A CRITICAL FUEL IMBALANCE !

Original idea from NTSB

From London to Athens : how a fuel imbalance lead to control difficulty !

HISTORY OF THE FLIGHT

The B737-400 departed from London Gatwick for a scheduled flight to Athens with the first officer as Pilot Flying (PF). A fuel load of 13,200 kg had been selected by the captain and this resulted in full wing tanks and 4000 kg in the center tank. In accordance with standard operating procedures, all six booster pumps (two in each of the three fuel tanks) were selected on prior to start. With these switch positions, pressure differentials within the fuel system would mean that the center tank fuel would be used before the fuel in the two wing tanks. A fuel schematic diagram is shown in Figure 1.

The take-off and climb were uneventful and the first officer engaged Autopilot "B" as aircraft climbed through FL140. Towards the top of the climb, the captain noticed a small imbalance of fuel; the left wing was indicating approximately 150 kg more than the right wing. He mentioned this imbalance to the first officer and advised him of his intention to balance the fuel. By now, the aircraft was level at FL290 and the crew were advised by ATC that FL290 would be the final cruising level rather than the planned FL330. At approximately 0912 hours the captain then selected the left center booster pump to off; no other fuel switches were moved. His intention was that the left wing tank would supply fuel to the left engine and the center tank would supply fuel to the right engine, thereby balancing the fuel between the two wing tanks. The captain annotated his Flight log with "Fuel Bal" and drew an "attention line" down the right side to a point approximately 27 minutes later; the captain also made a mental note to check the balance after five minutes. Subsequently, fuel check figures were entered on the Flight Log by the captain at 0921 hours, 0942 hours, 0954 hours and 1008 hours.

As the flight continued over Northern Italy, the aircraft entered cloud and encountered some light turbulence. Some time later at 1029 hours, while the captain was consulting the Flight Management Computer (FMC), the first officer noted that aircraft had continued past a 'waypoint' without following the required track to the left; at the time, the Mode Control Panel (MCP) was in Lateral Navigation ("L Nav") mode. Additionally, the "trend vector" started to show a turn to the right. The first officer's initial impression was that there was a problem with the FMC and selected "Heading" on the MCP.

However, this had no apparent effect and the aircraft was now banking increasingly to the right. With a bank angle approaching 30° to 35°, the first officer's thought was that the autopilot had malfunctioned as the bank angle limit set on the MCP was 25°. He disconnected the autopilot by using the switch on the control wheel and the aircraft

Typical B737 Fuel Balancing Procedure (Timer equipped !)

Maintain main tank no. 1 and no. 2 fuel balance within limits.

NOTE: Fuel pump pressure should be supplied to the engines at all times. Above 30.000 ft without fuel pump pressure, thrust deterioration or engine flame-out may occur.

■ **Center tank contains fuel**
- Center Tank Fuel Pump Switches ..... OFF
- Crossfeed Selector ..... OPEN
- Fuel Pump Switches (Low Tank) ..... OFF
- Timer ..... SET

When quantities are balanced:
- Fuel Pump Switches (Main Tank) ..... ON
- Center Tank Fuel Pump Switches ..... ON
- Crossfeed Selector ..... CLOSE

Procedure completed.

■ **Center tank contains NO fuel**
- Crossfeed Selector ..... OPEN
- Fuel Pump Switches (Low Tank) ..... OFF
- Timer ..... SET

When quantities are balanced:
- Fuel Pump Switches (Main Tanks) ..... ON
- Crossfeed Selector ..... CLOSE

Procedure completed.

immediately banked further right. As the first officer countered this movement by moving the control wheel to the left, he was also aware of the captain maneuvering the control wheel. The captain had heard the first officer say "selecting heading select" and had looked up. Almost immediately, he heard the first officer say "taking the autopilot out". The captain could see that they were IMC, with a large angle of bank and that the control wheel was in a left bank attitude. He can recall stating that he had control and remembers applying back pressure and a large left roll input to the control wheel.

The aircraft rolled wings level and began to climb; the first officer was now just following through on the controls and giving the captain attitude information. The crew were aware that the aircraft had diverged from its assigned level by at least 800 feet and also from its assigned track. By now, ATC were concerned with the maneuvering of the aircraft and there was some confusion until the aircraft was re-established at FL290 on the required track.

The captain was now flying the aircraft manually and needed a considerable left control wheel deflection to maintain straight and level flight. The crew checked the aircraft systems but could find no reason to explain the situation. After discussing the predicament, the captain declared a "PAN" and requested a diversion to Rome. Once the aircraft was heading for Rome, the first officer suggested that he take the handling duties, thereby enabling the captain to properly review the situation. This was agreed and, shortly afterwards, the captain noticed the fuel imbalance. With the first officer monitoring his actions, the captain reconfigured the fuel system to resolve the imbalance. Then, once the crew were satisfied that there was no further problem with the aircraft and that they still had the required fuel, they cancelled both the emergency and the diversion.

A normal landing was subsequently carried out at Athens at 1211 hours.
At the time of the incident, the cabin staff were setting up the duty free trolley and some passengers were queuing for the toilets.

As the captain was recovering the aircraft from the uncommanded roll, cabin crew members experienced a violent rolling maneuver and a sensation of being pressed to the floor; the purser and two passengers fell to the floor. Afterwards, once the cabin staff had ensured that all the passengers were in their seats with their seatbelts fastened, the purser went to the flight deck.

The captain informed her that the incident was under control but that they would be diverting to Rome; she returned to the cabin to prepare for the landing and to reassure the passengers. Shortly afterwards the captain advised her of the cause of the incident and subsequently made a Public Address (PA) to the passengers; thereafter, once the imbalance had been corrected, he visited the cabin to further reassure the passengers.

OPERATING INSTRUCTIONS

Relevant information contained within the Company operating manuals is detailed below :

1. The maximum fuel imbalance between the two wing tanks is 453 kg.

2. With 1000 kg or more fuel loaded in the center tank, all pumps must be on and the crossfeed selector closed.

3. Both pilots must monitor selections made to restore fuel balance. "THE TIME AT WHICH BALANCING WILL BE COMPLETED MUST BE CALCULATED AND EITHER NOTED DOWN BY BOTH PILOTS OR A TIMER SET OR SUITABLE WAYPOINTS INSERTED IN THE FMC."

4. To balance the fuel loads between tanks Nr. 1 (left wing) and Nr. 2 (right wing), "With fuel in the center tank, turn center tank fuel pumps OFF, then balance fuel between tanks Nr. 1 and Nr. 2. When tanks are balanced turn center tank pumps ON."

5. "A minimum of once per sector and at least once per hour in the cruise, record on Flight Log a fuel check from the PDCS/FMS, or by calculation using tanks fuel and Flight Log "REQ" fuel. If the calculated fuel differs significantly from the planned figure on SWORD this must be investigated." There is a requirement to check the FMC fuel figure against the tanks fuel prior to start.

AIRCRAFT INFORMATION

The aircraft involved in the incident is one of 27 similar types operated by the Company at this base. However, it is one of eight which came from another company and, at the time of the incident, none of these aircraft had a timer, with an associated audible bell, fitted on the flight deck; these are referred to as "egg timers". All other company similar types at all bases were fitted with "egg timers".

PERSONNEL INFORMATION

The captain had recently completed his command training which was carried out at another base and on aircraft which all had "egg timers". He passed his final line check on 04 February 1996. During the investigation, he made the point that the "egg timer" was routinely used during his line command training for various activities including fuel balancing. He also acknowledged that the way he attempted to balance the fuel on this occasion is not in accordance with Company procedures and that none of the training staff had mentioned this method of fuel transfer.

The first officer had a total of 609 hours flying experience of which 205 hours were on type. His training had been carried out at another base and he passed his final line check on 17 July 1996. He stated that the only way he had been shown to balance the fuel was in conjunction with the 'egg timer'.

BOEING INFORMATION

During the investigation, Boeing Commercial Aeroplane Group were asked if there were any technical reasons why the system of fuel balancing used by the captain should not be used. They confirmed that the Boeing standard procedure is as described in the Company manuals but that there is no purely technical reason why the procedure used in the incident should not be used.

RECORDED INFORMATION

FUEL GAUGES ON B737 NG

The Cockpit Voice Recorder (CVR) continued to operate after the incident and the record of the event was subsequently overwritten. The Flight Data Recorder (FDR) was replayed by both the company and by the AAIB.

The data showed that, initially the aircraft was level at FL290 and steady on a heading of 1200M. With the autopilot engaged, the left aileron began a slow but progressive deflection while the aircraft remained wings level. This movement continued until the aileron was at the maximum authority allowed by the autopilot. For the next five minutes, the left aileron maintained this position at 4.5° deflection and the aircraft remained wings level. Thereafter, for an additional 2 minutes, the aircraft rolled to the right with a corresponding change in heading. As the roll reached 45° of right bank, the autopilot was disengaged and a substantial left roll demanded. However, almost immediately, the roll demand was reversed resulting in the aircraft going to a maximum of 54° of right bank before a large left roll was again demanded. Simultaneously, a substantial elevator demand was applied to climb the aircraft. Over the next 2 seconds, the B737 climbed 1000 feet and a maximum normal acceleration of 1.9 g was recorded.

By now, the aircraft had changed heading by approximately 100° to the right. Then, the aircraft descended to FL286 before climbing to and levelling at FL290. Four and a half minutes after the autopilot was disengaged, the aircraft was re-established at FL290 and on a steady heading of 120°. There was no indication of any rudder input during the flight, prior to the disengagement of the autopilot.

SUBSEQUENT INFORMATION

The maximum aileron deflection with the autopilot engaged is approximately 4.5°, corresponding to a control wheel deflection of 20°. In manual flight, the aileron can be deflected up to 20° and this corresponds to a control wheel displacement of about 82°. The autopilot has no authority over the rudder. Calculations suggest that the probable extent of the fuel imbalance at the time of autopilot disengagement would have been approximately 1600 kg.

INCIDENT DISCUSSION

The aircraft was fully serviceable throughout the flight. The first abnormal event occurred when the captain decided to balance the fuel as the B737 reached cruising level. He decided to do this with an imbalance of approximately 150 kg, while the engines were being supplied from the center tank. This imbalance is well within the maximum allowable of 453 kg. He then used a non- standard procedure to balance the fuel. Although the manufacturer confirmed that there is no purely technical reason why this particular fuel balancing procedure could not be used, one disadvantage is that the balance correction would take approximately twice as long as the normal procedure. Furthermore, it is not a procedure detailed in any of the aircraft manuals or one which had been demonstrated by the training staff. The initial decision to balance the fuel was premature and possibly unnecessary, and the subsequent balancing procedure used was non-standard. As he started to balance the fuel, the captain noted down a timing reminder on his Flight Log but the first officer did not.

Furthermore, although the captain informed the first officer that he was going to balance the fuel, the captain did not then fully involve him in the procedure. The Company regulations require that both pilots are involved in any procedure involving the fuel system; additionally, for any fuel balancing, they should both note down a reminder on their Flight Logs or set a timer or insert a suitable waypoint in the FMC. The fact that the first officer was not fully involved in the switch selection would mean that he was less likely to monitor the fuel situation, confident that the captain was doing so. Effectively, there was only one pilot "in the loop".

Over the next one hour and 17 minutes, the captain made four fuel checks but completed them without specific reference to the aircraft fuel gauges. There is a requirement for the pilot to make a comparison between the fuel gauges and the FMC prior to engine start; this was done and was satisfactory. In flight, the Company procedures are for the pilot to compare the required fuel from the Flight Log with the "established fuel on board"; with a satisfactory pre-flight cross check between the fuel gauges and FMC, it is acceptable for the FMC fuel figure to be used. However, the existing fuel check does not cover the fuel distribution. The Company report of the incident highlighted this aspect and recommended a review of the in-flight fuel checks. Although a comprehensive fuel check should be considered as "Airmanship", the review is sensible.

An associated point is the provision of "egg timers". Both crew members had recently completed training at another base and both had used the "egg timers" for fuel balancing. However, at their operating base, not all aircraft had the "egg timers" fitted. Airmanship should preclude this degree of fuel imbalance happening but, if the crews get used to operating with "timers", they will become reliant on them. A mix of aircraft with and without "timers" would create more risk of this type of incident than would a fleet of standard fit aircraft, even without "egg timers". The Company report recommended that "egg timers" be fitted to all their B737 aircraft.

During the increasing imbalance, the aileron moved gradually to its maximum autopilot deflection of 4.5° to maintain level flight. The control wheel would have moved in sympathy with the ailerons up to the maximum of 20° and would then have maintained this deflection. The FDR shows that the aileron deflection of 4.5° was maintained for 5 minutes; this means that the control wheel was also deflected by 20° for the same length of time. It is surprising that this deflection was not noticed by either pilot. Thereafter, this deflection was not sufficient to maintain wings level as the fuel imbalance increased further

A problem eventually became apparent to the crew when the first officer noticed that aircraft was not following the required track to the left. Initially, he attempted to change the autopilot lateral mode but, when there was no improvement in the situation, he then disconnected the autopilot. His manual input was correct and the bank angle decreased but, shortly afterwards, the captain became aware of the situation and reached for and took control of the control wheel. The aircraft bank then increased momentarily to 54° as a result of control wheel input before rolling left to wings level although with a nose high attitude.

There is no doubt that the crew was under some pressure to resolve the undemanded roll. The captain had been alerted to the situation initially by the first officer commenting on his selection of "Heading" and then by his statement that he was disengaging the autopilot. Neither crew member is certain of exactly when the captain called that he had control but both were sure that he had taken control while the aircraft was banking back left.

The captain has no specific recollection of applying a brief control wheel input to the right. At that time the aircraft was banked to the right but with the control wheel demanding a roll to the left. However, with no external references, the captain may initially have thought that, with the control wheel demanding a roll to the left, the ADI was showing a roll to the left. This initial misinterpretation may have resulted in him applying the right roll demand for a short period before correctly re-applying left roll. This roll demand was accompanied by a positive pitch demand causing subsequent large excursions in height.

The question of who is best placed to recover an aircraft from an unusual attitude is a command decision. The pilot who is handling the aircraft when it begins to depart from the required profile is normally the best one to retain control but this depends on his experience and handling skills. It would be instinctive for the captain to take control in any situation where he was unhappy about the aircraft attitude. This incident shows the value of all flight crew having experience of unusual attitudes. While this type of incident is fortunately rare, other incidents such as wake turbulence could result in a similar situation of someone suddenly needing to interpret the aircraft attitude from the instruments and take the appropriate action. The company report included a recommendation for simulator training to be provided to pilots on recovery from unusual attitudes. Additionally, one other major UK airline has recently instituted a simulator program to give their flight crew experience in the recognition of and recovery from unusual attitudes. These are sensible and practical training initiatives but may not necessarily be addressing the basic problem.

Modern aircraft are increasingly designed to be flown by an autopilot and/or flight director. This is normally very efficient but the human flying and monitoring skills may be decreasing due to increasing use of, and trust in, the automatics. This incident involving a B737-400 may be an indication that the basic pilot skill of instrument interpretation, particularly in attitudes beyond those the pilot normally sees, is being degraded…

FUEL - SCHEMATIC (737-300/-400)