ACCIDENT

Aircraft Type and Registration:	Tornado GR4A, ZA 371
No & Type of Engines:	Two Rolls-Royce RB 199 Mk 103 turbofan engines
Date & Time (UTC):	5 August 2008 at 1556 hrs
Location:	Newcastle Airport
Type of Flight:	Military
Persons on Board:	Crew - 2 Passengers - None
Injuries:	Crew - None Passengers - N/A
Nature of Damage:	Damage to nose landing gear and forward underside panels
Commander's Licence:	Qualified Service Pilot
Commander's Age:	28 years
Information Source:	AAIB Field Investigation

Synopsis

The aircraft diverted to Newcastle Airport following a bird strike. During landing, an electrical connection in the right engine reverse thrust control system became intermittent, producing random oscillations of the engine's reverse thrust buckets. The fault was such that it was not clearly indicated to the crew until the aircraft had travelled a considerable distance along the runway and the pilot did not take the appropriate action of retarding the right power lever. With full dry power selected on both engines throughout the landing roll, there was thus a considerable forward component of thrust, and the pilot was unable to stop the aircraft before it overran the runway end.

Background to the investigation

The accident was the subject of a full investigation by a Royal Air Force Board of Inquiry (RAF BoI), assisted by the AAIB under the terms of a standing agreement. Additionally, as the accident occurred at a civilian airport, the Chief Inspector of Air Accidents ordered an AAIB Field Investigation under the provisions of the *Civil Aviation (Investigation of Military Air Accidents at Civil Aerodromes) Regulations 2005*.

History of the flight

The aircraft was the second of a pair of Tornado aircraft, engaged on a routine squadron sortie. It was crewed by a pilot and a weapon systems operator (WSO). The former was an experienced Tornado pilot, who had recently completed an instructional tour on Hawk aircraft. The WSO had recently completed operational training and had joined the squadron a month earlier.

The aircraft was manoeuvring about 40 nm north-west of Newcastle when it suffered a bird strike. Recorded flight data showed that it occurred as the aircraft was accelerating through 440 kt, at a height of 430 ft above ground level (agl), parameters which were within the authorised limits for the exercise. The pilot climbed the aircraft to a safe altitude, whilst the crew of the lead aircraft performed a visual inspection. This revealed damage to the Forward Looking Infra-Red (FLIR) sensor, which is mounted in a blister below the forward fuselage. Considering the possibility that an engine may also have suffered damage, the crew elected to divert to Newcastle Airport for a precautionary landing. There was some discussion between the pilot and WSO about the suitability of Newcastle. It was agreed that the airport was a suitable diversion, although there was no discussion about the runway length or its configuration.

Before starting the recovery to Newcastle, the crew carried out a low-speed handling check, using a forward wing sweep/MID flap configuration in accordance with recommended procedures. An approach speed of 175 kt was calculated (based on the aircraft's mass), which was expected to correspond to an approach Angle of Attack (AoA) of 10 units[1]. This was considerably faster than normal landing speeds, because of the reduced flap setting (MID rather than DOWN) and higher than normal landing fuel load. The aircraft was capable of jettisoning fuel, but this was not discussed by the crew.

Although both engines appeared to be operating normally, the crew planned for a precautionary single-engine approach profile, to cater for a possible loss of engine thrust during the approach. However, there was no discussion about the stopping capability of the aircraft should an engine actually fail before landing, which would leave only half of the reverse thrust capability (reverse thrust being the main aid to deceleration after landing).

The crew informed Newcastle Air Traffic Control (ATC) of the damaged FLIR and requested a remote parking location, deciding there was a potential, although small, risk to personnel from damaged internal components. Runway 07 was in use, with light winds; the visibility was greater than 10 km, with scattered cloud cover at 2,000 ft, and rain showers in the vicinity. Once the aircraft had commenced recovery to Newcastle, the lead Tornado climbed from the area to return to base.

At about 5 nm from touchdown, ATC issued landing clearance and passed a surface wind of 120º(M) at 5 kt. The aircraft touched down 90 m (295 ft) beyond the runway displaced threshold, at 180 kt; the lift dump system operated normally and the pilot selected reverse thrust. He reported that cockpit indications of correct reverse thrust system operation were obtained, before he advanced the power levers to the maximum 'dry power' (non-reheat) position.

Most eye-witnesses on the ground later reported that the aircraft appeared fast during landing and did not slow down on the runway as quickly as they had expected. As the aircraft approached the runway mid-point, the pilot became aware of the poor deceleration and saw flickering of the cockpit indication of right engine reverse thrust. He selected the system to OVERRIDE and started wheel braking (on the Tornado, the wheel brakes are normally only used towards the end of the landing roll). As he did so, a red REV warning caption illuminated on the Central Warning Panel (CWP), accompanied by an audio alarm tone which indicated that a fault had occurred which affected the deployment of an engine thrust reverser. Both power levers remained at the maximum dry power setting throughout the landing roll.

Although the aircraft decelerated at an increased rate with wheel brakes applied, the pilot realised that it might

Footnote

[1] Approach and landing in the Tornado, as with many fast jet aircraft, is flown primarily with reference to AoA.

still overrun the runway and warned the WSO to this effect. The aircraft left the paved surface at 33 kt ground speed, still with both power levers at maximum dry power and with reverse thrust selected. The aircraft's nose landing gear dug into the soft ground and collapsed rearwards. The aircraft came to a stop in a nose-low attitude, its nose 30 m beyond the paved surface. The pilot shut down both engines and ordered an emergency ground egress: the WSO left the aircraft first, 36 seconds after it came to a stop, followed 17 seconds later by the pilot. Three rescue appliances of the Airport Fire Service (AFS) had already taken up standby positions adjacent to the runway, so were on scene shortly after the aircraft came to a stop. There was no fire.

Airport operations were suspended for about 90 minutes, before recommencing with reduced runway operating distances. Normal operations were resumed at 0622 hrs the following morning, after the aircraft had been removed from the Runway 07 overrun area.

Initial aircraft examination

When first examined by the AAIB, the aircraft had been salvaged and was resting on a 'low loader' vehicle with landing gear retracted. This prevented any more than an external examination. In particular, access doors on the underside of the fuselage could not be opened. The aircraft showed clear evidence of damage from the overrun. The nose gear leg had been displaced aft to beyond the normal angle as the result of an overload failure of the lug attaching the drag link to the aircraft structure. The right-hand thrust reverser bucket was seen to be not fully flush with the surrounding structure, suggesting incomplete retraction and stowage but the left reverser bucket appeared fully retracted and stowed.

When the aircraft was placed on trestles and jacks, a more detailed examination was possible, as well as functional testing of the reverse thrust system, Testing utilised an external pneumatic power source. Following the tests on the left reverser, an electrical connector, designated C3, joining the engine wiring loom to the solenoid powering the air selector valve for the reverse thrust system on the right engine, was seen to be incorrectly secured. The screw cap of the harness connector was seen to be positioned at the outer end of the threaded section on the solenoid housing. On further examination, it was found to be resting against the end of the threaded portion, held in position by the geometry and rigidity of the harness.

Recorded information

Recorded information was available from: radar and radiotelephony (R/T) data from Newcastle Airport; various recording equipment on board the aircraft; conventional and Forward-Looking Infra-Red (FLIR) video from cameras mounted on the AFS rescue vehicles, and Newcastle Airport's CCTV security cameras. The information in the following paragraphs was derived from this recorded information.

During final approach, there was some discussion on a discrete frequency between the pilot and the crew of the lead Tornado (which was by now climbing from the area) about the damaged IR and associated after-landing procedures. As the aircraft descended through 700 ft agl, the pilot tasked the WSO with consulting the Flight Crew Checklist (FCC) to see if there was a procedure for FLIR damage, which there was not. Further discussion between the pilot and the lead aircraft continued intermittently until ZA 371 was less than 200 ft above the runway.

Lift dump deployed one second after touchdown and was verbally confirmed by the WSO. There was no recorded data concerning the cockpit selection of reverse thrust, but both engine power levers were advanced from idle to maximum dry power between two and three seconds after touchdown. Both engines responded normally and reached commanded power about seven seconds after touchdown.

A memory module in the right engine control unit stored reverse thrust bucket position data, recorded at half second intervals. The two positions capable of being recorded were 'fully deployed' and 'not fully deployed', the signal for both coming from the same 'deployed' sensing microswitch that signalled correct reverser deployment in the cockpit. The data showed that the right reverse thrust buckets had not reached a fully deployed state at any stage of the landing roll. The left engine was not equipped with a memory module, so there was no recorded on-board data concerning the actual position of the left thrust reverser.

Thirteen seconds after touchdown, the aircraft had slowed to 140 kt, with slightly more than 1,067 m (3,500 ft) of LDA remaining. Between touchdown and this point, three very brief sounds were recorded, which were confirmed by spectral analysis to be the Central Warning System (CWS) audio tone, though too brief to be easily recognisable as such. There was no apparent crew reaction to these sounds.

Just below 140 kt, the pilot said "…BRAKING", which was followed almost immediately by a further, recognisable CWS audio tone. It lasted about 1.5 seconds: the pilot said (apparently in response to the CWS activation), "OK THAT'S A REV CAPTION GONE TO OVERRIDE". About two seconds later, at 104 kt and with about 575 m (1,890 ft) of runway remaining, the CWS audio tone sounded again, for about 3.6 seconds. As the aircraft approached the runway end, the pilot steered it left by about 20°; it left the paved surface at 33 kt ground speed.

Infra-red (IR) video of the aircraft, recorded by cameras on the AFS vehicles, showed an apparently normal reverse thrust exhaust IR signature from the left hand engine (the right side not being visible); a significant amount of reverse thrust was clearly being achieved on the left engine during the landing roll and at the point the aircraft left the paved surface. However, the images also showed a strong IR plume extending horizontally behind the aircraft from the engine nozzle area. IR images of the rear of the aircraft for some time after the accident showed a significant variation in the IR signature about both engines: the left nozzle area and surrounding structure exhibited more widespread heating than the right side, which showed heating effects confined to the nozzle area only. By about 60 minutes after the accident, IR signatures of both engines were of similar size and shape.

Airport CCTV footage (with frames at one second intervals) also showed an apparent anomaly at the rear of the aircraft which persisted for the entire recorded landing roll. The appearance of the left and right engine nozzle areas was different: what appeared to be reflected sunlight was seen only from the region of the left engine nozzle. As the aircraft left the paved surface, two debris clouds were seen, caused by reverse thrust exhaust efflux; there was a notable difference in size of the two clouds, the left one being larger.

Aircraft information

General

The Tornado GR4A is an armed tactical reconnaissance variant of the Tornado GR4 variable geometry all-weather attack aircraft. The accident aircraft was in a standard squadron configuration, carrying two 1,500 litre external fuel tanks and a range of external stores specific to its role.

Central Warning System (CWS)

The CWS alerts the crew to abnormal and emergency situations, and sytem failures. These are indicated by illumination of amber and red captions on a CWP in each cockpit. Amber captions signify secondary alerts while red captions denote primary warnings and are accompanied by an audio tone. All captions are accompanied by two flashing 'attention getters' on the coaming in each cockpit. Generally, an illuminated caption will cancel automatically when the condition causing it no longer exists. The audio tone and attention getters cancel if the condition no longer exists, or if a crew member pushes either of the attention getters.

Reverse thrust system

Reverse thrust is achieved by swinging buckets into the engine exhaust efflux, deflecting it forwards. The buckets are electrically signalled and pneumatically operated, and each incorporates a mechanism to lock it in the stowed position. Locking is achieved following reverser retraction by linear movement of a dowel into engagement with a lug mounted on the relevant bucket.

Reverse thrust operation is possible only on the ground, when the right main undercarriage 'weight on wheels' switch is made. It is selected by pilot action on the power levers, which sends control signals to the thrust reversers of both engines simultaneously. High pressure engine air is then routed to unlock the reverser buckets, if stowed, and to drive an air motor in either the 'deploy' or 'stow' direction. Three microswitches signal the buckets' positions to the electronic control for safety circuits and cockpit indications.

With the buckets in the reverse thrust position, forward movement of the power levers gives reverse thrust. The power levers can be moved to the maximum dry power position after selection of reverse thrust, irrespective of whether the buckets actually reach the fully deployed position. However, with reverse thrust selected, the reheat range is not selectable.

Reverse thrust system: cockpit indications and controls

Figure 1 shows the main cockpit indications and controls. With the exception of training variants of the Tornado, the control panel is in the front cockpit only. Two three-position magnetic indicators (MIs) show the pilot the status of the reverse thrust buckets. The indicators show grey when the buckets are stowed, cross-hatched when they are in transit, and REV when they are fully deployed. The signals for the MIs come from the microswitches on each engine's reverser mechanism.

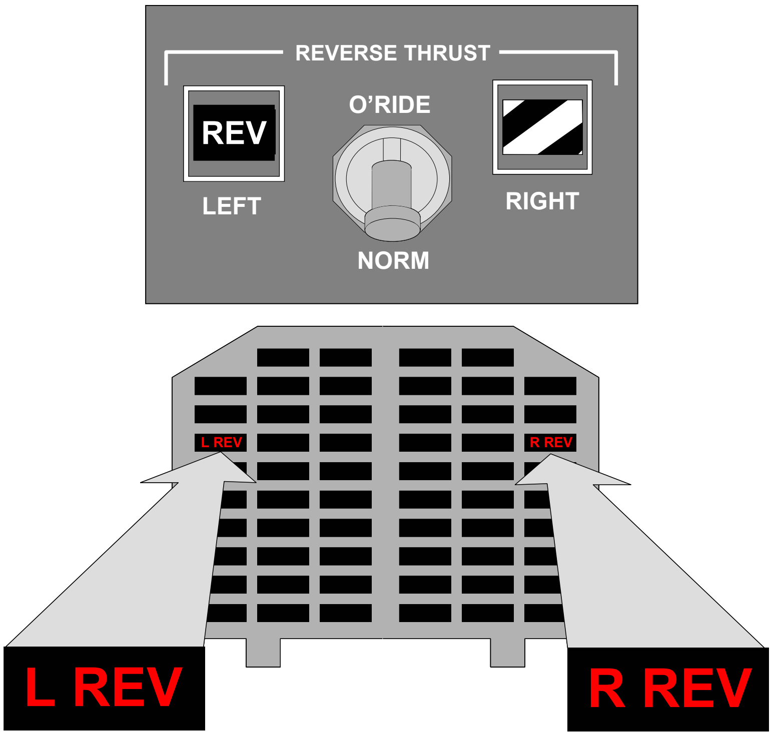

Figure 1

Control panel (top) and CWP (bottom)

Between the MIs is an override switch, used in cases of malfunction and in certain procedures. The CWP includes two red captions, L REV and R REV, which illuminate to indicate thrust reverser malfunction. To avoid confusion in this report, a red CWP caption is hereafter referred to as a CWP REV warning, whilst the MI indication of correct reverse thrust is referred to as an MI REV indication.

Reverse thrust system malfunctions

An inhibit circuit ensures that the reverser buckets of one engine cannot deploy whilst those of the other engine remain in the stowed position. Should an engine's reverser buckets not start to deploy within 0.5 seconds of being commanded, the electrical signals to both engine reversers will be interrupted, causing the buckets to re-stow. Should this occur, the associated CWP REV warning illuminates on the CWP, accompanied by the audio tone. In this case, the warning is 'latched' and can only be cleared by maintenance action. The pilot can still use reverse thrust on the other engine by selecting the system to OVERRIDE; this restores electrical supply to the serviceable reverser, enabling its deployment.

If, having unstowed correctly when commanded, one reverser should fail to reach the fully deployed position, the other reverser will not be inhibited from operating. However, the failed reverser will be indicated to the crew after a two-second delay by illumination of the relevant CWP L REV or R REV warning, together with the audio tone. In this failure case, the CWP REV warning is not latched; it will extinguish (and the audio tone will cease) if the microswitches subsequently sense a fully deployed or stowed condition. As the serviceable reverser system is not inhibited in this case, the override switch has no effect.

The FCC gave crew actions for a CWP REV warning in flight but not during landing. Similarly, the Aircrew Manual for the Tornado GR4/GR4A did not give crew actions for a ground malfunction. It was noted that the system description in the Aircrew Manual could be read in a way that could cause the reader to understand, incorrectly, that anytime a CWP REV warning illuminated, both engines' reverser buckets would re-stow automatically, when in fact this only occurred if one reverser failed to unstow within 0.5 seconds of selection, as described above.

Reverse thrust system testing

A series of tests were carried out using external pneumatic pressure supplies and external electrical power. The left engine reverse thrust system was tested and functioned normally. The right engine reverse thrust system failed to function when tested in its 'as found' condition, but tested normally when the C3 connector was electrically bypassed. The connector, and the servo valve to which it connected, were subjected to detailed examinations; these showed that both were serviceable items.

Further tests, designed to simulate an intermittent connection at the C3 connector, were conducted on a ground training aircraft at a Tornado maintenance training facility. When the reverse thrust system was operated with the simulated intermittent C3 connection present, the reverse buckets on that engine would 'hunt' in various positions. It was found that they could move briefly to the fully deployed position, before retracting again and hunting about the stowed position. On occasions, the reverse buckets 'bounced' into the locked position, initiating movement of the locking dowel. However, the buckets quickly moved out of the locked position again, before the locking dowel could engage. As a result, the tests sometimes ended with the buckets sitting against the locking dowel, in the manner in which the lower right hand bucket of ZA 371 had been found after the accident.

During the tests, a cockpit REV indication showed on the MI when the buckets reached the full deploy position, but would flicker at other times. It was noted that a CWP REV warning, and audio tone, could be generated if the reverser did not reach the fully deployed or stowed positions within two seconds. However, momentary closure of the position sensing microswitches as the buckets hunted often resulted in very brief activation of the warning and tone.

Airport information

Newcastle Airport (elevation 266 ft amsl) has a single runway, designated 07/25, which is 2,329 m long. The threshold of Runway 07 is displaced by 120 m, giving a Landing Distance Available (LDA) of 2,209 m. There is also a 15 m stopway[2] and a 90 m Runway End Safety Area[3] (RESA). The runway and stopway are 46 m wide, with an overall 0.35% down slope. The runway is equipped with lighting appropriate to a major airport, including red runway end lights. By comparison, the main runway at the crew's home base was 2,786 m long with arrester cables at between 488 and 690 m from each end. In common with other military runways, it is equipped with 'distance-to-go' marker boards, placed at each 1,000 ft along the runway: the runway at Newcastle Airport, like most civilian runways, was not so equipped.

The Newcastle runway is grooved along its full length to aid removal of surface water and thereby improve the takeoff and landing performance of aircraft. The runway was inspected hourly by the airport authority for condition and defects: the last inspection before the accident was at 1539 hrs, when the runway was reported to be serviceable.

Landing performance

The Tornado is unusual amongst modern fighter/attack aircraft in that it employs reverse engine thrust to aid stopping performance. It also uses a lift dump system, which deploys spoiler panels on the upper surface of each wing after landing. Reverse thrust is the main stopping aid. Wheel brakes are normally only used towards the end of the landing roll, and not normally above 140 kt. The aircraft is also equipped with a hook which is capable of engaging arrester cables, although cables are not installed at most civilian airfields in the UK.

Following the accident to ZA371, the aircraft manufacturer made a number of performance computations (based upon flight test results and computer modelling), for the aircraft's actual mass and configuration. These showed that, with only one engine at maximum reverse thrust and the other engine remaining at forward idle thrust, the aircraft was capable of stopping well within the LDA at Newcastle if wheel brakes were used from 140 kt. It was also determined that the aircraft could have been stopped within the remaining LDA when the first recognisable CWP REV warning occurred, at about 130 kt, provided that the right engine power lever was retarded to idle at that point and full wheel braking was used.

Footnote

2 Stopway is an area immediately beyond the end of the declared LDA, capable of supporting the aircraft's weight but not necessarily sharing all the runway's characteristics. At Newcastle, the stopway is a paved surface.

3 RESA is an area beyond the end of the runway and stopway, intended to reduce the risk of damage to an aircraft undershooting or overrunning the paved surface.

Previous disturbances of the reverse thrust system

The RAF BoI found that, since the right engine (complete with its reverse thrust system), was installed in the aircraft in December 2007, there had been no documented maintenance action which was likely to have disturbed the C3 connector; it was considered unlikely that an unofficial and unrecorded disturbance had taken place.

The last known disturbance of the C3 connector prior to engine installation was following post-rebuild engine runs, carried out on a dedicated engine test-bed. The reverse thrust system was inhibited for these runs, but reinstated prior to installation in the aircraft, and a maintenance requirement raised for functional testing. Existing documentation called for an independent inspection of the thrust reverse system, including the C3 connector, when it was disturbed during this process. However, it was found that this procedure was not routinely followed during the engine run and installation process.

The RAF BoI concluded that the C3 connector had been incorrectly fitted after the engine runs, when the reverse thrust system was reinstated prior to engine installation. No independent inspection of the connector took place and the engine was installed in ZA 371 in this condition.

Analysis

The flight was correctly authorised, and the crew was operating the aircraft within applicable manoeuvring limitations when the bird strike occurred. There was a choice of diversion airfields, but Newcastle Airport was the closest. The decision to divert there was in line with normal operating procedures.

The approach and landing were made at a heavier than normal landing mass (although below maximum), and with a reduced flap setting. These factors produced a final approach speed considerably in excess of the norm. Although the aircraft was capable of landing and stopping on the runway, the LDA was shorter than at the crew's home airfield, and the runway had no arrester cables. Consequently, any malfunction likely to adversely affect the aircraft's landing performance would require prompt recognition and response by the crew. The lack of runway distance-to-go marker boards would compound the situation, as it deprived the crew of critical information normally available to them at military airfields.

Considering the unusual configuration and speed, and consequent reduced safety margins, more detailed and relevant discussion between the pilot and the WSO may have better prepared the crew to deal with a subsequent reverse thrust failure. Although a precautionary single-engine approach profile was flown, the inferred possibility of landing at high speed with only one thrust reverser operative was not voiced in the cockpit. The discussion between the pilot and the crew of the lead Tornado about the damaged FLIR was a distraction at a critical time of the approach and probably contributed to the lack of a pre-landing briefing.

It is probable that the incorrectly fastened C3 connector had been present as a latent fault on the aircraft since the right engine was installed some eight months before the accident. The connector had been held in place by the electrical harness to which it was attached and it was probably the friction of the two contact pins that enabled them to remain engaged. The unfastened state of the connector, however, would have permitted progressive disengagement of the contact pins to occur over a prolonged period. During touchdown on the accident flight, this movement became sufficient for the connection to become intermittent. The reverser buckets probably deployed briefly initially, before oscillating between the stowed and deployed positions. The result of the right reverser bucket movement sequence was that the aircraft spent most of the landing run with full reverse thrust on one engine and a thrust situation varying between full reverse and full forward thrust on the other engine.

The left engine thrust reverser was serviceable and had operated correctly during the landing. The right engine control unit memory had not recorded a buckets 'fully deployed' signal at any stage of the landing roll, indicating that periods at full deployment would have been short (less than half a second). This, with the observed stopping performance and cockpit indications, suggests that the right engine reverse thrust buckets probably moved about a mean position which was closer to fully stowed than fully deployed.

Tests proved that the fault was capable of producing intermittent MI REV indications (as seen by the pilot later in the landing roll), and the sequence of very short CWS audio tones heard on the recordings. It was considered by the RAF Board of Inquiry that the pilot had probably seen the correct reverse thrust indications before advancing the power levers. He next looked at the MIs when it became apparent that the aircraft was not decelerating. Up to this point the lack of a recognisable CWP REV warning would have tended to confirm to the crew that the reverse thrust system was operating normally.

Reverse thrust malfunction indications were reportedly not uncommon during landing, though they were normally the result of minor microswitch rigging errors, causing the timer relays to sense an incorrect operation. This would be most likely to occur within 2 seconds of the pilot selecting (or deselecting) reverse thrust; fault indications part way through the landing roll were far less common. Thus, on most occasions when pilots were faced with CWP REV warnings, the power levers would be at idle. For a reverse thrust malfunction on landing, pilots would expect to have to make a decision about which power lever to *advance*, not about which to retard.

The action of selecting OVERRIDE would allow deployment of a serviceable reverser only if it had been inhibited from deploying through the 0.5 second timer relay. In all other cases (including this accident), selecting OVERRIDE would have no effect, since the serviceable reverser was not inhibited from operation. The logic of the system design was aimed at limiting the possibility of inadvertent thrust asymmetry. Whilst this was effective in the case of a 'hard' failure, it was not designed to cope with a rapidly changing condition between open and closed circuit in part of the operating system.

The pilot selected OVERRIDE when he noticed the MI REV indication flickering, and just before he first noticed the CWP R REV warning illuminate, at about 130 kt. His mindset would initially have been that the power levers were in the correct place for reverse thrust, since he had perceived no contrary indications to that point. When the REV warning then extinguished, it would have served to confirm to the pilot that his action had been successful, although a further check of the MIs would have shown that the right-hand buckets were still cycling. It is probably only when the CWP REV warning illuminated again shortly afterwards, that the pilot realised his action had not corrected the situation. At this point, the remaining stopping distance had reduced to about 600 m and, with the aircraft still at about 100 kt, the pilot recognised that a runway overrun was likely. The overrun situation rapidly became the pilot's priority (crew ejection may be warranted in a serious overrun case), particularly as the WSO was relatively inexperienced. The pilot therefore had minimal time or capacity, from that stage on, to further analyse the reverse thrust indications.

Although the malfunction as presented to the pilot may have been confusing and was certainly not common, the meaning of both a CWP REV warning and the lack of a REV indication on an MI was unambiguous – the reverse thrust buckets for the associated engine were not fully deployed. In either case, the priority should have been to retard the power lever to idle, and if this had occurred in a timely manner in response to either indication, the aircraft would, according to the performance analysis, have stopped on the paved surface.

Recommendations

The RAF BoI made a number of recommendations. These included actions to improve and clarify working practices within the relevant maintenance departments at the aircraft's base airfield, and improvements to Tornado flight crew training and reference documentation.

Conclusion

The latent fault in the right engine's reverse thrust system manifested itself during a precautionary landing which, because of the aircraft's weight and configuration, had to be made at unusually high speed. The nature of the fault was such that it was not clearly indicated to the crew until the aircraft had travelled a considerable distance along the runway, the poor deceleration probably being masked initially by the higher than usual speed. Cockpit indications accurately reflected the fault, but faced with an unusual and poorly documented failure case in a time-critical situation, the pilot did not take the appropriate action of retarding the right power lever.