Department of Transport and Regional Development Bureau of Air Safety Investigation

Human factors in airline maintenance: A study of incident reports



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Abbreviations

AME	Aircraft Maintenance Engineer
ATA	Air Transport Association
CAA	Civil Aviation Authority
CFIT	Controlled Flight Into Terrain
CRM	Crew Resource Management
ETOPS	Extended Range Twin-engine Operations
FAA	Federal Aviation Administration
ICAO	International Civil Aviation Organisation
LAME	Licensed Aircraft Maintenance Engineer
MEDA	Maintenance Error Decision Aid
OH&S	Occupational Health and Safety
SHEL	Software Hardware Environment Liveware
TCAS	Traffic Alert and Collision Avoidance System

Summary

Maintenance incidents contribute to a significant proportion of worldwide commercial jet accidents, yet until recently, little was known of the nature of maintenance incidents and the factors which promote them.

In face-to-face interviews, maintenance technicians were asked to report examples of maintenance incidents which they had experienced first-hand. Eighty-six incident reports were recorded.

Human factors were involved in most of the reported incidents, with workers on duty between the hours of 0200 and 0400 having a greater chance of having an incident than workers on duty at other times of the 24-hour clock. The frequency of incidents increased as the shift progressed up to the second-last hour, after which the frequency of incidents diminished.

For those incidents which had the potential to affect the airworthiness of an aircraft, difficulties with procedures emerged as the most significant factor. This included misunderstandings and ignorance of procedures.

For those incidents which had the potential to affect the health and safety of workers, difficulties with tools and equipment emerged as the most frequent factor.

The majority of the human errors involved in incidents were rule-based mistakes, many related to mistaken assumptions. Absent-minded slips and lapses were involved in approximately one-third of the incidents.

The final section of the report contains suggested safety actions, intended firstly to reduce the frequency of human error and maintenance incidents and secondly, to reduce the consequences of any such errors which do occur.

Introduction

The cost of maintenance failures

Air safety statistics have tended to understate the significance of maintenance as a contributing factor in accidents. Figures for the worldwide commercial jet transport industry for example, show maintenance as the 'primary cause factor' in only 5.9% of hull loss accidents, compared with flight crew actions implicated as a 'primary cause factor' in greater than 70% of accidents (Boeing 1996). Yet when safety issues are presented alongside the fatalities which have resulted from them on worldwide airline operations for the period 1982–1991, maintenance and inspection emerges as the no. 2 safety issue after controlled flight into terrain (Russell 1994) (see Figure 1).





Maintenance incidents are not merely costly in terms of life and property, but can also impose significant costs when flights are delayed or cancelled. In 1989 maintenance constituted 11.8% of US airline operating costs or more than US\$8 billion per year (Shepherd 1992). The annual cost to the Australian airline industry is likely to be in the order of several hundred million dollars per year. Gregory (cited in Marx & Graeber 1994), estimated that each delayed aircraft costs an airline on average US\$10,000 per hour, while each flight cancellation can be expected to cost approximately US\$50,000. When these costs are considered, it is apparent that airlines stand to gain significant benefits by even a small reduction in the frequency of maintenance-induced delays, particularly those which occur closest to scheduled departure times, during line maintenance or when an aircraft is being prepared for departure.

Existing data on maintenance failures

Despite the importance of maintenance quality, there is a lack of empirical research on the nature of maintenance incidents and the human factors which contribute to them. The UK CAA produced a list (Civil Aviation Authority (UK) 1992) of the most frequent maintenance incidents in aircraft over 5,700 kg. Most of these incidents did not lead to accidents. The top eight problems were as follows:

- 1. incorrect installation of components;
- 2. the fitting of wrong parts;
- 3. electrical wiring discrepancies (including cross-connections);
- 4. loose objects (e.g. tools) left in the aircraft;

- 5. inadequate lubrication;
- 6. cowlings, access panels and fairings not secured;
- 7. fuel/oil caps and refuel panels not secured; and
- 8. landing gear ground lock pins not removed before departure.

In 1993, Boeing researchers analysed 122 maintenance occurrences involving human factors and concluded that the main categories of maintenance 'error' were:

- 1. omissions (56%);
- 2. incorrect installations (30%);
- 3. wrong parts (8%); and
- 4. other (6%) (International Civil Aviation Organisation 1995).

In recent years, human factors issues in maintenance have begun to be examined by human factors researchers. Much of the recent research has been sponsored by the US Federal Aviation Administration (FAA) Office of Aviation Medicine. Research has been directed at a wide variety of issues including the organisational structure of maintenance organisations (Taylor 1990), visual inspection issues (Drury & Gramopadhye 1990; Latorella & Drury 1992), advanced technology as an aid to maintenance training (Johnson 1990), employment of women and minorities in military aviation maintenance (Eitelberg 1991), illumination in maintenance workplaces (Reynolds and others 1992), the design of work control cards (Patel, Prabhu & Drury 1992), future availability of aircraft maintenance personnel (Shepherd & Parker 1991), and the introduction of crew resource management to maintenance training (Taggart 1990; Stelly & Taylor 1992)

While the research outlined above has undoubtedly contributed to airline safety, to date, researchers have focused on highly specific maintenance issues and there has been few broad examinations of aircraft maintenance incidents.

Such an examination could be achieved by examining the errors which occur when airline aircraft are being maintained. In essence, there is a need for a system to categorise and describe maintenance errors. The information obtained would be central to the design of system improvements.

Human error

Most accidents to complex industrial systems such as powerplants or transport systems feature some involvement of human error. The terms 'error' and 'human error' are widely used in the safety field and do not imply that operators are *blamed* for workplace incidents. Nevertheless, concluding that human error was involved in an accident or incident does not generally help to prevent such occurrences from happening again. In order to more fully understand why the event occurred, it is necessary to describe in some detail the type of error the person made, and if possible, to identify some of the reasons or factors which led to the error. Different types of errors may require different preventative strategies.

One of the most basic description systems for human error is to categorise errors as those of omission, commission or substitution, based on the work of Swain (Miller & Swain 1987). An error of omission occurs when a person fails to perform a step in a task which should have been performed; an error of commission occurs when a person performs an action which should not have been performed. A related type of error is substitution, where an undesired action is performed in place of the desired action. A fourth category of mis-timed actions can also be included. This simple system of describing errors has the advantage of being relatively straightforward, but unfortunately does not describe the error in detail and does not give much insight into why the person made the error.

A more detailed system of describing errors which gives insight into why the person made the error was developed by Rasmussen, partly as a result of his examination of the errors of nuclear powerplant operators. Rasmussen proposed that performance can be categorised according to the level of cognitive control which the person is expending on the task at the time of the error.

His skill-rule-knowledge framework (1983) has become a widely accepted model of human error. Using this framework, the activities of a maintenance engineer can be divided into three types of actions: knowledge-based behaviour, rule-based behaviour and skill-based behaviour.

1. Skill-based behaviour

Skill-based behaviour is unconscious, rapid, does not seem to take conscious mental effort and most importantly, is automatic. Many skilled routine actions such as opening and closing panels can be performed automatically. Skilled workers possess an extensive repertoire of skill routines which can be initiated consciously and then left to run their course. Any maintenance task which is performed frequently is likely to involve skill routines. One of the most common skill errors is 'environmental capture' or habit intrusion. This occurs when a well learnt routine action is performed in familiar surroundings, despite an original intention to perform another action. A person who is distracted may carry out a well learnt action without modifying it to new or unusual circumstances. A frequent error of this type is filling in a cheque in January and writing in the previous year.

Another common skill error is the 'omission following an interruption'. If a well-practised routine is interrupted, it may never be completed, or may be picked up again at the wrong stage. One of the most dangerous manifestations of this in aviation is the interrupted checklist. Omissions following interruption have particular relevance to aircraft maintenance.

Skill-based performance calls on very little mental effort and generally results in few errors. The automatic nature of skill frees workers to think about other things, but the cost of this is that they are less likely to monitor what they are doing. As a result, absent minded slips and lapses are a particular risk. It is very difficult to *modify* an automatic skill once it has been learnt. However, this is not to say that checks cannot be built into work performance.

A further difficulty with skill-based performance is that skilled operators are generally unaware of the automatic procedures they are following and may be unable to explain to another person how the task is performed.

2. Rule-based behaviour

People use rules or plans constantly in everyday life, without necessarily being aware of them. These rules are often procedures which have been learnt through trial and error and are then applied to situations as an aid to decision making in an 'if...then...' manner, for example, 'If the dipstick indicates that the engine oil is low, then top up the oil'. Although it is often a conscious process, it does not require the person to go back to first principles in the way that knowledge-based behaviour does. Aircraft mechanics constantly apply rules or expertise which enable them to deal effectively with familiar or common situations. Many of these rules are formally laid-down procedures; however, just as important are the unwritten work practices which are applied to particular situations. Rule-based errors may occur when a person applies an inadequate rule to a situation or misapplies a good rule.

3. Knowledge-based behaviour

Knowledge-based behaviour is required when there is no pre-packaged solution to a situation. Knowledge-based behaviour tends to be slower than other forms of behaviour and is very demanding of mental resources, but is necessary when a person is faced with an unfamiliar problem. Knowledge-based errors are errors of decision making, and may reflect a lack of information on the task.

The skill-rule-knowledge distinction helps to explain why errors occur and to predict the types of errors that will occur under various circumstances. Errors at the skill-based level are commonly referred to as *slips* and *lapses*, while errors at the rule-based and knowledge-based levels are commonly referred to as *mistakes*. Many of the same basic error types have been observed in a wide range of industrial settings, supporting the view that human errors are not usually random deviations from normal performance, but rather follow systematic patterns and hence can be partly predicted and prevented.

The Reason model of accident causation

In addition to the immediate unsafe acts or errors committed by operators, investigations typically reveal that longstanding systemic failures have had a role in causing, permitting or exacerbating accidents and incidents. Therefore it is important to consider not just the immediate circumstances of maintenance incidents, but also the underlying or systemic failures which make such incidents possible.

The model of system breakdown proposed by James Reason, illustrated in Figure 2, has become a standard framework for analysing accidents in industrial and transport settings (see Reason 1990, 1991). The model has been advocated for accident investigation purposes by ICAO (International Civil Aviation Organisation 1993), has been used in the analysis of anaesthetic accidents (Runciman and others 1993) and has been applied by its originator to the analysis of accidents in various settings, including nuclear power plants, chemical plants and transport applications . While the Reason framework was initially proposed to account for accidents, it can also be applied to less catastrophic occurrences.

Figure 2 The Reason model



Reason recognises that human behaviour is the greatest contributor to system failure. He considers that system breakdowns result from combinations of active failures and latent failures, sometimes in conjunction with unusual environmental forces. Active failures are the events which immediately precede the breakdown. Unsafe acts such as errors or violations are the most commonly identified active failures.

In Reason's terminology, latent failures are the longstanding system problems which create the circumstances in which active failures occur, and have the potential to make the consequences of active failures especially serious. Latent failures include inadequate defence systems and conditions which promote unsafe acts in the workplace. Latent failures often have their origin in management and may be put in place well before the breakdown occurs. Using a medical analogy, Reason has given the label 'resident pathogens' to longstanding system failures.

The SHEL model

The SHEL model is a human factors analysis framework originally proposed in the 1970s by Edwards and now formally recommended by ICAO (International Civil Aviation Organisation 1992). The letters in the acronym SHEL represent Software, Hardware, Environment and Liveware (see Figure 3).

Figure 3 The SHEL model



In contrast to the Reason model, the SHEL model is most useful in considering human factors at the 'sharp end', that is, the performance of individual operators. The SHEL model and the Reason model complement each other and can be used jointly.

The SHEL model enables human factors issues to be divided into four broad areas. The first is the interaction between people ('liveware') and software such as procedures, documentation and manuals. The second element of the model is the interaction between people and hardware, such as tools and equipment. The third element of the model represents the interaction between people and the environment. The last element of the model represents the interactions between people in the system, and includes issues such as communication, teamwork and group interactions.

The SHEL model provides a simple but powerful framework in which most individual human factors problems can be described. The SHEL model provides a useful guide to assist in the investigation of maintenance incidents as it acts as a prompt to ensure that all relevant factors have been identified.

Aims

This study was conducted with the aim of achieving a better understanding of maintenance incidents, including the role of human error and the underlying factors which lead to such incidents; identifying areas where safety improvements can be made; and making recommendations to achieve improvements.

Method

Maintenance technicians were asked to provide examples of incidents, following a structured questionnaire based on the critical-incidents technique pioneered by Fitts and Jones (1947) in their study of pilot error and further developed by Flanagan (1954). The critical-incident technique is a key human factors method which has been used for many years in the aviation industry, and has also been applied in medicine and the nuclear power industry. The technique involves gathering first-hand accounts by operators of critical incidents, accidents, mistakes and near accidents which have occurred in the performance of job tasks. The technique is particularly useful where a system has been in operation for some time and where operational difficulties have been experienced but where the nature of the difficulties is not well understood. A copy of the questionnaire can be found at appendix 1.

During interviews held in 1994 and 1995, maintenance technicians were asked to report incidents which had occurred in the previous 12 months in which they had a first-hand involvement, either as a participant or as an observer. All participants in this study were involved in the maintenance of aircraft with a certified maximum seating capacity greater than 38 seats and/or a maximum payload exceeding 4,200 kg. Although the primary focus of BASI is on incidents which could affect the safety of public transport operations, incidents which could have affected the safety of workers were also collected. Both types of incidents can arise from underlying deficiencies in maintenance organisations.

Safety incidents frequently involve a sequence of events, so the incidents were broken down into event sequences using a system developed by Williamson and Feyer (1990) at the National Institute of Occupational Health and Safety. The coding system used to analyse incidents can be found at appendix 2. This system was originally developed to examine fatal workplace accidents. As well as considering each incident as a sequence of events, each event was categorised according to whether it involved the actions of a person, a failure of equipment or an environmental event such as wind or rain. The contributory actions of people in the incident sequence were categorised according to Swain's omission, commission, substitution categories of human error and the SRK framework of Rasmussen (1983). Each event was considered as a separate 'sub-incident' and was assigned contributing factors where appropriate. A sample of the incidents was coded independently by two coders to evaluate the reliability of the coding system. The results of this evaluation can be found at appendix 3. Definitions of terms used during coding can be found at appendix 4.

Results

General

Of the 86 incident reports collected, 46 were classified as airworthiness occurrences, as they had the potential to affect the operation of an aircraft, and 49 were classified as occupational health and safety (OH&S) occurrences as they related to the health and safety of maintenance personnel. Nine incidents fell into both categories, in that they related to both airworthiness *and* worker safety. A significant number of incidents (54%) had not been reported through official channels. Error types were categorised with a system developed from Boeing's Maintenance Error Decision Aid (MEDA) system (Boeing 1994). A brief summary of the incident events can be found at appendix 5. Note that an incident may have involved more than one type of error (see Table 1).

The most frequently reported type of error was *system operated in unsafe condition*. This included incidents where aircraft systems such as flaps or thrust reversers were operated during maintenance when obstructions or workers were in the vicinity. In some cases aircraft systems were operated while the system was partly disassembled. The following incident is an example of a system operated in an unsafe condition:

Table 1	
Frequency of Maintenance Error Types	
Type of Error	
System operated in unsafe condition	16
Towing event	10
System not made safe	10
Equipment failure	10
Degradation not found	6
Falls and spontaneous actions	6
Incomplete installation	5
Work not documented	5
Person entered dangerous area	5
Person contacted hazard	4
System not reactivated/deactivated	4
Did not obtain or use appropriate equip.	4
Unserviceable equipment used	4
Verbal warning not given	3
Vehicle driving (not towing)	2
Pin or tie left in place	2
Warning sign or tag not used	2
Not properly tested	2
Safety lock or warning removed	2
Vehicle/equipment contacted aircraft	2
Material left in aircraft/engine	1
Access panel not closed	1
Contamination of open system	1
Equipment not installed	1
Panel installed incorrectly	1
Required servicing not performed	1
Unable to access part in stores	1
Wrong equipment/part installed	1
Wrong fluid type	1
Wrong orientation	1
Unable to be coded	6

On a night shift at about 2.30 a.m., the crew were performing a rigging check on the leading edge slats after gearboxes had been changed. At the end of this work, one torque tube was left disconnected from a gearbox. The crew went for a break and after they returned they extended the slats on hydraulics as a check of their work. One section of the slats did not move, because of the unconnected torque tube. As a result part of the leading edge was torn off. The crew would normally have checked their work before extending the slats, but this check had been omitted because of the interruption caused by the break. The reporter considered that in hindsight, it would have been more sensible to have extended the slats electrically as they would have moved more slowly. In addition, had docking been available, they could have walked along the length of the wing to check the connections.

The second most frequently reported error reflects the potential for damage to aircraft as they are manoeuvred by maintenance personnel in areas where space is restricted. The following is an example of such an incident:

As a large multi-engine aircraft was being pushed out of a hangar on a dark night, the left winglet hit the left stabiliser of a twin-engine aircraft. An engineer stationed under the wing saw that the collision was about to occur and made torch signals to alert the licensed engineer stationed near the nose of the aircraft, who could have given the tug driver a signal to stop the tug. However, the licensed engineer did not see the torch signals in time to prevent the collision. The twin-engine aircraft had to be re-scheduled while the damage was repaired. The reporter stated that he was not aware of any standard procedures for stopping aircraft with torch signals. The reporter considered that fatigue was a factor in this occurrence.

The third most frequent error, *system not made safe*, refers to situations where an aircraft system was not disabled or locked out appropriately before work commenced. Included are instances where electrical power was left on while electrical work was carried out and instances where hydraulically activated systems were not isolated from hydraulic power.

Equipment failure refers to situations where an item of maintenance equipment or an aircraft component failed and this was not a result of maintenance actions. On some occasions, an equipment failure combined with a human error to create the incident; for example, there were two occasions where workers' unsafe behaviour brought them into contact with faulty electrical equipment, resulting in non-fatal electric shocks.

Incident outcome

Incidents were coded using the coding sheet reproduced in appendix 2. The end results of the incidents are summarised in Figure 4.



Figure 4 Outcome of maintenance incidents.

Incidents which related to the safety of workers (OH&S incidents) were classified according to whether they resulted in death of a worker, exposure of the worker to a hazard or potential exposure of the worker to a hazard. None of the reported incidents resulted in death. Incidents with airworthiness implications were classified according to whether they resulted in damage to an aircraft, potential damage to an aircraft, an aircraft signed off with an unrectified problem, a delayed aircraft, an aircraft signed off with a problem which resulted from maintenance action, or the detection and correction of a problem.

Note that nine incidents involved both an airworthiness element and an OH&S risk. In Figure 4, these incidents have been counted separately under both the appropriate airworthiness and OH&S category. As can be seen, the most frequently reported incident outcome was *potential hazard*, where there was a risk that a worker could have been exposed to a hazard such as hydraulically activated aircraft components or dangerous working surfaces. *Exposure to hazard* refers to situations where the final outcome of the incident was that a worker came into contact with a hazard, whether or not they had any control over the situation. Two examples of this incident type are a worker who was doused in fuel and a worker who received a cut hand when he came into contact with windmilling engine fan blades. *Correction of problem* refers to situations where a maintenance error was made but then recognised and corrected before the work was signed off. For example, a part was installed upside down, but then removed and reinstalled correctly by the same workers. *Potential damage to aircraft* includes situations where an aircraft system was not disabled before maintenance work was carried out and where the system would have been damaged if it had been activated during maintenance.

Reporting of incidents

Most incidents which had an airworthiness element had been officially reported within the company; however, only a minority of the incidents with OH&S implications had been officially reported (see Figure 5). In considering the unreported airworthiness incidents, it should be noted that it would not normally have been necessary to report an incident which resulted in only potential damage to an aircraft or where a mistake was rectified.





Previous occurrence of similar incidents

The results summarised in Figure 6 emphasise the recurring nature of many incidents. In most cases the reporter considered that the type of incident had happened before, and in nearly all cases, reporters said the incident could happen again.

Figure 6 Previous occurrence of similar incidents



Area of aircraft involved

The area of the aircraft which was involved or was being worked on when the incident occurred was coded using standard Air Transport Association (ATA) descriptions. As Figure 7 indicates, engines, flight controls and thrust reversers featured most frequently in the reported incidents. Engines were involved in the largest number of OH&S incidents, but also featured significantly in airworthiness incidents. The number of airworthiness incidents involving thrust reversers and flight controls (particularly flaps), largely reflects the potential to damage these systems by deploying, stowing or retracting them while maintenance is in progress. The airworthiness incidents involving wings generally occurred while aircraft were being manoeuvred in confined spaces.

Time of incident

The times of day at which incidents occurred is summarised in Figure 8. There were two peaks, one in the late morning after 1000 hours, the other in the mid-evening between 1800 and 2000. Care should be exercised in interpreting these figures as they may reflect the hours at which most maintenance work is carried out and may not necessarily indicate a higher rate of incidents in a particular time period.

As there were no discernible differences between the time at which OH&S and airworthiness incidents occurred, and because of the relatively small number of incidents in each 2-hour time period, information relating to the time of occurrence is not broken down by incident type.

At the time that the study was conducted, the day shift commenced at 0600 and concluded at 1400, the afternoon shift commenced at 1400 and concluded at 2200, and the night shift commenced at 2200 and concluded at 0600. There were approximately three times as many workers present during morning and day shifts as during night shifts. Hence, if the frequency of incidents reflected only the number of workers present and not the time of day, it would be expected that there would be three times as many incidents during morning and day shifts as during night shifts.

Figure 9 presents the relative number of incidents at each time of day when the variation in the number of workers present has been taken into account by dividing the incidents which occurred during morning and day shifts by a factor of three.

In essence, this figure presents the relative frequency of incidents which could be expected if the same number of workers were present at all times throughout the day. A cyclic pattern of incidents can be seen, corresponding to the three shift patterns described above. However, the greatest relative frequency of incidents occurred on the night shift between the hours of 0200 and 0400.



Figure 7 Area of aircraft involved in the incident

Figure 8 Time of incident







Time into shift

All the incidents were reported by workers on 8-hour shift patterns. As can be seen from Figure 10, there was a tendency for incidents to become more frequent as the shift progressed. An exception to this was that relatively few incidents were reported to have occurred in the last hour of the shift. This may indicate that the last minutes of the shift are used to perform clean-up and 'housekeeping' tasks which are less likely to lead to incidents.



Figure 10 Timing of incidents within 8-hour shift pattern

Incident involvement

An incident may have involved more than one event. For example, a worker may have made an error during the installation of a component and a second worker may then have failed to detect the error during a check. Each event in the incident sequence was classified according to whether it involved the actions of a person, a failure of equipment or an event in the environment (such as a gust of wind).

Eighty-seven per cent of the incident events involved the actions of people. Equipment failures accounted for 12% of events, while environmental events represented less than 1% of the total events (see Figure 11).





Human errors

Errors were categorised with Swain's error classification system, described earlier.

Omissions constituted the greatest proportion of human errors in the incidents (see Figure 12). Commissions constituted the second-most frequent type of error.





Analysis of Incidents

In the following section, the incidents are analysed using models of human error and accident causation. Maintenance errors are first analysed with the skill-rule-knowledge framework developed by Rasmussen. The Reason model is then applied to the incidents, first by examining the local factors which contributed to the incidents and then by considering the wider organisational factors which were involved in incidents. This section concludes with a qualitative analysis guided by the SHEL model described in the introduction of this report.

Results in terms of the skill-rule-knowledge model of human error

The errors made by technicians were divided into skill-rule-knowledge categories, see Figure 13. Some errors could not be categorised with complete certainty, but were assigned to a category on the basis of probability. Some reports identified risky behaviour or conscious rule violations. For the purposes of this study, no distinction was made between *violations* and *errors* and such behaviours were coded as errors.



Figure 13 Human error types (skill-rule-knowledge)

Knowledge-based errors were relatively rare and only 4% of errors were classified as 'probably' knowledge-based errors. Thirty-four per cent of the errors were skill-based. There was a degree of uncertainty in classifying these errors, and most of these errors could only be classified as skill-based errors with less than complete certainty. An example of a skill-based error follows.

A technician working under the fan cowl of an engine left a large spanner wedged between tubing. After the aircraft had departed, the technician realised that the spanner was missing but did not take steps to alert the airline. The technician retrieved his spanner when the aircraft returned.

The initial error in this case was a skill-based lapse, related to an inadvisable work practice (resting tools on convenient parts of aircraft). The technician's subsequent response to this lapse can be seen as a rule-based mistake.

In 52% of cases, the action took the form of a rule-based error. For example:

An ignition check was being performed on a GE CF6 engine using a test box. Both ignition plugs were disconnected and one igniter at a time was plugged into the box where it was fired. The wrong cannon plug at the low tension end had been disconnected, with the result that the igniter which had been left hanging free in the air was still connected. During the igniter check, the loose igniter fired and sparked across to the engine. The person who disconnected the cannon plug had thought (wrongly) that

the upper ignition box connected to upper ignition. But in fact in the CF6 engine, the top ignition box provides power to the bottom ignition and vice versa. The reporter conceded that it had been a bad maintenance practice to leave both leads out at the same time.

The person involved made a rule-based mistake by assuming that disconnecting the top cannon plug would deactivate the top igniter.

Local factors in terms of the Reason model

Local factors were assigned to each event in the incident sequence on the basis of the information provided by the reporter. A *local factor* is a situation which existed in the local work area and which had a deleterious effect on the work of people at the time of the incident. Some local factors may have only occurred at the immediate time and place of the incident, while others may be more widespread within the organisation.

Each event could be assigned multiple factors. It was apparent that the local factors assigned to OH&S incidents were significantly different to those associated with airworthiness occurrences. For this reason, the local factors for OH&S and airworthiness incidents are presented separately.

Local factors in OH&S incidents

The most frequent local factors in OH&S events are presented in Figure 14. The factor *tools and equipment* refers to difficulties such as broken stands and faulty electrical equipment. Examples of *environment* factors are weather, darkness and slippery work surfaces. *Convenience* was coded as a factor in incidents where a worker was motivated by a desire to reduce inconvenience. Examples are not using uncomfortable safety equipment or not obtaining the correct equipment for a small task when the equipment is not readily at hand.



Figure 14 Most frequent local factors in OH&S events

Local factors in airworthiness incidents

The most frequently assigned factors in airworthiness incidents are presented in Figure 15. The factor *procedures* reflected several difficulties with procedures, including uncertainty about correct procedures, and differences in interpretation between crews. Communication breakdowns most frequently occurred between crews or shifts. Control and supervision issues typically emerged with the work of apprentices, and most occasions where the factor *'knowledge, skills & experience'* was listed related to the work performance of apprentices. Space restrictions in general related to difficulties moving aircraft in confined areas.





Some factors were reported less frequently than anticipated. For example, fatigue was not one of the more frequent factors. When it was reported, the fatigue had sometimes been induced by social life outside work rather than the work itself. Anecdotal evidence suggests that task interruption is a significant challenge to work quality, yet this factor was mentioned in only a few cases.

Organisational factors in terms of the Reason model

Organisational factors were coded for each incident, using the coding sheet presented at appendix 2. An evaluation of the reliability of coding for organisational factors indicated that the reliability of coding between the two coders was low (see appendix 3).

Figure 16 presents organisational factors in terms of the Reason model. Given the low reliability of the coding system, the information on organisational factors should be viewed as opinion rather than as factual information. As can be seen, organisational factors were identified more frequently in airworthiness incidents than in OH&S incidents.



Figure 16 Organisational factors

Control of procedures emerged as the most frequent organisational factor. A *local* difficulty with the application of procedures may reflect a wider *organisational* problem in the development and dissemination of procedures. Hence, procedures feature as both local and organisational factors. These results suggest that management may need to take a more active role in standardising and documenting procedures, and in ensuring that procedures are followed.

Equipment maintenance emerged as an organisational level factor relevant to both OH&S and airworthiness incidents. This is closely related to the incidence of equipment deficiencies as a local factor, in that the presence of broken or faulty equipment (such as stands and lighting) on the hangar floor may reflect a wider organisational problem in the maintenance of equipment.

System defences generally refers to procedures such as engine runs and dual inspections intended to ensure that maintenance has been carried out correctly. On some occasions where this factor was identified, incorrect maintenance was not detected and corrected before the aircraft was released from maintenance.

Results in terms of the SHEL model

In the following section, incidents are analysed according to the SHEL model. In contrast to the previous sections of this report, this does not involve an analysis of the frequency of various factors. However, the SHEL model provides a simple framework within which to review and discuss some of the common features of the incidents.

The procedural issues identified in this study fall into the 'software' element of the SHEL model.

Software (procedures, training and defences)

Variations in procedures

There were cases in which disagreements had arisen concerning the correct procedures to be followed. This may indicate a problem with initial or recurrent training. For example:

A servicing crew had commenced an A-check on a twin-engine jet aircraft. There was a requirement to lock out the thrust reverser on a GE CF6 engine, although there was no work to be done on the thrust reverse system. The crew elected to use a lockout plate to de-activate the reverser; however, there was no requirement to write up the deactivation in the defect log, and hence no log entry was made. After a shift change, a second crew completed the A-check. The task card called for system re-activation; however, because no work had been done on the reverser system, the crew did not expect that reverse thrust would have been de-activated and did not check the status of the lockout plate. The aircraft was dispatched with an inoperative and undocumented reverse thrust system.

This incident was considered to involve two events. First, the thrust reverser was locked out using the lockout plate: an unusual but permitted work practice. Although this action was a departure from normal work practice, it was not an error. Second, the crew responsible for system reactivation did not check the status of the reverser lockout plate, as they assumed that the thrust reverser had not been locked out, which represents a rule-based error.

The following factors were relevant to this incident: Methods of thrust reverser deactivation were not standardised across crews and some crews did not lock out reversers if they were not working on or near that system. There was no requirement to write up the de-activation in the defect log. The relevant task card did not specify that reverse thrust should be reactivated but instead referred to 'system re-activation'. The lockout system on the aircraft uses a small metal plate situated inside the thrust reverser cowl. Once the cowl is closed, there is no indication that the lockout plate is in place. Other aircraft operated by this airline use a pin and streamer system which provides a more noticeable indication of system lockout. There was no requirement for a reverser functional check before dispatch.

A second example of a variation in understanding of procedures also involved a large twinengine jet transport aircraft. One maintenance crew was working on the left engine of the aircraft. Another crew working on the right engine had locked out the leading edge flaps, and had reverser cowls open but had not locked out reversers. If the reversers had been activated, it would have severely damaged the reverser halves. The crew working on the left-hand engine believed that procedures required the reversers to be locked out and documented. A disagreement ensued between members of the two crews about whether it was necessary to lock out the reversers.

In another case, a crew reported that they performed additional functional checks on aircraft systems, not called for in procedures, as they believed that the procedures were inadequate. While the additional checks may be beneficial, they result in a variation in procedures across crews.

Some small tasks, such as activating hydraulics or moving flight controls appear to be performed according to the individual work habits and common sense of the engineer rather than in accord with formal procedures or guidelines. This informal aspect of task performance increases the chance that steps will be omitted, that systems will be activated in unsafe conditions, or that tools or other devices will be left inside aircraft. A greater use of formal checklists or procedures could help to avoid some of the incidents which were related to lapses or incorrect assumptions about system status. It should also be possible to periodically review the work practices of individuals and crews and ensure that divergent work practices do not develop and that procedures are understood.

Aircraft towing procedures

The methods used to ensure that aircraft do not contact obstructions during towing in confined spaces are in need of revision. At present, in most circumstances, engineers walking under the wings of a towed aircraft give 'thumbs up' signals to an engineer walking near the nose of the aircraft. This engineer typically has an interphone connection to the engineer riding in the cockpit, but cannot talk to the tug driver. Communication with the tug driver is generally via hand signals, or in an emergency, via a stop or caution button located on the outside of the tug. If the tug is moving forward, the driver is unlikely to be looking directly at the engineer walking near the nose and is less likely to see signals from the engineer.

Dell and Ojczjk (1996) reviewed 47 aircraft pushback accidents which had occurred worldwide between 1964 and 1993. They concluded that changes to the pushback methods are required to reduce the rate of injury to personnel.

Training

There was a view among some interviewees that recurrent training was lacking. This included refresher training and training in some new systems. It was reported that some personnel had serviced systems such as the Traffic Alert and Collision Avoidance System (TCAS) without appropriate training.

There were also indications that the training system does not always receive adequate feedback on the problems which occur on the hangar floor. For example, some recurring problems could be addressed by changes to the training system.

Defences

Authorities on human factors in aviation such as Hawkins (1993) recommend a 'two-pronged' approach to human error. First, errors should be minimised. Second, the consequences of those errors which nevertheless occur should be reduced. Defences are part of this second approach to error. Defences can be built into the system to catch errors before they have the opportunity to cause serious consequences.

Examples of defences in maintenance are functional checks, dual certification and visual inspection of systems. Several incidents indicated that defence 'safety nets' were failing to catch maintenance errors which had occurred in earlier maintenance procedures. The following incident involved a defence which failed to identify a maintenance error.

A fuel filter was being re-fitted to a GE CF6 engine after a fuel pump had been changed. Six studs held the filter on, with two in an inaccessible position. It was not possible to see the nuts on two of the studs without a mirror. These two nuts were left off, but the other four had been installed correctly. Two workers were performing the task, an apprentice and a licensed aircraft maintenance engineer (LAME). They knew there were six nuts to install, but thought they had fitted them all. There were many loose parts around. A leak check at idle power didn't reveal any leaks. When the aircraft took off, the pilot was advised by air traffic control that there was vapour streaming from the engine. The aircraft continued to its destination, and on landing, the pilot was again informed of vapour by the tower. A power run was carried out at the destination and the problem was identified. It was subsequently determined that more than 20 such incidents had occurred worldwide at various airlines.

In this case the defence, a leak check, failed to disclose a problem which subsequently became evident at takeoff. This was not the only occasion in which an idle power run or engine spin failed to show up a problem.

People issues ('liveware')

The following issues relate to the L-L element of the SHEL model, namely, the interactions between people.

Shift handover

Overseas accident experience has indicated that inadequate shift handover can be a significant problem for maintenance organisations. However, shift handovers were attributed as a factor in fewer than 10% of the current airworthiness incidents. No information is available on the proportion of jobs which require more than one shift to complete. If such information were available, it would be possible to express shift handover problems as a proportion of all shift handovers.

The following relatively minor incident was related to a shift change:

During a routine engine change during night shift, a strut inspection was performed after engine removal and it was noticed that there was a crack in the pre-cooler. The fault was marked on the pre-cooler and was documented. A new pre-cooler was ordered and was delivered and put under the engine before the night shift went home. The day shift arrived and in their eagerness to get the job done, installed the new engine without changing the pre-cooler. This was partly understandable as the work schedule did not include the pre-cooler and the crew did not browse through the documentation sheets before starting work.

Communication

Sometimes the dissemination of information within maintenance organisations is inadequate. For example, at times a new task such as a modification led to mistakes when a crew was tasked with performing the work for the first time. Other crews which had previously performed the task had also made the same mistakes, yet the lessons had not been communicated to all appropriate personnel.

Communication between technicians with differing trade backgrounds can also be a problem. This was evidenced by several incidents which involved misunderstandings between specialist technicians such as personnel with electrical qualifications and those with engine and airframe licences.

Crew resource management (CRM)

Accident investigations and research have determined that a lack of flight crew coordination can pose a serious threat to the safety of airline operations. However, research has also indicated that improvements in crew performance can be achieved through training which focuses on important, but sometimes overlooked, non-technical skills. In recognition of this, most major airlines now provide flight crew with training in non-technical skills such as delegation of tasks, communication, management and leadership (Wiener, Kanki & Helmreich 1993).

There is an increasing recognition that non-technical skills such as communication and assertiveness are as important within maintenance operations as they are for flight crew (for example, Taggert 1990).

Maintenance organisations tend to be strongly hierarchical, with a strict order of status from apprentices through tradesmen, licensed aircraft engineers, leading hands, supervisors and management. For example, those lower in the hierarchy are expected to show deference to those above and are more likely to be asked to perform menial or dirty tasks. While this system has its benefits, it also has the potential to diminish team performance. Some potential problems are junior staff being unaware of the 'big picture' of why a task is being performed, and junior staff being reluctant to express disagreement with senior staff. The following incidents illustrate this problem:

The aircraft was at the terminal and had to be towed to the run bay. An engineer was working in the engine on the variable inlet guide vanes. The APU was started to provide hydraulic power (but no air was supplied to the engine). The acting leading hand suggested that to save time, the engineer should continue working in the engine as the aircraft was towed to the run bay. The engineer remained in the engine as the aircraft was towed. There was some disagreement in the crew about whether this was a good idea. About 10 minutes was saved.

The crew had the task of 'panelling up' an aircraft after work had been carried out by another crew on an engine. The aircraft was scheduled to depart shortly but was delayed in getting to the run bay due to a problem with the delivery of catering supplies. During the engine run, an oil leak was detected. Oil lines were checked to try and locate the leak. As this was being done, the tug arrived to take the aircraft to the terminal for departure. Time was limited and after tightening some oil lines, a dry spin was performed. No leak was detected during the spin. Some crew members considered that an additional engine run should have been performed but did not forcefully express this view to more senior personnel. The engine was subsequently shut down in flight due to oil loss from loose oil lines.

The concept of cockpit authority gradient has been applied to explain why flight crew performance is sometimes poor when there is a steep difference in authority between senior and junior crew (Hawkins 1993). The above incidents appear to illustrate a similar difficulty within maintenance. However, just as a steep authority gradient can reduce performance, so too can an excessively flat gradient or a laissez-faire approach prove to be a hazard, as the following incident illustrates.

The crew had just finished installing an upper deck escape slide (a job which takes about 4 man-hours). During the job, the crew were noisily fooling around, people were talking to the LAME in charge, and there were many disturbances; however, the LAME did not want to get the other workers to be quiet as it would have made him look foolish. At the end of the job there is a test to make sure that the door goes from auto to manual smoothly. The door was accidentally left in 'automatic', and when the door was operated at the end of the job, the slide partly fired. Although the slide did not inflate, it hit docking. The LAME realised that they had not been taking the job seriously enough.

CRM for flight crew generally entails coordinating the work of people within a single crew. Maintenance personnel face the additional challenge of coordinating the work of multiple crews, particularly when a task extends for longer than one shift or more than one crew is working on an aircraft simultaneously.

A significant number of incidents collected in this study reflected the difficulties of more than one crew working on an aircraft at the same time. The following example illustrates this:

A crew was working on the centre hydraulic system in the wheel well of a twin-engine aircraft. Some hydraulic lines (which operate at 3,000 lb/in²) were disconnected. A member of another crew was in the cockpit changing a light bulb on an overhead panel switch for the centre hydraulic system. Although the switch was believed to have been tagged to prevent activation, the worker pushed in the switch and the hydraulic system activated. The engineers in the wheel well evacuated the area when they heard the hydraulic system activate. Not all the information collected indicated poor CRM performance. Most crews obviously perform their work in a coordinated and efficient manner and some positive CRM practices were noted. For example, some leading hands encourage all crewmembers to browse through the task documentation at the start of the shift.

Equipment issues—hardware

The *hardware* element of the SHEL model refers to the physical equipment used in the job. Several issues emerged concerning this aspect of the work of maintenance engineers, particularly in incidents with OH&S implications.

Equipment maintenance

Problems with the maintenance of hangar equipment such as stands, lighting system and vehicles featured frequently in incident reports. In some cases, equipment which had been identified as unserviceable was still available for use. For example:

While changing the logo light in the tail of an aircraft, the lift truck, which had been extended over the tail (horizontal stabiliser), slowly dropped onto the stabiliser. The truck had been snagged as unserviceable due to a hydraulic leak, but had still been issued to the workers. When the truck platform was retracted, the main supports gouged into the leading edge of the stabiliser. The worker reported that he had learnt from this experience to avoid, where possible, putting ground equipment over an aircraft.

Although some equipment has been in service for many years, several reporters specifically mentioned that some older equipment, particularly old stands and mobile stairs, were still useful for many maintenance tasks.

Warning and lockout devices

Several incidents involved various lockout devices, ties or pins being left in place. This finding is consistent with the UK statistics referred to in the introduction which indicated that the failure to remove ground lock pins was a significant error in maintenance. This may reflect difficulties with the control and storage of this equipment. For example, such devices are not always stored in a manner which would make it obvious when a device has been unintentionally left in place. Storage of these devices in slots or boxes would make it easier to detect when one has gone astray.

A crew was required to do a functional check after rigging work had been performed on the flight controls of an aircraft by another crew. During the check to make sure all rigging pins were removed from the control runs inside the aircraft, it was found that one rigging pin was still in place (in the tail of the aircraft). Pins are issued with long red plastic streamers attached, but there was no streamer on this pin. The controls of the aircraft could have been damaged had they been moved with the pin in place. When asked why he thought the incident happened, the reporter mentioned that some rigging pins are stored in a box (which makes it easy to keep track of how many have been collected), but these ones might not have been stored in this way. He thought the other crew had forgotten about the pin and he said it was not easy to see if all pins had been collected.

Design issues

There were several incidents where an error made by engineers was related to the design of aircraft or engines. For example, several incidents were reported in which thrust reversers were left locked out on twin-engine aircraft (an example of such an incident has been reported earlier). All of these incidents involved aircraft equipped with GE CF6 engines: none occurred on Pratt and Whitney engines. These incidents appear to be directly related to the design of the lockout system. Other incidents involving the incorrect or incomplete assembly of components appear to reflect designs which increase the potential for error. The example of an incomplete installation of a fuel filter referred to earlier illustrates this problem. It would appear that ergonomic maintenance considerations are sometimes overlooked when aircraft and systems are being designed. Better feedback to manufacturers on the errors which occur during the maintenance of their products may help to reduce design-related maintenance errors.

Discussion

The data collected in this project has provided some useful insights into the nature of maintenance incidents.

Most types of incidents were repetitive. The recurring nature of such incidents means that they are to some extent predictable, and hence measures can be taken to prevent them.

Many incidents involved flight controls, engines, and thrust reverser systems.

Human error featured in most incidents, with omissions being the most frequent type of error. The skill-rule-knowledge framework proved to be an adequate classification system for maintenance errors, although in some cases, the framework was difficult to apply. Errors due to inadequate knowledge were rare and were usually committed by trainee technicians. Skillbased errors occurred in approximately 34% of the incidents. However, the majority (52%) of the errors took the form of rule-based mistakes. Many of these errors took the form of mistaken assumptions, particularly where workers wrongly assumed that an aircraft system was in a particular configuration.

Williamson and Feyer (1990), in examining the errors which preceded a sample of 1,020 workrelated fatalities, found that just over 50% of errors were skill-based, while fewer than 14% were rule-based mistakes and fewer than 14% were knowledge-based mistakes. In contrast, the current study, while based on a significantly smaller number of incidents, would appear to indicate that formal and informal rules play a significant part in guiding the actions of maintenance technicians and that these rules provide a significant source of errors.

A common rule-based error was the activation of an aircraft system (such as hydraulics), without first checking the status of cockpit controls. Remedial action for such errors could include ensuring that technicians acquire appropriate situational awareness before activating systems, possibly by the use of checklists to guide performance of routine actions.

The type of error which can be expected on a given task appears to be closely related to the frequency with which that task is performed. By definition, rule-based or knowledge-based mistakes can be expected to be particularly prevalent when the task is unusual, but to become less common on tasks which are performed frequently. Skill-based slips and lapses, on the other hand, are relatively uncommon on unusual tasks but may become problematic on tasks which are performed routinely.

For example, frequently performed tasks such as routine boroscope inspections have the potential to produce skill-based errors because of the familiarity of the work and the potential for absent-minded task performance. An important consequence of the relationship illustrated in Figure 17 is that by categorising tasks according to the frequency of their performance, main-



Figure 17 Task frequency and the prevelance of error

tenance managers will be better placed to anticipate errors and introduce appropriate countermeasures. A further implication of this relationship is that for individual workers, there may be an optimum level of task familiarity lying somewhere between the extremes of highly unusual and highly routine tasks.

Several patterns emerged in the timing of incidents. In general, the frequency of incidents gradually increased as the shift progressed, with a peak of incidents in the second-last hour of the shift. The last hour of the shift, however, was the time when the least number of incidents occurred. This may reflect a change in the work being carried out, as workers clean up work areas and prepare to finish work for the day.

Research on the timing of workplace and transport accidents indicates that the early hours of the morning and early afternoon are times at which accidents are particularly likely to occur. For example, Williamson and Feyer (1995) found that when the number of people at work throughout the 24 hours of the day is taken into account, fatal workplace accidents in Australia are more likely to occur at night than during the day. The results of this study are consistent with those findings, and indicate that the rate of incidents per worker is greatest in the period between 0200 and 0400.

The local factors underlying airworthiness incidents were generally different to those underlying OH&S incidents. For airworthiness incidents, procedures, control and supervision and communications emerged as the most significant factors. For OH&S incidents, tools and equipment, perceived pressure or haste, and the physical environment were the three most frequent local factors.

Attributing local factors was relatively straightforward in most cases. However, organisational factors could not be identified with a high level of reliability using the coding sheet presented in the appendix.

Much of this document to this point has been concerned with the factors which lead to errors. However, it is important to recognise that errors can also be addressed in at least two other ways.

First, some errors occur while preventative maintenance or inspection tasks are being performed. It is possible that in some cases, the risk of a system failure caused by a maintenance error will be greater than the risk of a failure if the system is left undisturbed. A well known example which illustrates this problem occurred in North America when an L1011 lost oil from all three engines when magnetic chip detectors were fitted without O-rings. The benefits of the inspection program would certainly have been outweighed by the risk of such an error occurring (National Transportation Safety Board 1984).

In planning maintenance tasks, it may be necessary to factor in the probability of a human error occurring during the task. For example, an inspection task which requires the frequent opening and closing of access covers is likely to produce occasional skill-based lapses where access covers will be left unsecured. Where the maintenance is designed to achieve financial rather than safety benefits, such as extending the service life of a system, there may be occasions where it would be preferable to leave a system undisturbed in order to avoid the possibility of a maintenance error.

The second approach to human error is to acknowledge that errors will occur from time to time and to design procedures and systems which can tolerate such errors. Avoiding the simultaneous performance of the same task on similar systems is an example of such an approach. For example, on 25 February 1995, a European-operated 737-400 was forced to divert shortly after departure following a loss of oil quantity and pressure on both engines. Both of the aircraft's engines had been subject to boroscope inspections during the night prior to the incident flight. High-pressure rotor drive covers had been left unsecured on each engine and, as a result, nearly all the oil had been lost from each engine during the brief flight (Air Accidents Investigation Branch 1996).

Where extended range twin-engine operations (ETOPS) are being conducted, the performance of identical maintenance actions on multiple elements of critical systems is avoided wherever possible. Engines, fuel systems, fire suppression systems and electrical power are examples of

ETOPS critical systems on aircraft such as the B767 and B737. Boeing lists several approaches designed to minimise the impact of human error in maintenance of ETOPS aircraft. These include performing maintenance actions on different legs of a flight, having two identical tasks performed by different mechanics, adding inspections to detect errors, and carrying out tests to verify that maintenance has not introduced a problem (Boeing 1994a). However, these precautions to minimise the impact of human error are not generally applied to aircraft with more than two engines, or to twin-engine aircraft which are not being maintained in accordance with an ETOPS maintenance program.

The extension of ETOPS philosophies to non-ETOPS aircraft would help to contain maintenance induced problems. For example, staggered maintenance may reduce the risks associated with simultaneous maintenance of similar systems.

Conclusion

It should be noted that this study is based on a limited sample of maintenance incidents that may not be representative of all possible maintenance incidents. Hence, the issues raised in this report will not necessarily apply to all maintenance operations. Furthermore, much of the information in this report is derived from the knowledge and experience of maintenance engineers themselves and the results will to some extent reflect their perceptions. Nevertheless, a picture has emerged of the types of incidents which occur during maintenance work and the factors which lead to these problems. The airworthiness incidents examined in this report indicate that procedures, equipment, communications and control, and supervision of work may be worthwhile areas for attention.

Safety Actions

The following suggested safety actions are presented as a result of this study. Organisations will need to assess the extent to which these suggested safety actions are appropriate for their own operations.

1. Procedures

- 1.1 Maintenance organisations should periodically review documented maintenance procedures to ensure that they are accessible, consistent and realistic.
- 1.2 Maintenance organisations should periodically examine work practices to ensure that they have not evolved to the extent that they differ significantly from formal procedures. Narrowing the gap between work practices and formal procedures may require modifications to procedures as well as to work practices.
- 1.3 Maintenance organisations should, where possible, ensure that standardised work practices are adhered to across their maintenance operations.
- 1.4 Maintenance organisations should evaluate the ability of checklists, whether performed from memory or from paper, to assist the performance of maintenance personnel in routine situations such as activating hydraulics, moving flight surfaces or preparing an aircraft for towing.

2. Managing the risk of human error

- 2.1 Maintenance managers should reconsider the need to disturb normally functioning aircraft systems to conduct non-essential periodic maintenance checks or inspections, as each disturbance to a system carries with it the risk of a maintenance error.
- 2.2 Maintenance organisations should formally review the adequacy of defences, such as engine runs, designed to detect maintenance errors. Such a review could commence with a listing of hazards followed by the listing of existing defences designed to address these hazards. The aim of such a review would be to identify absent or inadequate defences.
- 2.3 Where possible, the simultaneous performance of the same maintenance task on similar redundant systems should be avoided, whether or not the aircraft is an ETOPS aircraft.

3. Communication

3.1 Maintenance organisations should ensure that adequate systems are in place to disseminate important information to all maintenance personnel, particularly where procedures have changed or where an error has occurred repeatedly on a task.

4. Tools and equipment

- 4.1 Maintenance organisations should review the systems by which equipment such as lighting systems and stands are maintained to ensure that unserviceable equipment is removed from service and repaired rapidly.
- 4.2 Lockout devices should be stored in such a way that it is immediately apparent when they have been inadvertently been left in place. For example, storage of gear-lock pins in a slotted box would be preferable to loose storage in plastic bags.

5. Shift handover

5.1 Maintenance organisations should review the adequacy of shift handover practices, with particular attention to documentation and communication, to ensure that incomplete tasks are seamlessly transferred across shifts.

6. Supervision

6.1 Maintenance organisations should recognise that supervision and management oversight may need to be increased, particularly in the last few hours of each shift, as errors become more likely.

7. Towing aircraft

7.1 The procedures and equipment used to tow aircraft to and from maintenance facilities should be reviewed. Particular attention should be paid to the possible need for a direct verbal communication link between engineering personnel and tug drivers, to reduce the current heavy reliance on hand signals. The procedures used to maintain safe clearance between towed aircraft and obstructions in confined spaces should also receive attention.

8. Design issues

8.1 Manufacturers should give greater consideration to maintenance ergonomic issues when designing systems and should actively seek information on the errors which occur when systems are being maintained.

9. Training

- 9.1 Maintenance organisations should consider introducing crew resource management training for maintenance engineers and other personnel (such as tug drivers) who interact with maintenance personnel.
- 9.2 Regular refresher training should be offered to maintenance engineers with particular emphasis on company procedures. Such training could help to reduce the frequency of incidents related to misunderstandings of company procedures.

10. Feedback on maintenance incidents

- 10.1 Maintenance organisations should ensure that engineering training schools receive regular feedback on recurring maintenance incidents in order to target corrective programs at these problems.
- 10.2 Managers of maintenance organisations should ensure that they receive regular, structured feedback on maintenance incidents, with particular emphasis on the underlying conditions or latent failures which promote such incidents.

Appendix 1 Maintenance Incidents

I am studying incidents in aircraft maintenance. By maintenance incident, I mean any situation in which something happened which could have prevented the aircraft from operating normally or could have put the safety of anyone (including maintenance workers) at risk. I am interested in any occasion when a problem happened in maintenance, including the big problems and the small mistakes and including the times when a problem occurred but was corrected before the aircraft was signed back to the line.

I know that most of the time, maintenance is uneventful, but by gathering information about the occasions when things go wrong, I hope to learn about the entire maintenance system.

A. First, I would like you to describe an incident that put at risk your safety, or the safety of one of your workmates. I am only interested in incidents that happened in the last 12 months or so, that you actually saw happen, either to you or to someone else. Your identity will remain confidential and if you want, the information you give me will also remain confidential. I am interested in the incident itself, and what it tells us about the maintenance system. I am not interested in individuals and I am not interested in blaming people for things that have happened.



- 1. How long ago did it happen?
- 2. Is this the first time that this has happened?
- 3. Was it officially reported? Was corrective action recorded?
- 4. Could it happen again?
- 5. What time was it?
- 6. How long into the shift was it?
- 7. Did it involve another shift/another crew?

8. Was it a routine task?

-was the person distracted?

-would their actions have been correct in other circumstances?

9. Did the incident occur while a problem was being dealt with?

-was there a standard set of rules to deal with this problem?

10. What type of work was being performed at the time?

11. What part of the aircraft was being worked on?

12. Why do you think the incident happened?

-People

-Equipment

-Environment

–Task

13. Would you object if I included this incident in a report for Unions and Management?

B. Now can you tell me about a maintenance incident that could have prevented an aircraft from operating normally. Again, I am interested in incidents which occurred in the last 12 months or so, that you actually saw happen, either to you or to someone else.

1. How long ago did it happen?

2. Is this the first time that this has happened?

- 3. Was it officially reported? Was corrective action recorded?
- 4. Could it happen again?
- 5. What time was it?
- 6. How long into the shift was it?
- 7. Did it involve another shift/another crew?
- 8. Was it a routine task?
 - -was the person distracted?
 - -would their actions have been correct in other circumstances?
- 9. Did the incident occur while a problem was being dealt with?
 - -was there a standard set of rules to deal with this problem?
- 10. What type of work was being performed at the time?
- 11. What part of the aircraft was being worked on?
- 12. Why do you think the incident happened?
 - -People
 - -Equipment
 - -Environment
 - –Task

13. Would you object if I included this incident in a report for Unions and Management?

Appendix 2 Human factors in maintenance coding sheet

1. Case number___Coder___Reporter___Aircraft type_____

2. Type of Incident

- (a) OH&S incident resulting in__:
- (A1) death
- (A2) exposure to hazard
- (A3) potential hazard
- (A4) not OH&S incident
- (b) Maintenance incident resulting in__:
- (B1) actual damage to aircraft
- (B2) aircraft signed off with unrectified irregularity
- (B3) aircraft signed off with irregularity resulting from maintenance action
- (B4) potential damage to aircraft
- (B5) delayed aircraft
- (B6) correction of problem
- (B7) no maintenance problem
- 3. Events in sequence____
- (3.1) Description of event 1

(16.2) Description of event 2

(16.3) Description of event 3

 (16.4) Description of event 4

_____ _____ _____ 4. How long ago did it happen? Weeks 5. Is this the first time that this has happened? Y N DK 6. Was it officially reported? Y N DK 7. Was corrective action recorded Y N DK YES NO MAYBE 8. Could it happen again? 9. What time was it? Hours Hours 10. How long into the shift was it? 11. Did it involve another shift/another crew? ΥN 12. What type of work was being performed at the time? _____ _____ 13. What part of the aircraft was involved? (ATA Chapter) 14. Would the reporter object if this incident was made public? ΥN 15. EVENT 1 (15.1) Type of event (A1) Behavioural event (B1) Environmental event (C1) Equipment related event (15.2) If event was behavioural: (Circle one of 'Yes' or 'Probably' for each question) (15.2.1) Is this the way the job is normally done? (A) Yes (B) Probably (C) Probably not (D) No (E) Don't Know (15.2.2) Was action (A) Consistent with good safety practices? Yes Probably (B) Inconsistent with good safety practices? Yes Probably (C) Not known whether consistent or inconsistent Yes

(15.2.3)

What was the highest level of cognitive control called for?

(A) Skill-based behaviour	Yes Probably
(B) Rule-based behaviour	Yes Probably
(C) Knowledge-based behaviour	Yes Probably
(D) Unclassifiable	Yes

(15.2.5)

If behaviour was abnormal and/or rule breaking, was action:

(A) Omission	Yes Probably
(B) Commission	Yes Probably
(C) Substitution	Yes Probably
(D) Mis-timed action	Yes Probably
(E) Unclassifiable in above categories	Yes

16.1 Local factors relating to event 1

1 PHYSICAL FACTORS

- 1A Anthropometric characteristics
- 1B Sensory limitations
- 1C Fatigue
- 1D Drugs (including alcohol)

2 COGNITIVE FACTORS

- 2A Distraction from task
- 2B Memory
- 2C Workload
- 2D Knowledge, skills and experience
- 2E Perceived pressure or haste
- 2F Convenience

3 BETWEEN PEOPLE

- 3A Planning within crew
- 3B Visual signals or visibility of other workers
- 3C Communication
- 3D Control and supervision of work

4 TASK ASPECTS

- 4A Shift change
- 4B Procedures
- 4C Documentation
- 4D Task order within work package

- 4E Interruption
- 4F Conflict between norms and formal procedures
- 4G Job scheduling
- 4H End of shift
- 5H Overtime

5 PHYSICAL OBJECTS

- 5A Inadequate tools and equipment
- 5B Space restrictions
- 5C Illumination
- 5D Design of aircraft component or system
- 5E Automated systems

6 PHYSICAL ENVIRONMENT

Includes:

(Temperature extreme, glare, noise, air quality, weather, darkness, heights, working surface or ground surface)

16.2 Organisational factors relating to event 1

- (A) Incompatible goals
- (B) Inappropriate structure
- (C) Poor communications
- (D) Poor planning
- (E) Management oversight, control and monitoring
- (F) Design failures
- (G) Inadequate system defences
- (H) Unsuitable materials
- (I) Control of procedures
- (J) Poor training
- (K) Inadequate maintenance of equipment
- (L) Inadequate regulation
- (M) Conflict between norms and formal procedures

Appendix 3 Reliability of coding

For event types and skill rule knowledge error types, the reliability of coding was assessed by calculating values of Cohen's kappa (Breakwell, Hammond & Fife-Schaw 1995). Cohen's kappa ranges between 0 and 1 and represents the proportion of agreement corrected for chance. Fleiss (1981) describes values of Cohen's kappa greater than 0.75 as 'excellent', and values between 0.6 and 0.75 as 'good' (reported in O'Hare and others 1994).

Forty incidents were coded by a second coder, in addition to the coding conducted by the primary coder. The forty incidents contained a total of 63 incident events.

Breakdown into event types

Events were broken down into event types following the method developed by Williamson and Feyer (1990). Events could be either behavioural, equipment-related or environmental. For the first events in the incident sequences, a 100% level of agreement was obtained. Lower levels of agreement were obtained on second, third and fourth events. The value of Cohen's kappa for these subsequent events was 0.71.

An overall value of Cohen's kappa for all events was not calculated as the number of coding choices was different when coding first events than when coding subsequent events. There were three potential choices for first events, behavioural, equipment related or environmental, and four potential choices for subsequent events (as above but with the additional possibility of no event).

Skill-rule-knowledge error types

A value of Cohen's kappa was calculated for the skill-rule-knowledge categorisation system for those cases where both coders agreed that a behavioural event had occurred. For the purposes of calculating Cohen's kappa, 'probably' codings were combined with 'yes' codings to achieve an overall assignment to skill-rule-knowledge categories. The value of Cohen's kappa was 0.72.

Incident factors

Local factors

For the purposes of calculating the reliability of factor codings, local factors were aggregated into the broad category headings as seen on the coding sheet elsewhere in the appendix. Local factors assigned to events by the primary coder were also identified by the second coder on 65% of occasions.

Organisational factors

The reliability of organisational factors was significantly less than that for local factors, and only 33% of organisational factors identified by the primary coder were identified by the second coder.

Appendix 4 Definitions

Communications. Information which is essential for the safe functioning of the organisation does not reach the necessary recipients. Includes communication from the shop floor upwards and from management downwards.

Commission. An error which occurs when an operator performs a task incorrectly or performs a task which is not appropriate to the circumstances.

Conflict between norms and formal procedures. Actual work practices do not reflect formal procedures. In some cases this may because formal procedures are cumbersome or difficult to comply with.

Control of procedures. Important safety, working or operational regulations and procedures are not clear, difficult to follow, incorrect, incomplete or inaccessible.

Design failures. Relates to the design of tools, equipment, work environments and procedures. Inadequate design may promote errors or violations or may produce situations where non-standard performance results in negative and irreversible consequences.

Environmental events. Relates to elements of the physical environment in which the task was being performed which cannot be changed or compensated for. Weather-related phenomena are examples of environmental events.

Equipment-related events. Concerns breakages or malfunctions of equipment, tools and machinery, including aircraft components.

Event. An occurrence, action or closely related series of actions which occurred at a particular place and time. Where the actions are behavioural, and a series of actions were performed by different people, separate events are required for each person.

Inadequate maintenance of equipment. Deficient management of maintenance of tools and equipment, including lack of preventative maintenance, poor maintenance scheduling and excessive delays in repairing equipment.

Inadequate regulation. Inadequate surveillance by government bodies or their delegated authorities. Absence of appropriate laws to regulate dangerous operations.

Inadequate system defences. An absence or inadequacy of 'safety nets' in the system. Such defences can serve to detect or prevent unsafe job performance, or minimise the consequences of such performance. Includes cases where existing defences are circumvented.

Inappropriate structure. Relates to the structure of the organisation. For example, management responsibilities may be blurred or poorly defined.

Incident. A situation in which events occurred which could have prevented an aircraft from operating normally or could have put the safety of any person (including maintenance workers) at risk.

Incompatible goals. Organisations are generally pursuing several goals at the one time, for example safety and production. This factor should be coded in cases where the incident events reflect a poorly resolved goal conflict.

Knowledge-based errors. Occur when a person is required to solve an unfamiliar problem for which no procedures exist. Knowledge-based errors are typically related to an inappropriate mental model of the system or a lack of resources for dealing with a complex problem. Rule-based errors and knowledge-based errors are commonly referred to as *mistakes*.

Management oversight, control and monitoring. Relates to the way management monitors the performance of planned work and ensures that work is completed in accord with guide-lines.

Planning. Where management planning and scheduling of activities has not adequately taken safety considerations into account.

Poor training. Indicated by deficiencies in the knowledge or skills of employees.

Rule-based errors. Occur in familiar situations where, in the process of dealing with a situation, the worker either applies a bad rule or misapplies a good rule. A typical case is the application of a general procedure to a specific situation which calls for a modified version of the procedure .

Rule-based errors and knowledge-based errors are commonly referred to as *mistakes*.

Skill-based errors. Occur in rapid automatic mode where the person has invested a minimum of mental resources to the task at hand. Such errors occur in familiar situations involving highly practiced automatic routines which may have developed after extensive training and experience.

Two particular types of skill-based errors are *slips* and *lapses*. Slips are errors in which an operator intends to perform a correct action but accidentally performs another well-learnt action or action sequence. A lapse is a failure to carry out an intended action. An example is the omission of a step in a procedure following an interruption.

Substitution. An error in which an operator performs an action in place of the desired action. Substitution can be considered to be a special type of commission error.

Unsuitable materials. To be coded where the event is related to the provision of unsuitable tools and equipment or other work materials.

Appendix 5 Maintenance incident events

Note: This listing of incident events excludes six incidents where the reporter asked that the incident remain confidential.

Event description

- -Thrust reversers locked out during A check, not documented.
- —Thrust reversers not reactivated.
- ---Worker knowingly used unserviceable stand.
- —Acting leading hand suggested that worker remain in engine during towing.
- —Worker remained in engine as the aircraft was towed.
- -During work on leading edge slats one torque tube not connected.
- -Slats extended with one torque tube not connected.
- -Stair locking mechanism failed.
- —Worker on stairs reacted inappropriately to situation by holding onto engine while still standing on stairs.
- -Worker did not take wind into account when depressurising reservoir.
- —Wind blew hydraulic fluid into eyes.
- -Rigging pin used without attached streamer.
- -Rigging pin left in flight controls (found before work signed off).
- -Circuit breaker pulled without being tagged before engine spin.
- -Worker pushed circuit breaker in to its normal position and fuel spilled.
- -Thrust reversers locked out when not strictly necessary.
- -Thrust reversers not reactivated before aircraft dispatch.
- -Crew ran engines causing blast to affect other workers.
- -Tug driver delayed stopping once signal to stop had been given.
- -Tug driver delayed stopping once signal given.
- -Stairs rolled back as locking system failed to hold.
- ---Workers on stairs reacted inappropriately by holding onto aircraft while still standing on stairs.
- -Tradesperson pressed hydraulic switch button while it was tagged as not to be used.
- —During a fuel pump change a fuel line was not reconnected properly.
- -Lead hand did not check that everyone was clear before calling for a wet spin of engine.
- -During inspection of the engine serious damage to part of a fan air valve was missed. (discovered later).
- -Incoming shift reinstalled engine without changing pre cooler as documented.
- -Igniter circuit breakers not pulled before conducting a wet spin.
- —LAME reacted incorrectly to engine start by shutting off fuel and starter, instead of just fuel.
- -Driver misjudged tow, aircraft scraped docking.
- -Thrust reversers inspected with power running without them being locked in place.
- -Incorrectly installed panel on twin-engine aircraft.

- -Flap lever had been moved up while flaps were in down position with power off.
- -Hydraulics had been started without first ensuring that flaps and flap lever were consistent.
- -Crew not looking, towed aircraft hit a tree.
- -Engine jammed as it was being hoisted.
- -Person put fingers between engine and mounts.
- -Crew failed to notice that rod end was incorrectly adjusted.
- -Previous crew had left aircraft with flap lever inconsistent with flap position and hydraulics off.
- —Worker in cockpit started hydraulics without first confirming that flap lever and flap position were consistent.
- —Mechanical crew told electrical crew that it was OK to run flaps with panel incompletely fitted, flaps damaged.
- -Foot slipped while working on engine.
- -Worker did not pull circuit breakers before starting electrical work.
- -Tool crib permitted truck to be used which had been snagged US.
- -Truck settled on hydraulics while positioned over horizontal stabiliser.
- -Platform retracted, scraped aircraft.
- -Worker slipped on wet surface.
- -Worker attempted to perform task without appropriate equipment.
- -Person drove vehicle near engine that was about to be started.
- —AME left parked tug with engine running.
- -Tug transmission slipped into reverse, collided with engine cowl of 737.
- -Cleaner drove vehicle into unsafe area.
- -LAME on interphone did not see warning signal of wingman, continued tow until collision.
- —Two nuts left off fuel pump filter.
- —System did not leak under a leak check.
- —Jet blast from B747 affects hangars.
- -Worker failed to torque 2 nuts on GE CF6 fuel system.
- -Technicians started pneumatics without first warning other workers working on the aircraft.
- -Electrical crew failed to lock out reversers when thrust reverse cowls open.
- -Workers seen riding on the tray of a utility vehicle, in contravention of safety guidelines.
- -Crew failed to re-activate thrust reverse during system re-activation.
- -Worker positioned in dangerous location without adequate handholds, resulted in fall.
- —Aircraft wingtip struck a tree while being towed.
- -No warning PA was made before aircraft was towed, worker was up ladder in cabin at time.
- -Crew members sheltered from rain as aircraft pushed back from terminal, insufficient people to check clearance.
- —Tug driver could not follow line due to poor visibility, aircraft struck parked aircraft.
- -Upper deck door was left on automatic after test.
- —Door opened automatically, slide deployed.
- -Failed to find and correct aircraft fault.

- -Valve stuck open directing fuel to an area which could have been occupied by a worker.
- ---Worker did not pull out circuit breaker before working on electrical system, resulted in electric shock.
- -Stand was not moved out of the way before aircraft was towed out of hanger.
- -Crew failed to notice that the aircraft was too close to the stand, in time to prevent contact.
- -No warning sign used when radar switched on with people in vicinity.
- —All four reverse thrust blocker doors were activated while people were working on the aircraft.
- -Wrong valve fitted to aircraft pneumatic system.
- -Valve broke—distributing metal fragments in pneumatic system, damaging heat exchangers.
- —AME left spanner under engine cowl.
- -After aircraft departed, suspected where spanner was, but did not notify company.
- -Before compressor wash, blanked off wrong sense line.
- -Washed compressor with wrong lines blanked off.
- -LAME started APU even though it was tagged for safety reasons.
- -Towing cable attached to blast fence badly worn.
- —Worker did not ensure that a fire extinguisher was available while conducting work with the fire system inoperative.
- —After adding oil to RB211, LAME replaced oil cap but did not push locking flap down.
- -One igniter was left disconnected while other was being checked.
- -Wrong igniter was fired, sparked across to engine.
- —Worker started working in slippery dangerous area without first taking precautions to reduce the risk.
- —Worker slipped and cut hand on rotating turbine blade.
- —Unable to find part (static invertor) in computerised parts inventory system.
- -Part was 'robbed' from another aircraft.
- -Details of 'robbed' part were passed to an apprentice instead of being documented in log.
- —Apprentice did not act on the information.
- —AME accidentally put engine oil into hydraulic system of B747.
- —Water heating system (hot cup) failed due to short circuit.
- -LAME tested system by placing hand into 'live' water, received shock.
- —Fault not found on walkaround.
- -Earth pin on power lead broken.
- -Worker attempted to plug two live leads together.
- -Door power assist system malfunctioned when door opened.
- —Aircraft signed out of hangar with inoperative spoilers, reason not established.
- -Reporter forgot to lower wheels of towbar before tug drove away, towbar dropped on foot.
- -Ladder slipped on stand while worker was trying to reach radome.
- -Technicians climbed from stand onto an engine.

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