect or malfunction that could have caused or contributed to the accident.

(iii) The aircraft was below the maximum landing weight authorised by British Airtours for the runway, and its centre of gravity was within permitted limits.

(iv) The speed and height of the aircraft over the landing threshold were within the limits required for the achievement of the scheduled landing performance of the aircraft.

(v) The downslope on the first part of the runway potentially reduced the landing distance available but the pilot achieved a touchdown within the normal distance from the threshold.

(vi) The runway surface was reported to the commander as wet, and he was advised that there had been a recent moderate rain shower.

(vii) The aircraft exceeded its scheduled landing distance required by 199 metres before running over the end of the paved concrete surface.

(viii) More reverse thrust was used throughout the landing roll than is allowed for in the scheduled landing performance.

(ix) The commander's braking technique complied with British Airtours standard procedures but differed from that specified in the Flight Manual as necessary to achieve the scheduled performance.

(x) The friction available on the runway was less than that upon which the wet runway landing performance of the aircraft was scheduled.

(xi) The scheduled wet runway performance of the aircraft and the Reference against which it was determined may not be valid.

(xii) The aircraft suffered substantial damage when the nosewheel collapsed in soft ground beyond the end of the runway.

(xiii) Emergency evacuation procedures worked correctly and all passengers left the aircraft quickly without serious injury.

(xiv) The airport fire service and local ambulance services reacted promptly and efficiently.

(xv) The discrepancy revealed between the groundspeed derived from the recorded airspeed and that derived from the longitudinal accelerometer warrants further investigation by the CAA.

(b) *Cause*

The accident was caused by the failure of the aircraft to achieve the expected level of braking effectiveness on the wet runway.

4. Safety Recommendations

It is recommended that:

4.1 The UK CAA should re-examine the scheduled runway performance of the TriStar as derived from the trials conducted at Boeing Field in 1972.

4.2 The UK CAA should re-examine the Reference Wet Hard Surface to ensure that its friction characteristics are appropriate to the present standards in use for detecting runways liable to be slippery when wet.

4.3 In conjunction with 4.2 above, the UK CAA should review the scheduled runway performance of all aircraft whose performance was measured for certification purposes against the Reference Wet Hard Surface.

4.4 The UK CAA should examine the nature of the texture of runway 14 at Leeds Bradford Airport to ensure that it offers a safe level of friction for aircraft in wet conditions.

4.5 Regulatory authorities should identify runways with initial downslopes that are severe enough to affect significantly aircraft landing performance, and should require aircraft operators to take account of such slopes when determining maximum landing weights.

4.6 UK registered aircraft above 11,400 kg maximum all up weight should be equipped with a CVR installation complying with the current CAA Specification 11.

4.7 Provision should be made for brake pressure to be recorded on all existing aircraft having a maximum weight exceeding 230,000 kg and on all new aircraft having a maximum weight exceeding 27,000 kg.

M M Charles
Inspector of Accidents

Accidents Investigation Branch
Department of Transport

January 1987