Department of Transport and Regional Services

Australian Transport Safety Bureau

ATSB Survey of Licenced Aircraft Maintenance Engineers in Australia

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EXECUTIVE SUMMARY

Aircraft maintenance errors are estimated to be involved in 12% of airline accidents worldwide. Records maintained by the Australian Transport Safety Bureau (ATSB) indicate that 4.5% of Australian aircraft accidents involve maintenance deficiencies. Human error in aircraft maintenance is poorly understood and has not been the subject of previous studies in Australia. In late 1998 the Bureau of Air Safety Investigation (now ATSB) distributed a survey to Licensed Aircraft Maintenance Engineers (LAMEs) in Australia. The survey was designed to identify safety issues in maintenance, with a particular emphasis on the human, or non-technical aspects of the job.

The survey provided LAMEs with the opportunity to describe occurrences that had the potential to threaten the safety of an aircraft, or the safety of maintenance workers. Six hundred and ten occurrence reports were reported via the survey. In most cases the reported events resulted in relatively minor consequences. The most common form of occurrence was one in which an aircraft system was activated in an unsafe manner during maintenance. The next most common form of occurrence involved the incomplete installation of components. Over 95% of the occurrences involved the actions of people. The most common forms of human error contributing to the events were memory lapses and procedure shortcuts. The contributing factors most frequently listed by survey respondents were time pressure, equipment deficiencies, inadequate training, coordination difficulties and fatigue. There was evidence that the frequency of safety occurrences fluctuated throughout the 24 hour day and that the early hours of the morning were times of particular risk for maintenance occurrences.

Several safety deficiencies were identified in the course of this study. These included: a current lack of programs to limit the extent of fatigue experienced by maintenance workers; a lack of recurrent training for licenced aircraft maintenance engineers; a need for maintenance personnel to be trained in crew resource management skills such as communication and the management of production pressures; a widespread blame culture in aircraft maintenance which discourages personnel from officially reporting incidents; and the simultaneous maintenance of critical multiple redundant systems, which can make the consequences of errors more serious. The report concludes with recommendations directed at these issues.

ABBREVIATIONS

AME	Aircraft Maintenance Engineer
AOG	Aircraft on Ground
ATSB	Australian Transport Safety Bureau
BASI	Bureau of Air Safety Investigation
CRM	Crew Resource Management
ETOPS	Extended-range Twin-engine Operations
FOD	Foreign Object Damage
JAR	European Joint Aviation Requirements
LAME	Licensed Aircraft Maintenance Engineer
MEDA	Boeing Maintenance Error Decision Aid
NTSB	U.S. National Transportation Safety Board

1 BACKGROUND INFORMATION

1.1 Human error and accidents

Researchers in a wide range of fields have concluded that worldwide, human error contributes to the majority of accidents in transport, industry and medicine. It is estimated that 70% of aircraft accidents involve pilot error, while 80% of shipping accidents involve human error.[1,2] Professor Lucian Leape of the Harvard University School of Public Health has estimated that each year in the US, 180,000 people die as a result of medical errors.[3] Clearly, human fallibility can have serious consequences, and understanding more about the nature of human error is of crucial importance.

At present very little is known about the nature of human error in aircraft maintenance. The research described in this report was directed at this issue.

1.2 Maintenance-related occurrences worldwide

Deficiencies in the maintenance of the world's airline aircraft are estimated to be involved in 12% of major accidents.[4] Some authorities consider that improper maintenance is now contributing to a greater proportion of accidents than it did in the past.[5] US National Transportation Safety Board member John Goglia has stated that of 12 recent major accidents involving US airlines, five were a result of maintenance deficiencies.[6]

Fortunately, there have been few maintenance-related accidents to airline aircraft in Australia, however accidents and serious incidents in Asia, Europe and North America have been traced back to errors which occurred during maintenance. The following three examples, each from a different continent, illustrate ways in which maintenance errors can compromise safety.

> In June 1990, a windscreen of a British BAC 1-11 jet blew out as the aircraft was climbing to its cruising altitude, partially ejecting the pilot through the open window. The accident was traced to the incorrect installation of a new windscreen during the previous night shift. The windscreen had been installed by a shift maintenance manager using the wrong bolts.[7]
>
> In 1983, all three engines of a US operated Lockheed L1011 failed in flight after oil leaked from the engines because maintenance personnel had omitted to fit O ring seals to master chip detectors during routine maintenance.[8]
>
> In 1985, the world's worst single aircraft accident claimed the lives of 520 people when a Japanese operated Boeing 747 become uncontrollable after the rear pressure bulkhead failed in flight, destroying vital aircraft systems. The failure occurred after an improper repair.[9]

1.2.1 Cost of maintenance occurrences

Maintenance errors are not merely expensive in terms of life and property, but can also impose significant costs when flights are delayed or cancelled. It has been estimated that around half the engine-related flight delays and cancellations experienced by airlines are due to maintenance errors. An aircraft delayed due to a maintenance problem costs an airline on average US$10,000 per hour.[4] In total, the errors of maintenance and ground personnel cost the US airline industry around one billion US dollars per year.[10] Even apparently simple maintenance errors can impose major uninsured costs on an airline. A maintenance-related air turn-back of a Boeing 747 resulting in the need to accommodate passengers overnight, can cost around $250,000.[11] 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, not to mention accidents.

1.2.2 The nature of human error in maintenance occurrences

It is becoming apparent that maintenance anomalies often reflect human, rather than technical failures, yet the involvement of people in maintenance deficiencies is an overlooked issue.

In one of the first examinations of the problem, the UK Civil Aviation Authority produced a list of the most frequent maintenance errors in aircraft over 5,700 kg.[12] 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: omissions (56%); incorrect installations (30%); wrong parts (8%); and 'other' (6%).[13]

While these studies have helped to identify the consequences of maintenance errors, they provide limited information on the origins of these errors. Authorities in various parts of the world are increasingly recognising that there is a lack of information on the contributing factors which lead to maintenance anomalies and that many official reports of maintenance-related aircraft accidents rarely provide more than cursory details on the role of maintenance workers in the development of the accident circumstances.[4, 14]

The aim of the current research was to examine the human involvement in aircraft maintenance occurrences in order to understand the nature of human error in maintenance, and the factors that promote such errors.

1.3 Maintenance-related occurrences in Australia

In the years 1990 – 2000 BASI/ATSB records indicate that there were 2,525 aircraft accidents in Australia (excluding sport, military, gliding and ballooning operations). Of the 2,525 accidents, 110 (or 4.5%) are recorded as having involved aircraft maintenance deficiencies, however there is no evidence to suggest that the frequency of maintenance errors is increasing or decreasing. Most of these accidents occurred to aircraft utilised in general aviation operations such as private flying. The following occurrence involved an aircraft used for agricultural operations.

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The pilot was making a test flight following the installation of an overhauled engine in the aircraft. The engine test run was reported as normal but shortly after take-off the engine failed and the pilot was forced to make an off-airport emergency landing. The aircraft was extensively damaged and the pilot, who was the only occupant, received minor injuries.

The investigation revealed that previous maintenance action during the engine installation had resulted in the P5 engine bleed air line being crossed with an engine drain line at the fuel control unit. This in turn resulted in no metering air being provided to the fuel control unit to schedule the propeller governor. The error was not detected during the check inspection of the connections carried out by another Licenced Aircraft Maintenance Engineer after the engine installation.

2 THE AUSTRALIAN TRANSPORT SAFETY BUREAU AIRCRAFT MAINTENANCE SURVEY

2.1 General

In late 1998 BASI (now the ATSB) distributed a safety survey to Licenced Aircraft Maintenance Engineers (LAMEs) in Australia. The survey was designed to identify safety issues in maintenance, with a particular emphasis on human, or non-technical aspects of the job. The survey gathered information on the working arrangements of maintenance personnel and also provided respondents with the opportunity to report occurrences and make general comments on safety topics.

While all surveys such as this necessarily reflect the experience and points of view of the respondents, the results are a useful supplement to data from other sources such as accident and incident investigations.

2.2 Response to survey

Of the approximately 4,600 surveys distributed, 1,359 were returned, representing a response rate of around 29%. This was considered to be a good result, given the generally low return rate on postal surveys.

2.3 Occurrences reported through the survey

Six hundred and ten respondents used the survey to report a safety occurrence. Occurrence reports were not linked with particular organisations or individuals as the focus of this study was on broad safety issues rather than specific companies or individuals. While most occurrences had happened within the previous year, just under 50% of occurrences had happened more than a year previously. As the aim of the study was to examine the general nature of human involvement in maintenance safety, no distinction was made between recent and less-recent occurrences.

Reports were analysed to determine the outcome of the occurrence, the events (including errors) which led to it, and the factors which contributed to the occurrence. Checks were carried out to ensure the reliability of the analysis method.

2.4 Occurrence outcomes

The outcome of each occurrence was categorised using a system based on the Maintenance Error Decision Aid (MEDA) system developed by Boeing.[15] Outcomes are defined in annex 1. Although the primary focus of the ATSB is on issues which could affect the safety of transport operations, reports of incidents which could have affected the safety of workers were also collected. Both types of incidents can arise from underlying deficiencies in maintenance organisations, and threats to the safety of workers may also have direct or indirect implications for the quality of maintenance work.

Information was not gathered on the in-flight consequences of maintenance anomalies. Nevertheless, the information available in reports indicates that very few of the anomalies resulted in accidents and in most cases, the problem was corrected before flight. Examples of reported occurrences appear in text boxes throughout this report.

As table 1 indicates, the most common outcome (accounting for 13% of occurrences) was 'System operated unsafely during maintenance', where aircraft systems such as thrust reversers were activated during maintenance when it was not safe to do so. In some cases, this was because maintenance personnel or equipment were not clear of the area.

> 'An AME gave a clearance to put air on a wing (activate a pneumatic system) when a component was not fully tightened. They didn't ask enough questions about other jobs/tasks being performed and didn't see the person who was fitting the component.' *Survey occurrence report*

Table 1.
Most common occurrence outcomes*

Outcome	*N*	*Per cent*
System operated unsafely during maintenance	80	13
Incomplete installation	48	8
Person contacted hazard	45	7
Incorrect assembly or location	44	7
Towing event	44	7
Vehicle or equipment contacted aircraft	31	5
Material left in aircraft	27	4
Wrong equipment or part installed	23	4
Part not installed	22	4
Part damaged during repair	21	3
Panel or system not closed	21	3
Required service not performed	20	3
Equipment failure	15	2
Fault not found	15	2
Falls and trips	14	2
System not made safe before maintenance	12	2
System not reactivated/deactivated	10	2
Pin or tie left in place	9	1
Documentation error	9	1
Other	95	15

*Figures are rounded to nearest per cent; N = number of accorrences.

The second most common outcome, (accounting for 8% of occurrences) was 'incomplete installation'. This was where all necessary parts were present, but the installation procedure had not been completed. For example, a connection may have been left 'finger tight' rather than properly secured.

> 'I was changing an electronic component on an aircraft. To remove the component, it was necessary to disconnect the pilot static lines from an unrelated system. After the electronic component was changed, it was checked and operated normally. However, I failed to re-connect the pilot static lines which were in a darkened area, and I dispatched the aircraft with no pilot static source to some instruments. The aircraft aborted takeoff and ground returned. Lines reconnected. Brain went on walk about whilst performing a routine component change.' *Survey occurrence report*

'Person contacted hazard' is where a maintenance worker came into contact with a hazard which had the potential to cause injury. This includes electric shocks and exposure to substances such as aircraft hydraulic fluids. Such outcomes accounted for 7% of all occurrences.

> 'A LAME was working on the hydraulic system and was covered in oil whilst extracting himself from the area due to hydraulic oil in eyes and mouth. He slipped and fell 2-3 metres and dislocated his shoulder. Correct stands to accomplish the job were not available.' *Survey occurrence report*

'Incorrect assembly or location' refers to situations in which a component was installed or assembled incorrectly. Seven percent of outcomes took this form. This includes cases where parts were installed incorrectly oriented, such as upside down.

> 'I was supervising a team of workers in the hangar on night shift. The aircraft arrived late. At 0500, carrying out a final inspection of all work, I noticed that a job I had completed was incorrect as I had installed components in the wrong direction. The rest of the work was correct. We were able to reinstall the components without delay. Distraction by supervision duties and tiredness due to 'night shift syndrome' all contributed to reduced ability to concentrate at a critical stage in a routine task. Documentation is good and equipment is acceptable, but manpower delegation and supervision responsibilities need review and a less casual approach by management, who continue to apply 'dayshift mentality' to nightshift.' *Survey occurrence report*

'Towing events' accounted for 7% of occurrence outcomes. Generally, these were cases in which the aircraft contacted obstructions, such as maintenance equipment, while the aircraft was being moved by maintenance personnel.

While 'vehicle or equipment contacted aircraft' accounted for only 5% of outcomes, ground damage caused by such incidents can impose serious financial costs on operations.

> 'I parked a vehicle near the aircraft and applied the handbrake. I entered the aircraft to check on a job. When I returned to the vehicle after about ten minutes, it had rolled into the aircraft. I reported the incident to the LAME responsible for the aircraft. The incident happened because I didn't leave the van in gear and didn't turn the wheels away from the aircraft. Also, I believe that the handbrake was faulty'. *Survey occurrence report*

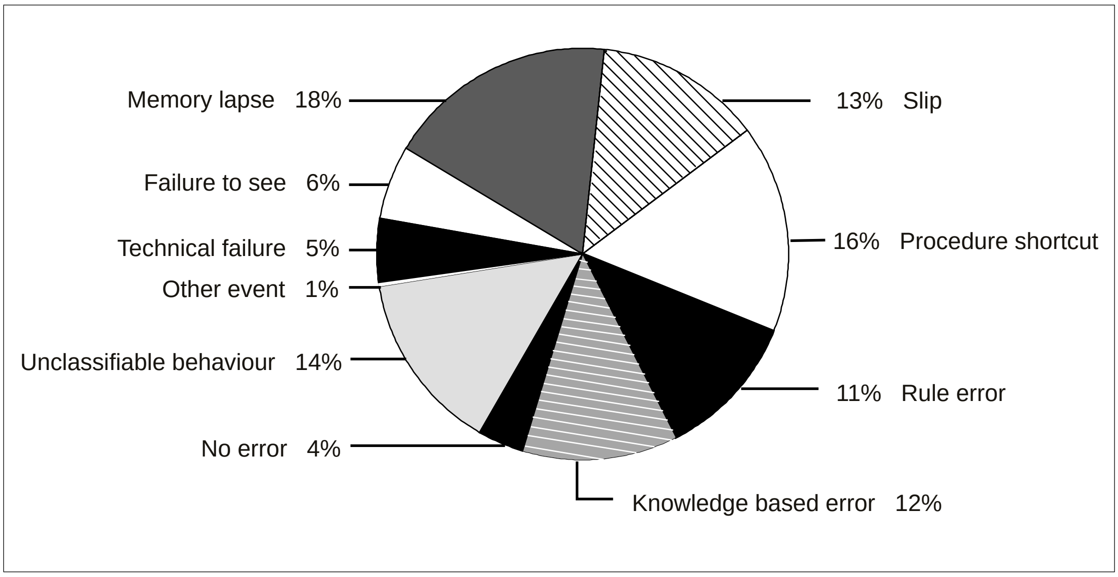
2.5 Personnel involvement in occurrences

For the purpose of this study, the actions of personnel involved in maintenance occurrences were categorised using error definitions based on those developed by James Reason.[16] These categories are outlined in annex 2.

Over 95% of the occurrences involved the actions of personnel. Figure 1 indicates that memory lapses, procedure shortcuts, slips, knowledge-based errors and rule-based errors were the most commonly reported errors. Note that figure 1 also indicates that a small number of occurrences were related to technical issues such as failures of components.

Eighteen percent of the unsafe acts were memory lapses, as illustrated by the following example.

FIGURE 1
Errors and other events leading to occurrences



> 'Just prior to the departure of the aircraft, I remembered I had left a blanking plug within the engine inlet area. I advised the pilot that I needed to check that area again and retrieved the blank.' *Survey occurrence report*

Sixteen percent of unsafe acts took the form of procedure shortcuts. Most shortcuts were well-intended and genuine attempts to complete a task in the face of time pressures or other challenges. More will be said about procedure shortcuts in a later section.

> 'I was asked to certify for other LAMEs/AMEs on the shift preceding and following who were not licensed on type. A LAME carried out an inspection behind a panel where horizontal stabiliser re-positioning was required to gain access to all screws for panel removal. He did not remove panel completely, just took out enough screws so he could lift panel edge up and carry out visual inspection with a torch, which meant that when inspection was completed he did not physically have to resecure panel in place. When I was asked to certify, I did not inspect the panel physically as all access stands had been removed and horizontal stabiliser had been re-positioned so that upper edge of panel screws were only visible, giving appearance from ground that panel was securely attached. During pre flight by another LAME and pilot, this was also not picked up and panel was missing on landing some time later.' *Survey occurrence report*

Slips are errors which occur during the performance of simple, routine actions. They include cases where workers tripped, fumbled objects, or carried out an 'automatic' action in a familiar situation when they did not intend to perform the action in the manner they did. Thirteen percent of errors took this form.

> 'Without thinking, I moved to wipe oil with a rag. The rag was ingested in the engine intake causing FOD.' *Survey occurrence report*

Rule based errors can occur when a person is working in a familiar environment but where they fail to take into account circumstances which would have been apparent at the time. As a result, their actions lead to unintended consequences. Rule based errors do not necessarily involve an intentional violation of procedures, but rather indicate that the person failed to apply unspoken rules of good practice to their work. Common forms of rule errors are untested assumptions, or failures to check systems before acting. For example, a worker may have assumed that it was safe to operate a system without fully checking whether this was the case. One of the most common rule based errors was activating hydraulics without first checking the position of cockpit controls.

Four percent of the events took the form of 'no error' in which an aircraft engineer performed a task correctly, but their actions nevertheless led to a maintenance problem. In most cases, this was because of a pre-existing error in procedures or documentation. The following example illustrates such a case:

> 'An aircraft engineer was carrying out a service procedure on an aircraft in accordance with the maintenance manual. The manual however, contained an error, which had led the manufacturer to issue an alert bulletin to modify the service procedure, but the company had not issued this bulletin to its staff. As a result of the incorrect service procedure, an aircraft system failed to operate correctly during a functional test at the end of the maintenance procedure. The fault was rectified before the aircraft was returned to service.' *Survey occurrence report*

2.6 Association between errors and outcomes

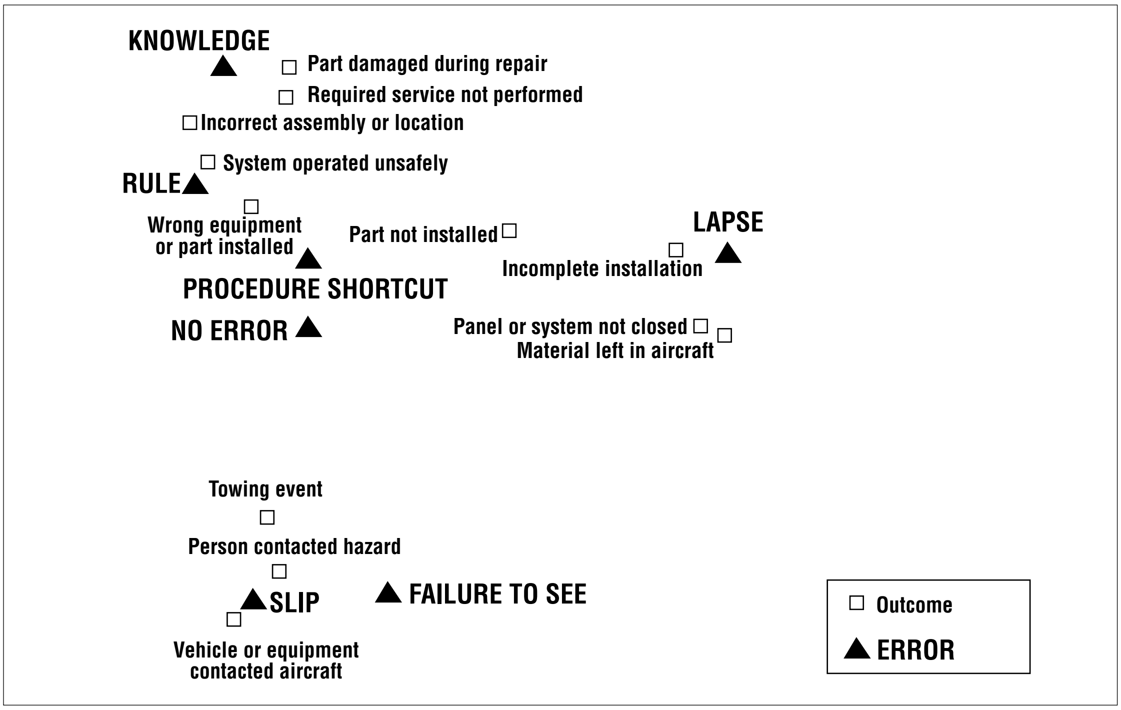
Figure 2 displays the relationship between errors and the most common outcomes. The diagram has been produced using a statistical procedure (correspondence analysis), which expresses in graphical form the relationships between categorical variables.[17] Errors and outcomes which appear together have a stronger association than those which appear apart in the diagram. It is apparent that error types were not evenly distributed across outcomes. Three main clusters of errors and outcomes emerged:

i. 'Towing event', 'person contacted hazard' and 'vehicle or equipment contacted aircraft' clustered together with slips and failures to see.

ii. ‘Incomplete installation’, ‘material left in aircraft’ and ‘panel or system not closed’ were associated with memory lapses.

iii. The third cluster of outcomes including ‘part damaged during repair’, ‘system operated unsafely during maintenance’ and ‘wrong equipment or part installed’ were associated with knowledge-based and rule-based errors, and to a lesser extent with procedure shortcuts.

FIGURE 2
Correspondence of errors and outcomes



2.7 Occurrence factors

Reporters were asked to describe the circumstances which they believed had led to the occurrence. Their reports were then reviewed and contributing factors were assigned to each occurrence where appropriate, using the definitions contained in annex 3. The most commonly nominated factors are shown in table 2. As can be seen, pressure, equipment, training, fatigue and coordination problems were the most commonly mentioned factors.

Table 2.
Occurrence factors

Factors	*Per cent**
Pressure	23.5
Equipment	14.4
Training	12.3
Fatigue	12.2
Coordination	12.2
Procedures	11.4
Supervision	10.4
Environment	5.4
Previous error	4.5

* Note that occurrences may have involved more than one factor, hence percentages sum to more than 100.

2.7.1 Pressure

Delays to aircraft caused by maintenance can impose significant costs on operators, and much maintenance work is carried out under time constraints. Pressure was mentioned as a factor in over 23% of accurrences.

While time pressure is an unavoidable aspect of aircraft operations, it appears that some maintenance personnel have had difficulty in dealing with the pressures imposed by aircraft departure times and maintenance schedules.

> 'Following an engine run, I was carrying out after-run oil tank inspections on the engines. I was rushing to complete the job and I failed to replace the engine oil cap on one of the engines. The aircraft was being prepared for departure. The oil cap was inspected and properly replaced at the terminal. I was informally counselled on the incident by my supervisor. It was a scary situation for me and I became more careful in the future.' *Survey occurrence report*

2.7.2 Equipment

The second most commonly cited contributing factor was equipment deficiency. For the current purposes, 'equipment' referred to physical objects used in the workplace, such as tools and work stands, but also included the aircraft itself.

The most frequent equipment problem (involved in 7% of occurrences) was a lack of correct ground equipment or tools. For example, a required tool may not have been available, leading to an improvisation. In 3% of occurrences, the design of an aircraft component contributed to the problem. The upkeep of ground equipment and the design of ground equipment were each involved in two percent of occurrences. For example, a ladder may have been faulty or poorly suited to a particular task. Many of the equipment problems resulted in hazards to maintenance workers themselves.

> 'We had some work to do in the forward cargo compartment. We wanted to get the maintenance done as quickly as possible, so an engine stand was used to access the cargo. The top of the stand is about 4 feet below the floor of the cargo, but was used because it was the only available stand in the area. A person fell out of the compartment onto the stand and then the ground after tripping while exiting the cargo compartment.' *Survey occurrence report*

In some cases, the design of an aircraft component permitted an error to occur, such as where a component could be fitted in the reverse sense.

> 'During an engine change, two identical hoses next to each other were cross-connected. When a ground run was carried out a large fuel vapour cloud ignited. Extinguisher located at scene – fire extinguished. Human error brought about by poor design. Hoses should have been different size fittings and better marked.' *Survey occurrence report*

In other cases, the design of ground equipment or tooling had been partly responsible for the incident.

> 'The previous shift had fitted a special tool to the aircraft but had forgotten to remove the tool at the end of the procedure. Also, they had not recorded fitment of the tool in the maintenance log. As I was preparing the aircraft to be towed, I noticed the tool and removed it, but I didn't realise that it was in two halves and as it was dark, I didn't see that part of the tool was still connected to the aircraft. The problem was noticed when the pilot did his control checks. The tool did not have a streamer attached to it, and was only painted bright red and white after the incident.' *Survey occurrence report*

When survey respondents were asked to make general comments (not necessarily related to an occurrence), equipment deficiencies were one of the most frequent issues raised. Some maintenance personnel working on airline aircraft raised concerns about a lack of appropriate tools, equipment and facilities, particularly in cases where work was being carried out in the open. A lack of spares was mentioned relatively infrequently in occurrence reports, but was a common complaint by survey respondents in the general comments section of the survey. A related issue was the increased tendency to cannibalise parts from other aircraft, which increases the workload and the potential for error. The difficulties in obtaining spares for ageing aircraft types was commonly raised by LAMEs working on general aviation aircraft. The increasing average age of the Australian general aviation aircraft fleet will mean that this problem is unlikely to diminish.

2.7.3 Training

Inadequate training was mentioned as a contributing factor in just over 12% of occurrences. While training issues were sometimes associated with AMEs or newly-qualified personnel, experienced LAMEs also reported incidents related to inadequate knowledge, skills or experience.

> 'I wanted to turn the radio master on but could not find it, as the switches were poorly marked or unreadable. I was unfamiliar with the aircraft, so I asked an airframe AME who was working on the aircraft and he pointed to a red rocker switch. I queried him and he said that must be it. I pushed the switch and the right engine turned over, with the propeller narrowly missing a tradesman who was inspecting the engine. There is no radio master in this aircraft. I immediately marked the 'start' and some other switches and learned a valuable lesson. Poor training was a factor.' *Survey occurrence report*

It appears that most LAMEs do not undergo refresher training after they have obtained their licence, other than that required to add additional ratings to their licences. The lack of refresher training for LAMEs was mentioned by a significant proportion of those who made general comments in the survey. Related to this was a level of confusion concerning regulations and documentation such as service bulletins and airworthiness directives. Several LAMEs suggested that refresher training could include coverage of licence privileges, regulations, human factors, and management issues.

2.7.4 Fatigue

Fatigue was listed as a contributing factor in just over 12% of occurrence reports. The fatigue may have resulted from long working hours and/or working during the night.

> 'After being on duty for 18 hours on a long overtime shift, the LAME was carrying out a general inspection on an engine at around 2200 hrs. He missed obvious damage to the internals of the cold stream duct area. The damage was only found after investigation of another defect.' *Survey occurrence report*

Among the respondents who wrote general comments in the survey, fatigue was the most commonly mentioned issue. This was particularly the case for maintenance engineers working on airline aircraft, with many respondents mentioning the need for duty limits. The increasing trend towards 12-hour shift patterns and a perception that airlines were expecting more overtime, were given as reasons why duty limits were now an important issue.

> 'LAMEs and AMEs are being put under greater pressure and workloads during nightshifts and in many cases expected to start new jobs at 3–4 a.m. (the witching hours). This is when fatigue is at its worst.' *LAME Comment*

> 'Given the degree of control over pilots' working hours, it is inconsistent that there is no control over the hours that LAMES work… There needs to be more control on the times that work packages, checks, [and] major component changes are called up so that the critical stages of these jobs that require considerable concentration and effort are not being done in the wee hours of the morning when lapses can and do occur and there is a temptation to take shortcuts.' *LAME Comment*

2.7.5 Coordination

Few maintenance workers work completely alone, and to perform their duties successfully, they must coordinate with other operational personnel. Coordination problems such as misunderstandings, poor teamwork or communication difficulties featured in just over 12% of occurrences.

The following example illustrates a coordination problem which involved an unspoken assumption and poor communication.

> 'Two of us were dispatching the aircraft. The nose steering bypass pin was left in. Aircraft began to taxi, but stopped as soon as no steering recognised. We removed pin and ops normal. This is a repetitive maintenance task, both of us assumed the other had the pin.' *Survey occurrence report*

On other occasions, communication was hampered by 'cultural' barriers and a lack of assertiveness.

> 'An airframe and engine tradesman did not properly secure an oil line. I did not say anything, though I seem to remember noticing, as electrical instrument LAME's comments on engine airframe systems are unwelcome/unheeded.' *Survey occurrence report*

The following report dealt with coordination between engineering personnel and flight crew:

> 'Difficulties with refuelling the aircraft had made us late. The captain was buzzing on the ground call while we were doing final checks, he interrupted the final walkaround inspection twice to ask us how much longer. The forward hatch was opened on transits on hot days to cool the electrical equipment. But this procedure is not used often, and this was not a hot day. We were not aware that the forward hatch had been opened and the warning light in the cockpit was unserviceable. This was in the log but we didn't have access to the log and the problem had not been communicated to us. The aircraft failed to pressurise after departure, had to dump fuel and return to blocks. This happened earlier in my career. At the time we were young and naive, didn't have the necessary skills to manage our time. Had too much respect for the Captain's authority.' *Survey occurrence report*

There is scope to improve the communication and coordination skills of maintenance personnel. United States NTSB board member John Goglia, who is himself an aircraft maintenance engineer, has noted that 'With their engineering focus, maintenance managers and technicians possess highly technical skills, but sometimes lack the communication skills to ensure safety in today's complex operations. What is needed is a better balance of technical skills and social skills.'

The importance of crew coordination has been well-recognised in aviation since the 1970s. Most airlines now provide their pilots and cabin crew with training directed at improving their communication and decision making skills, their assertiveness, and their management of stressors and pressure. Such training however, is not generally made available to maintenance personnel.

2.7.6 Procedures

The procedures factor, involved in 11.4% of occurrences, encompassed a broad range of issues including poorly documented or poorly designed procedures. Around half of these incidents involved problems with documentation, either where the documentation was not completed correctly, or where it was unclear. In a similar number of incidents, reporters mentioned problems with the design of procedures as a factor in the incident. In some of these cases, the formal documented procedure was inadequate, such as where a leak check was not effective in detecting a fuel or oil leak. In other cases, informal procedures had developed, for example where avgas was used as a degreasing agent.

2.8 Association between errors and factors

Figure 3 presents the correspondence analysis plot expressing the relationships between errors and contributing factors. It is clear that factors are not equally associated with all error types. The following associations between error types and contributing factors emerged:

i. The most common unsafe act type, memory lapse, was closely associated with pressure, and to a lesser extent with fatigue. The incidence of memory lapses in occurrences in which fatigue was involved was almost twice as great as its incidence in all occurrences.

ii. Rule-based errors were closely associated with procedures, coordination and previous errors.

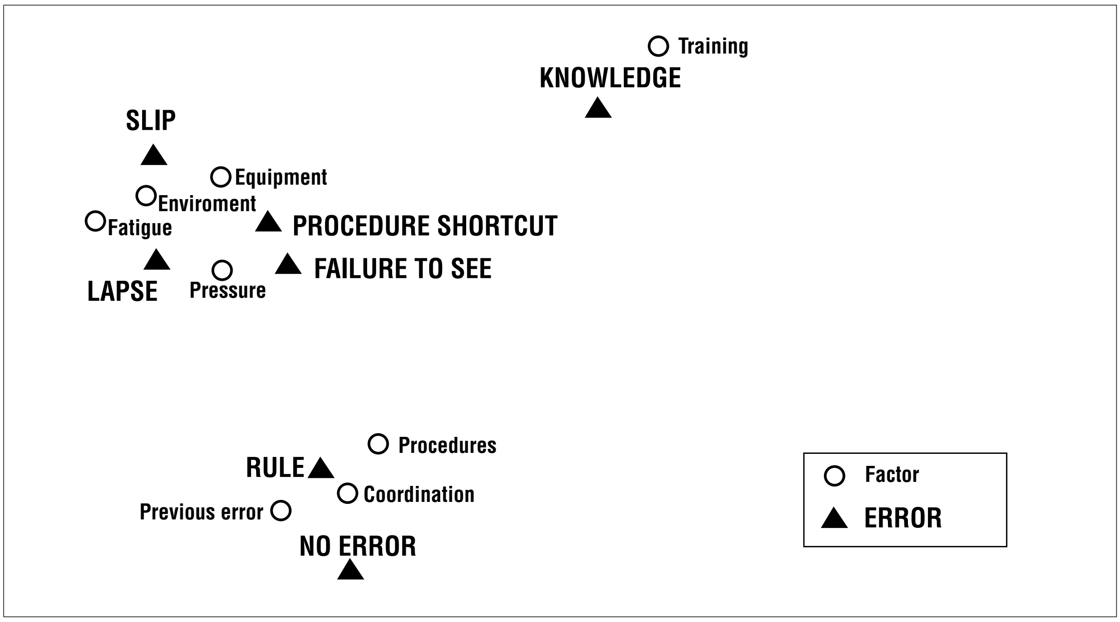
iii. Cases in which 'correct' actions led to an occurrence, (no error) tended to be associated with deficient procedures and poor coordination.

iv. Knowledge-based errors showed a strong association with training deficiencies.

v. Slips were most closely related to equipment deficiencies and fatigue.

vi. Procedure shortcuts were most closely associated with pressure, and to a lesser extent with equipment deficiencies.

FIGURE 3
Correspondence of errors and contributing factors



2.9 Procedure shortcuts and their role in occurrence sequences

Procedure shortcuts (or violations) are a significant problem in fields as diverse as oil production, rail transport and medicine. It has been estimated that violations may be involved in 70% of accidents in some industries.[18] In the aviation context, Boeing research has indicated that pilot deviation from basic operational procedures featured in 'crew caused' airline accidents more frequently than any other form of behaviour. A recent European study found that a third of maintenance tasks involved a deviation from official task procedures. [19,20]

The ATSB's survey results indicated that many maintenance workers perceive that management accept some level of minor rule violations in order to get the job done. Aircraft maintenance engineers are often faced with the pressure of being informed by companies to follow the procedures, but at the same time being encouraged to get work done to deadlines. One survey respondent summed it up this way: 'Management tell us to follow the procedures to the letter, but then they tell us not to be obstructive and to use common sense'. In the following example, a shortcut was taken in an attempt to avoid a delay.

> 'At the end of a shift we realised that an engine hadn't been run to check for oil leaks when the aircraft was to be placed on line. Under pressure to avoid a delay due to this oversight, the run was carried out too quickly and engine was not un-cowled properly to check for oil leaks and consequently after departure that particular engine ran out of oil as the result of a damaged seal. Several factors were involved here, primarily fatigue and inexperience.' *Survey occurrence report*

The 28% of occurrences which involved two events provided an opportunity to examine the place of procedure shortcuts in the sequence of events leading to maintenance occurrences. There was evidence that procedure shortcuts tended to combine with errors to lead to occurrences. The danger of a procedure shortcut in such a case is that it may reduce the margin for safety and increase the consequences of subsequent errors. In the following example, a procedure shortcut was followed by a memory lapse:

> 'In order to make a procedure more convenient, an aircraft engineer disconnected a canon plug, even though this action was not in accordance with the maintenance manual. The person did not document what he had done, but left a moveable work stand near where he had made the disconnection as a reminder that he needed to return and reconnect the plug. During the shift however, someone moved the work stand, and the aircraft engineer only remembered that he had left the plug disconnected when he arrived home at the end of the shift. A discrete phone call to a colleague rectified the situation.' *Survey occurrence report*

In the following case, a memory lapse was followed by a procedure shortcut:

> 'An aircraft engineer forgot to fill an engine oil tank. Due to a lack of available time, he then decided not to test run the engine on the ground before the aircraft departed. As a result, engine damage occurred, requiring extensive repair work.' *Survey occurrence report*

2.10 Time of day

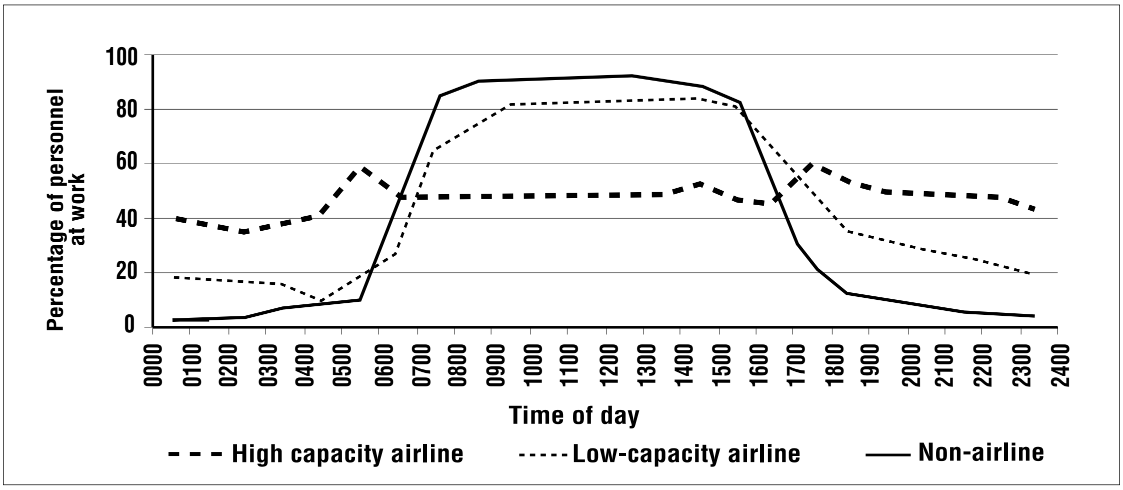
Several authorities have proposed that industrial accidents demonstrate a 24 hour pattern, and that this in turn, indicates the presence of cycles of human error throughout the 24 hour day with the early morning hours being a particularly error-prone time of day.[21,22] Several major industrial events involving human error, such as the Three Mile Island partial melt-down in 1979 and the Chernobyl accident, occurred in the early hours of the morning.[23] This time has long been recognised as a risk period for road accidents, even when the effects of alcohol are discounted.[24] The same hours of the morning are also the most frequent time for ship groundings and collisions, US Navy aviation mishaps, truck accidents involving dozing drivers and train drivers failing to stop at danger signals, once exposure to risk throughout the 24 hour day is taken into account.[25, 26, 27, 28]

2.10.1 Work attendance

All recipients of the maintenance safety survey were asked to report the start and finish times of their most recent work shift, regardless of whether they also reported an occurrence. The proportion of respondents present at work was then calculated for each hour of the 24 hour day.

Of the general survey respondents, 1,239 (or 96%) reported the hours they had been at work during their last work period. Figure 4 shows the percentage of personnel at work at each hour of the day and night. As can be seen, a significant proportion of the maintenance workforce at high-capacity airlines (N=799) was present at work throughout the 24 hour day. The peaks at 0600 and 1800 are likely to reflect shift hand-overs. Those working on low-capacity airline aircraft (N=120) tended to be at work during daylight hours. Although a significant percentage were at work in the evening up to midnight, less than 20% of these workers were present at work in the early hours of the morning. Those working on non-airline aircraft (N=323) showed a clear daytime employment pattern, with a very small proportion present at work between 1900 and 0700.

FIGURE 4
Percentage of workforce at work throughout the 24 hr day



2.10.2 Occurrences and time of day

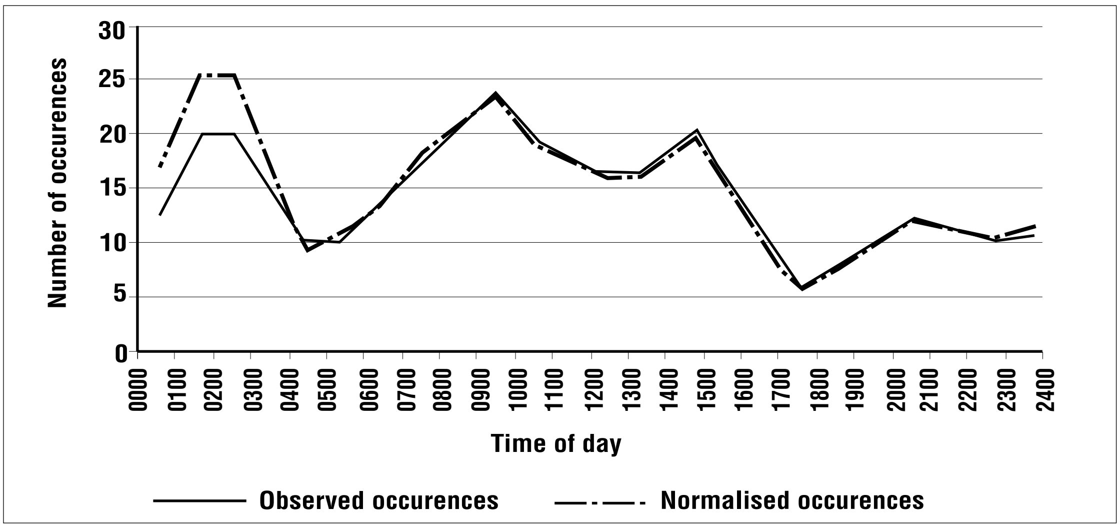
Time of day information was available for 340 high-capacity airline occurrences reported in the survey, 35 low-capacity airline occurrences and 142 non-airline occurrences. Low-capacity airline and non-airline occurrences were excluded from further analysis as the number of occurrences with time information was considered too small to divide into 24 one-hour periods.

Figure 5 shows the distribution throughout the 24 hour day of occurrences which involved high-capacity airline aircraft, and the distribution of the expected number of occurrences normalised to correct for the proportion of the workforce present at work throughout the 24 hour day. In each case, a three point moving average has been used in order to produce a smoothed curve.

As can be seen, the curve for occurrences shows several peaks, at around 0300, 1000 and at 1400. However, once the number of occurrences is normalised for the number of people present at work, it becomes apparent that the likelihood of an occurrence would in fact be greatest at 0300 had there been an equal number of people at work throughout the full 24 hour day.

This finding is consistent with data from other industries indicating that the early hours of the morning are a high risk period for human error.

FIGURE 5
Occurrences involving high-capacity airline aircraft throughout the 24 hour day



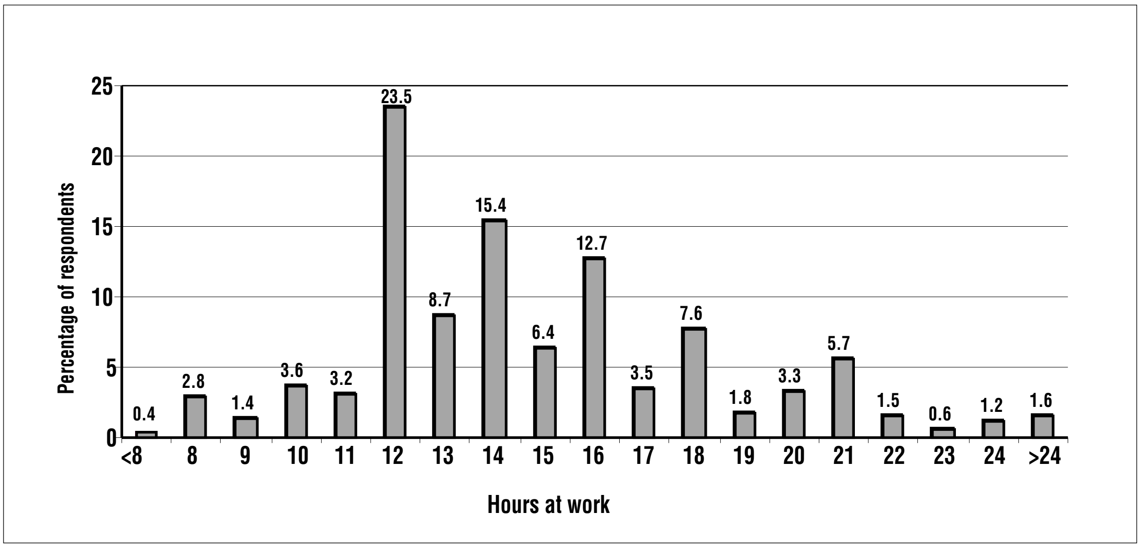
2.11 Duration of work days

Survey respondents were asked to report their longest period of work attendance in the last 12 months. While this information does not indicate the normal work attendance of maintenance personnel, it enables the prevalence of long work shifts to be evaluated. Shift lengths are displayed in figure 6. While 12 hour periods were the most common, approximately 70% of survey respondents had worked longer than 12 hours and over 15% of respondents had worked longer than 18 hours in the previous 12 months.

Recent research has shown that moderate sleep deprivation of the kind experienced by shift workers can leads to effects very similar to those produced by alcohol. After 18 hours of being awake, mental and physical performance on many tasks is affected as though the person had a blood alcohol concentration of 0.05%. Boring tasks which require a person to detect a rare problem (like some inspection jobs) are most susceptible to fatigue effects.[29] It is notable that whereas the duty times of pilots are strictly controlled, no such limits are placed on the hours of work of aircraft maintenance personnel. Extended work hours of the kind reported by some survey respondents have the potential to lead to significant levels of fatigue and in turn, impaired work performance. The following case study occurred at the end of an extended period of work attendance.

> 'The maintenance was AOG and was carried out and completed in a straight 36 hour shift. The aircraft was expected to be on line first thing in the morning and no backup aircraft was available. At about 5:30 AM a ground run was carried out with no defects evident. The aircraft was then released for a maintenance flight which was uneventful. On the post flight release to service, a rag was found caught on the main driveshaft and had shredded itself by about 50% by hitting the aircraft structure during the flight. I was very tired and failed to notice the rag before the ground run and the maintenance flight. No company policies were in place regarding working periods.' *Survey occurrence report*

FIGURE 6
Longest shift worked in last year



2.12 Occurrence reporting levels

Most occurrences had previously been the subject of official reports, nevertheless, the likelihood of reporting appeared to be related to the seriousness of the outcome. While 88% of occurrences in which an aircraft was damaged were officially reported, less serious occurrences (such as those in which an error was detected and corrected) went unreported in 50% of cases. Yet these events could have provided opportunities to identify deficiencies in procedures or systems. Evidence from overseas accidents and incidents indicates that the same error may occur a number of times before it eventually leads to an accident. Previous BASI research has indicated that most maintenance incidents have been preceded by similar events. In other words, relatively few incidents are unique.[30]

Sixty-three percent of respondents to the ATSB survey reported that they had corrected an error made by another maintenance engineer in the previous 12 months without documenting their actions in order to protect the person from blame. One reason for the lack of reporting appears to be a ‘blame culture' which prevails in some maintenance environments, in which the reporting of errors is effectively discouraged by disciplinary procedures.

2.13 Reducing the consequences of maintenance errors

While every effort must be made to reduce errors, it is also necessary to acknowledge that errors will occur from time to time, despite the best efforts of all involved. Therefore, as well as attempting to minimise the frequency of errors, it is necessary to design procedures and systems which can minimise the consequences of errors. The special maintenance precautions applied with extended-range twin-engine operations (ETOPS) are an example of such an approach. When an aircraft is being maintained in accordance with ETOPS procedures, 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. For example, ETOPS maintenance precautions reduce the risk that the same error will be made on both engines of a twin engine aircraft.

However, these precautions 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. There have been several recent incidents around the world in which in-flight engine problems developed after errors were made during multiple engine maintenance.

For example, in 1995, a European-operated Boeing 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 CFM-56 engines had been subject to boroscope inspections during the night prior to the incident flight. High-pressure rotor drive covers were not refitted on each engine by mistake and, as a result, nearly all the oil was lost from the engines during the brief flight.[31]

Two years later a BAe 146 operated by the RAF made an emergency landing after oil had been lost from all four engines. The investigation determined that the incident was the result of a maintenance error in which magnetic chip detector plugs had been installed in all four engines without ‘O’ rings.[32]

The extension of some ETOPS precautions to non-ETOPS operations would help to contain such maintenance-induced problems. Boeing has encouraged operators as a general practice ‘to institute a program by which maintenance on similar or dual systems by the same personnel is avoided on a single maintenance visit’.[33] BASI has published the following suggested safety action: ‘Where possible, the simultaneous performance of the same maintenance tasks on similar redundant systems should be avoided, whether or not the aircraft is an ETOPS aircraft’.[30] Such a practice, while helping to quarantine the consequences of maintenance errors, may also lead to improvements in dispatch reliability.[34]

3 CONCLUSIONS

While many of the occurrences reported in the course of the survey had minor consequences, they provide an insight into the manner in which maintenance anomalies can occur. It must be noted that maintenance anomalies are likely to reflect a wide variety of causal factors. While the current survey is unlikely to have identified all of the factors and circumstances surrounding maintenance occurrences, the results have emphasised the primary place of human behaviour in the development of such events. Memory lapses and procedure shortcuts emerged as particularly important in the development of occurrences. However slips, knowledge-based errors, rule-based errors, and failures to see also featured in occurrences.

Particular errors tended to lead to particular outcomes. Slips and failures to see tended to be associated with damage to aircraft, or health and safety threats to workers. Memory lapses on the other hand were associated with ‘things left undone’ such as parts not installed or incomplete installations.

These links suggest that specific adverse outcomes can be reduced by targeting the particular errors which lead to them. For example, the close association between knowledge-based errors and parts damaged during repair suggests that a useful way to reduce this outcome would be to target knowledge-based errors and the conditions which promote them, most notably inadequate training and inadequate supervision.

An important finding of the study was that procedure shortcuts sometimes combine with errors to lead to safety occurrences. A useful objective for safety promotion activities may be to ensure that maintenance workers understand that seemingly innocuous shortcuts may combine with errors in unexpected ways to create hazards.

The contributing factors referred to in occurrence reports are also likely to be appropriate areas for management attention. The most commonly identified contributing factor was pressure. While it is highly unlikely that time pressure can be entirely eliminated from the workplace, it may nevertheless be appropriate to train workers in strategies to cope with it. Interventions directed at work pressures are likely to particularly reduce the incidence of memory lapses and procedure shortcuts. In some cases, LAMEs considered that workload pressures reflected inadequate staffing levels. This issue has been the subject of previous BASI recommendations. In the most recent of these, BASI recommended that CASA ensure that airlines systematically monitor staffing with respect to workloads, and that these records be made available for CASA surveillance.[34]

The second most frequent contributing factor was a deficiency in equipment, such as the unavailability of tooling, equipment or spares. There is clearly room to improve the state of maintenance equipment in some workplaces, and in some circumstances improved storekeeping and parts inventory systems may help to alleviate problems.

Fatigue was the most commonly identified problem in the comments section of the survey, and was also a significant contributing factor in occurrence reports. Some level of fatigue appears to be an unavoidable consequence of shift work. Nevertheless, there was evidence that maintenance occurrences were more likely during the early hours of the morning, and also that workers were sometimes required to attend work for long periods. Fatigue was particularly associated with failures to carry out intentions (such as memory lapses, slips and failures to see). It can be predicted that better management of fatigue is likely to result in a reduced incidence of errors such as filler caps left unsecured or objects left in aircraft.

In 1999, a BASI study of the regional airline industry identified the lack of regulations specifying acceptable duty periods for aircraft maintenance workers as a safety deficiency.

More recently, the problem of fatigue among aircraft maintenance personnel was examined by the House of Representatives Standing Committee on Communication, Transport and the Arts. Recommendation 7 of the committee report stated: *The Civil Aviation Safety Authority should be required to develop hours of duty rules for aircraft maintenance engineers, incorporating fatigue management principles and auditable fatigue management systems.* (p. 48).[35] The incidents reported via the current survey have served to re-emphasise the need to limit the levels of fatigue experienced by aircraft maintenance engineers.

Training not only emerged as a significant factor in occurrence reports, but was also a commonly mentioned issue in the general comments section of the survey. Civil Aviation Regulations state: 'An operator shall ensure that provision is made for the proper and periodic instruction of all maintenance personnel, particularly in connection with the introduction into service of new equipment or equipment with which the maintenance personnel are not familiar, and the training programme shall be subject to the approval of CASA' 1988 CAR 214. Despite this, it appears that few maintenance engineers receive refresher training once they have gained their licences.

Any workplace in which people are required to work together in teams is susceptible to breakdowns in coordination, such as misunderstandings or poor communication. Such problems were frequent contributors to maintenance safety occurrences, particularly those in which systems were operated on the ground when it was not safe to do so. Research conducted since the 1970s, by the National Aeronautics and Space Administration (NASA) and organisations such as the University of Texas, has indicated that a lack of teamwork and coordination among aircrew is a potentially significant deficiency in airline operations. However, this research has also indicated that improvements can be achieved through training which focuses on the development of non-technical skills such as delegation of tasks, communication, priority management and the management of time pressures.

Crew Resource Management (CRM) principles such as those mentioned above have been taught in airlines since the 1970s, when Pan Am introduced Crew Concept Training. This early course was followed several years later by the United Airlines CRM course. CRM concepts and training have gained increasing acceptance worldwide and have been adopted by many major airlines.[37] While CRM has generally been directed at pilots and cabin crew, an increasing number of operators around the world are now providing such training for maintenance personnel.[38] Furthermore the International Civil Aviation Organisation specifies that licensed maintenance personnel should have knowledge of human performance and limitations relevant to their duties.[39] The European Joint Aviation Requirements (JAR-66) lists human factors knowledge among the basic knowledge requirements for certifying maintenance staff on commercial air transport aircraft. The recommended syllabus includes teamwork, working with time pressure and deadlines, communication and the management of human error.[40] Such training however, is not widely available in Australia and is not required by the Civil Aviation Safety Authority.

All field studies of safety occurrences suffer to a greater or lesser extent from the possibility that the data reflect biases. In the current study, judgements concerning factors were made on the basis of information provided by the reporter in response to prompt questions in the questionnaire. It is possible, and indeed likely, that the information gathered using this method has provided an imperfect picture of the context in which errors occur. Respondents may have been unaware of some of the circumstances surrounding the occurrence, or may have filtered or elaborated their responses on the basis of preconceived notions concerning errors and why they occur. Nevertheless, the data provided by the workers should not necessarily be seen as less accurate than that provided by expert accident investigators. It could be argued that the workers themselves are likely to have insights into the nature of their job, which would not be available from other sources.

Finally there is evidence that many minor occurrences are not reported, either to management or to outside agencies such as the ATSB. While the individual consequences of such occurrences may not be significant, such events when reported, provide an opportunity for maintenance organisations to identify problems and improve systems. The survey identified that a fear of blame was discouraging incident reporting on some occasions. A reluctance to report errors is not surprising given that some maintenance organisations impose financial and other penalties on personnel who have made an error, even when the error was an 'honest mistake'. While all involved in aviation safety must be prepared to take responsibility for their actions, a punitive response to genuine errors is ultimately counterproductive with respect to safety. Some maintenance organisations are instituting error-reporting policies designed to remove the fear of blame, which discourages staff from reporting incidents involving genuine errors. Airlines with such policies typically do not take disciplinary measures unless the employee's actions involved a reckless disregard of risk. The introduction of such a policy by maintenance organisations could help to remove the fear of blame and thereby increase the number of incidents which are officially reported.

4 RECOMMENDATIONS

As a result of this study, the Australian Transport Safety Bureau has made the following recommendations.

Air Safety Recommendation R20010032

The Australian Transport Safety Bureau recommends that where possible, maintenance organisations should avoid performing the same task on each element of critical multiple redundant systems on airline aircraft during the same maintenance visit, whether or not the aircraft is being maintained in accordance with ETOPS requirements.

Air Safety Recommendation R20010033

The Australian Transport Safety Bureau recommends that CASA ensures through hours of duty limits, or other means, that maintenance organisations manage the work schedules of staff in a manner that reduces the likelihood of those staff suffering from excessive levels of fatigue while on duty.

Air Safety Recommendation R20010034

The Australian Transport Safety Bureau recommends that CASA ensures that Aircraft Maintenance Engineers and Licensed Aircraft Maintenance Engineers are provided with appropriate recurrent training.

Air Safety Recommendation R20010035

The Australian Transport Safety Bureau recommends that maintenance organisations introduce clear error-reporting policies in order to encourage staff to report incidents related to human error. Such policies should set out in advance the consequences which will result should maintenance personnel report that they have made an error.

Air Safety Recommendation R20010036

The Australian Transport Safety Bureau recommends that maintenance organisations ensure that engineering personnel receive regular feedback on maintenance incidents in order to learn from such incidents.

Air Safety Recommendation R20010037

The Australian Transport Safety Bureau recommends that CASA, when conducting surveillance of maintenance organisations, considers the existence of an error reporting policy as a positive safety indicator.

Air Safety Recommendation R20010038

The Australian Transport Safety Bureau recommends that CASA requires Aircraft Maintenance Engineers and Licensed Aircraft Maintenance Engineers to undergo appropriate human factors training addressing non-technical performance in areas such as coordination, communication and the management of time pressures.

Air Safety Recommendation R20010039

The Australian Transport Safety Bureau recommends that maintenance organisations ensure that ground equipment, tooling and spares holdings are appropriate, and that there are systems in place to ensure that maintenance equipment is adequately maintained.

Air Safety Recommendation R20010040

The Australian Transport Safety Bureau recommends that CASA when conducting surveillance of maintenance organisations, ensures that ground equipment, tooling and spares holdings are appropriate, and that there are systems in place to ensure that equipment is adequately maintained.

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ANNEX

Annex 1.

Definitions of occurrence outcomes

Documentation error	Maintenance paperwork was not completed, or was completed incorrectly.
Equipment failure	Failure of an item of maintenance equipment such as a ladder or stand.
Falls and trips	A maintenance worker fell or tripped at work.
Fault not found	An airworthiness problem was not detected.
Incomplete installation	Although all necessary parts were present, the installation procedure had not been completed. For example, a connection may have been left 'finger tight' rather than correctly tightened.
Incorrect assembly or orientation	A component was installed or assembled incorrectly.
Material left in aircraft	An item such as a tool was inadvertently left behind by a maintenance worker.
Panel or system not closed	An access panel or cap (such as an oil cap) was not secured.
Part damaged during repair	A part was damaged by maintenance action.
Person contacted hazard	A worker came into contact with a hazard which caused, or had the potential to cause injury. Includes electric shocks, and exposure to aircraft fluids or other chemicals.
Pin or tie left in place	An item used to secure a system was not removed.
System not made safe before maintenance	An aircraft system was not made safe before maintenance work commenced.
System not reactivated	Failure to restore a system at the end of maintenance work, (such as failing to reset circuit breakers).
System operated unsafely during maintenance	Activating an aircraft system such as flaps or thrust reversers when it was not safe to do so, either because personnel or equipment were in the vicinity, or the system was not properly prepared for activation.
Towing event	A safety occurrence which occurred while an aircraft was under tow.
Vehicle or equipment contacted contacted	A stationary aircraft was contacted by a vehicle or aircraft maintenance equipment such as stairs or moveable stands.
Wrong equipment or part installed	An incorrect component was fitted to an aircraft.

Annex 2.

Error definitions

Error	*Definition*
Failure to see	The person failed to detect a sign which they were attempting to detect.
Memory lapse	The person omitted an action which they had intended to perform.
Slip	The performance of a familiar skill-based action at a time when this action was not intended, or the failure to carry out such an action correctly. This category included fumbles and trips
Rule error	A failure to correctly invoke familiar rules or procedures, either written or based on experience when dealing with a routine problems, or when taking decisions in familiar situations
Procedure shortcut	An intentional deviation from procedures or good practice.
Knowledge-based error	An error in a situation which was unfamiliar or which presented new problems for the person, for which neither automatic responses or rules existed.
No error	The person adhered to correct procedures but their behaviour was nevertheless instrumental in leading to the occurrence.

Annex 3.

Definitions of contributing factors

Error	*Definition*
Fatigue	Generally related to a lack of adequate night time sleep and/or night shift work.
Pressure	Where work was being performed under unusual time pressure or haste.
Coordination	Inadequate teamwork and communication between workers.
Training	Factors relating to inadequate training of personnel.
Supervision	Factors relating to inadequate charge of workers.
Previous error	Incorrect performance of a task at an earlier time, where this error remained latent and was not recorded as an event in the occurrence sequence.
Procedures	Poorly designed, documented or non-existent procedures, or where a deviation from procedures was routinely accepted by management and/or personnel.
Equipment	Including poorly designed or maintained equipment or tools, or a lack of necessary equipment, including aircraft spare parts. Includes aspects of aircraft design.
Environment	The physical environment in which the work was being performed, which was beyond the control of the worker. For example, darkness, glare, heights and excessive noise.
Medical	The worker’s performance was affected by a medical condition, sensory or physiological limitations.