

Department of Transport
Bureau of Air Safety Investigation

Human Factors in Aircraft Maintenance: a Preliminary Information Paper

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SYNOPSIS

Human factors in aviation have attracted a considerable amount of research attention; however, only in recent years have maintenance issues been examined by the human-factors community.

To date, human-factors maintenance research has focused on highly specific maintenance issues. A broad examination of anomalies in aircraft maintenance has not been conducted.

It is proposed to conduct original research into the human factors of maintenance. The research will aim to identify the nature and frequency of the anomalies which occur in aircraft maintenance and will apply existing models of error and system breakdown to the maintenance context with the objective of developing a model to account for maintenance anomalies.

Information on maintenance anomalies will be collected from three sources: critical incident interviews, work diaries and existing databases.

1. INTRODUCTION

Maintenance constitutes a significant and rising cost to the airline industry. In the USA, maintenance costs are increasing as a proportion of airline operating costs. In 1989 maintenance constituted 11.8% of US airline operating costs or greater than US\$8 billion per year (Shepherd 1991). The annual cost to the Australian airline industry is likely to be in the order of A\$500 million per year.

The increasing complexity and computerisation of modern aircraft presents particular challenges to the maintenance workforce, which must come to terms with highly automated systems. In this regard, advanced aircraft can be described as 'opaque complex systems'. Such systems are characterised by a complexity which exceeds the comprehension of the people who maintain and operate them (Perrow 1984).

Maintenance anomalies are serious safety issues for the airline industry. Boeing (1993) has estimated that in the period 1983-1992, 3.3% of US airline hull loss accidents had a maintenance discrepancy as the 'primary cause' of the accident. (A hull-loss accident is one in which the aircraft is destroyed or damaged beyond repair.) However, it has been estimated that 12% of major accidents involved maintenance as a contributing factor, although not necessarily the sole factor (Marx and Graeber 1994). The UK Civil Aviation Authority recently reported that 8% of occurrences to large aircraft involved a maintenance discrepancy (BASI 1992). However, it is possible that both of these figures are underestimations of the true incidence of maintenance-related accidents.

Some aviation authorities believe that the role of maintenance in airline accidents is increasing. Ramsden (1992) reports that whereas world airline activity increased by a factor of 20% from the first half of the 1980s to the second half of that decade, maintenance-related accidents increased by 40% over the same period. The world's worst single aircraft disaster, the JAL Boeing 747 accident of August 1985, in which 520 people were killed, was a maintenance-related accident.

In 1991 worldwide, there were at least four major airline accidents where maintenance was a likely causal factor. These were Lauda 767 over Thailand, United 737 at Colorado Springs, Nationair Canada DC8 in Saudi Arabia and Continental Express Brasilia in Texas. All four aircraft and a total of 530 occupants were lost (Ramsden 1992).

On a routine basis, maintenance workers must contend with environmental conditions such as cold, heat, rain, darkness, noise, heights, difficult-to-access work areas, awkward working postures, chemical hazards, night-shift work and the presence of heavy vehicles and moving aircraft. In some situations, such as during an engine run-up, the noise level is such that workers wearing ear protection are unable to communicate verbally.

For the purposes of this paper, the term 'maintenance anomaly' will refer to any incident in which maintenance work was carried out in a manner which had the potential to affect the safe or economical operation of an aircraft. This will include instances where anomalous work was detected and corrected before the aircraft was dispatched. Some examples of maintenance anomalies may help illustrate the diverse nature of the problem.

DC10 engine separation

Just after takeoff from Chicago, a wing-mounted engine of a DC-10 separated from the airframe. The crew subsequently lost control of the aircraft. Following the accident, it became apparent that the maintenance practices at the airline had played an important part in the accident. Although the manufacturer recommended that for maintenance purposes, the engine be removed from the wing in one operation and the supporting pylon be removed in a second operation, the airline had decided to raise and lower the engine and pylon as a single unit, using a forklift truck. This operation was reported to have saved 200 person hours of labour. The airline had not been aware that this procedure cracked part of the structure where the pylon joined the wing (Danaher 1989).

BAC 1-11 window blow-out in flight

As the aircraft was climbing to cruise altitude, the captain's side window blew out and the captain was partially sucked out the window. The subsequent investigation revealed that a shift supervisor, working on a night shift, had installed the window using incorrectly sized bolts. The event highlighted a number of problems with maintenance practices at the airline, including poor work practices, inadequate management monitoring of work standards and superficial CAA surveillance visits (AAIB 1/92).

Embraer Brasilia EMB 120 airframe failure in flight

As the aircraft was inbound to Houston, passing through 11,800 ft, the leading edge of the left horizontal stabiliser separated from the aircraft. As a result of the aerodynamic disruption, the aircraft pitched down and broke up in flight. All 14 persons aboard were fatally injured. The aircraft had undergone maintenance the night before the accident. Work had been carried out on the 'T-tail' of the aircraft, involving the removal of screws from the top and bottom sides of the tail. The work was only partially completed when a shift change occurred. Workers on the incoming shift were not aware that the screws on the top surface of the horizontal stabiliser had been removed while the screws on the lower surface were left in place. The aircraft was signed back into service with the top screws missing. During the morning pre-flight check, the flight crew would not have been able to see the top surface of the horizontal stabiliser.

The NTSB investigation identified deficient maintenance practices within the airline and raised concerns about the adequacy of FAA surveillance of airline maintenance (NTSB 1992).

1.1 Previous research into human factors in aircraft maintenance

Human factors in aviation have attracted a considerable amount of research attention; however, it is apparent that aircraft maintenance has been largely ignored. Extensive studies have been made of flight crew errors, from early studies such as Fitts and Jones (1947) through to more recent efforts e.g. Ruffel Smith (1979), Billings and Reynard (1984) and Sarter and Woods (1992). The human factors of Air Traffic Control have always enjoyed a high profile in the public eye and have been the focus of extensive research. Hopkin (1988) provides a brief summary. Cabin safety issues such as the behaviour of passengers during evacuations have been studied by Muir, Marrison and Evans (1989), among others.

Only in recent years however, have maintenance issues been examined by the human-factors community. One of the earliest studies in this field was carried out in the UK in the early 1980s (Lock and Strutt 1990). This study concentrated on aircraft inspection tasks. Data was collected via a questionnaire which was circulated to aircraft operators and by face-to-face discussions with inspection personnel. Lock and Strutt considered such practical issues as inspector eyesight, training, lighting, noise stands and access. The authors also identified potential problems with the workcard system, an area which has attracted further attention in the 1990s.

Much of the recent research into maintenance-related human factors has been sponsored by the US Federal Aviation Administration (FAA) Office of Aviation Medicine. At the time of writing, research has been directed at a wide variety of issues including the organisational structure of maintenance organisations (Taylor 1990), visual inspection issues (Drury and Gramopadhye 1990, Latorella and 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 and others 1992), future availability of aircraft maintenance personnel (Shepherd and Parker 1991) and the introduction of crew resource management to maintenance training (Taggart 1990, Stelly and Taylor 1992).

European interest in maintenance-related human factors is also becoming evident. A one-day conference organised by the Royal Aeronautical Society (1991) addressed issues such as training, aircraft design and the implications of new technology. However, no research results were presented at the conference.

Jim Reason of the University of Manchester has developed a computer-based system (known as MESH) to help managers monitor the safety 'health' of maintenance organisations. However, at the time of writing, no evaluations of the system were available.

While the research outlined above has undoubtedly contributed to airline safety, to date, researchers have focused on highly specific maintenance issues. It might be expected that before specific human-factors issues of maintenance anomalies were addressed, the general nature of the problem would first be examined. Surprisingly, a broad examination of anomalies in aircraft maintenance has not been conducted.

Such an examination could be achieved by cataloguing the anomalies which occur when airline aircraft are being maintained. The information obtained would be central to the design of intervention strategies.

It is highly likely that human error will feature significantly in maintenance anomalies and hence the concept of 'human error' must be considered. The terms 'error' and 'human error' are widely used in the literature and do not imply that operators are blamed for workplace incidents.

1.2 Human error

1.2.1 Studies of error in industry and transport

Since the early 1980s, there has been a growing preparedness to consider the role of errors in industrial and transport contexts. In addition to the aviation studies outlined above, writers in

the field have examined the errors which occur in situations such as nuclear power plants (e.g. Rasmussen 1980, Wu and Hwang 1989), railway accidents (e.g. Quist 1988), road accidents (e.g. Hale, Stoop and Hommels 1990, Groeger 1990) and operating theatres (Runciman and others 1993). Southcombe (1991) describes some of the precautions which aircraft designers take to minimise maintenance error.

1.2.2 Latent failures, active failures and accidents

It has long been recognised that accidents in complex technological systems can rarely be attributed solely to the actions of the people who directly operate the technology. In addition to immediate failures committed by operators, accident investigations typically find that longstanding systemic failures have had a role in causing, permitting or exacerbating the accident (Miller 1988). Therefore, it is important to consider not just the immediate circumstances of maintenance anomalies, but the underlying or systemic failures which made the anomaly possible.

The model of system breakdown proposed by James Reason and known as the 'Reason model' has become a standard framework for thinking about accidents in industrial and transport settings (e.g. Reason 1990, Reason 1991). The model has been advocated by the International Civil Aviation Organisation for accident investigation purposes (ICAO 1992), used in the analysis of anaesthetic accidents (Runciman 1993), and applied by its originator to the analysis of accidents in various settings including nuclear power plants, chemical plants and transport applications (Reason 1992). While the Reason framework was initially proposed to account for accidents, it can also be applied to less catastrophic system breakdowns.

Reason proposes that system breakdowns result from combinations of active failures and latent failures. 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 set the scene for active failures to 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.

Other researchers such as Williamson and Feyer (1990) have studied the origin of accidents and have developed systems to classify the events and factors leading up to accidents.

The proposed research will draw on existing models of accident causation to develop a model to account for the origin of maintenance anomalies. Such a model will provide a guide for the development of intervention strategies.

1.2.3 Theoretical issues of active failures

Recent research into the failures of person/machine systems has focused on the phenomenon of 'human error' or the 'unsafe acts' of Reason's model. Significant theoretical advances have included the Skill Rule Knowledge (SRK) framework of Rasmussen (1983), who proposed that errors can be categorised according to the level of cognitive control in operation at the time. According to this model, skill-based errors occur in familiar tasks where the person possesses an automatic action routine. Rule-based errors can occur when a person is faced with a task which does not prompt a skill-based action routine, but where the person possesses a set of stored rules to guide action. Knowledge-based errors can occur when a person is faced with an unfamiliar situation which does not prompt skill routines or stored rules, and a course of action must be decided upon by thinking through the problem. The SRK model has proved to

be a useful framework for the analysis of errors in a wide variety of industrial and domestic situations.

Other research in the field has complemented the SRK framework. Reason and Norman have divided errors into slips and mistakes. The term 'slips' encompasses the group of errors which occur at the skill-based level of performance. 'Mistakes' are errors at the rule- or knowledge-based level of cognitive control.

Reason (1990) makes an important further distinction between two forms of unsafe acts—errors and violations. Violations, in contrast to errors, are intentional unsafe acts.

Other authors such as Rasmussen and Vicente (1989) have proposed additional categorisation systems which can be applied in conjunction with the SRK framework.

1.2.4 Quantification of human error

In addition to understanding the types of errors which occur in aircraft maintenance, it is helpful to quantify the frequency of maintenance errors. Human Reliability Assessment (HRA) aims to assign probabilities to errors. HRA has been typically applied by designers of complex systems such as chemical plants or nuclear power stations where there is a need to estimate the probability of both individual errors and chains of human error. Kirwin (1992) provides a review of the field.

While the objectives of HRA are worthy, the complexity of the environment and of people themselves makes it very difficult to arrive at reliable assessments of human-error probabilities. The notion of quantifying human error has been criticised by Moray (1990) among others.

Nevertheless, while it may be unrealistic to expect to arrive at fixed probabilities of human error which apply to all situations, it may be possible to achieve a more modest assessment of error probabilities while acknowledging the complicating effects of task demands, environment and individual differences.

2. CONCLUSIONS

Aircraft maintenance is a crucial element of the aviation system, yet until recently, maintenance has been largely ignored by human-factors researchers.

Recent years have seen a growing interest in maintenance-related human factors, yet much of the published information has focused on specific problems or particular solutions. To date, there has been no broad examination of the human factor in maintenance.

An examination of maintenance anomalies could employ models of error and system breakdown which have proved useful in other areas of aviation and industry.

Following on from this information paper, BASI has commenced a wide-ranging examination of maintenance anomalies and the human factors which lead to them. Preliminary results will be available in the second half of 1994. The research plan is described in the appendix

Appendix

Research proposal: Human factors in aircraft maintenance

1. Aims of the proposed research

- (a) Identify the nature of the anomalies which occur in aircraft maintenance.
- (b) Identify the frequency of anomalies and the conditions which lead to or promote such anomalies.
- (c) Develop appropriate interventions to address the problem of maintenance anomalies.
- (d) Apply existing models of error and system breakdown to the maintenance context and if necessary, develop a model to account for maintenance anomalies.

2. Scope of the research

The research will concentrate on the maintenance activities of high-capacity airlines. Minor base servicing and maintenance carried out at the air terminal gate will be studied. Component maintenance and major maintenance will not be considered as these aspects of maintenance involve aircraft or components which are removed from day-to-day line operations. Inspection issues will not be considered as industrial inspection is a field of study in its own right and deserves separate consideration.

3. Proposed method

Information on maintenance anomalies will be collected from three sources: critical incident interviews, work diaries and existing databases.

Each of the three data sources has its own advantages and limitations, yet taken together, the three approaches should provide converging sources of information on maintenance anomalies.

Critical-incident interviews will be used to provide a broad picture of the nature of maintenance anomalies which have occurred in the past and to establish contact with workers. It is expected that the critical-incident interviews will be affected by a number of limitations, including a bias towards the reporting of memorable events and a tendency of subjects to forget details of events.

A diary system will be used to collect information on anomalies as they occur in 'real time'. In contrast to the critical-incident interviews, the diary system is less labour intensive and provides workers with a greater assurance of confidentiality. However, while the diary method has the potential to collect a representative sample of day-to-day incidents, it will be limited to a discrete time period and may fail to capture rare but significant anomalies.

Existing databases maintained by airlines and aviation authorities will provide information on the anomalies which have come to light via existing official channels. Overseas accident investigations are likely to be rich in information but will exclude those anomalies which for various reasons, did not lead to accidents. Internal company databases generally contain only brief details of events and include only those incidents which came to the official notice of the airline.

A uniform system of data analysis will be applied to the information, regardless of the source of the data. Comparing the information obtained from each of the three methods will provide a useful insight into the value of various sources of safety information.

The information collected from all sources will remain confidential to ensure that privacy is protected. Participants will be given a guarantee that the information collected will not be used for punitive purposes.

The proposed methods are detailed below.

3.1 Critical incidents interviews

3.1.1 Participants

Aircraft Maintenance Engineers (AMEs), Licensed Aircraft Maintenance Engineers (LAMEs) and apprentices will be invited to participate in the study.

3.1.2 Data collection

Maintenance workers assembled in focus groups will be asked to provide examples of times when 'things went wrong' in the maintenance of an aircraft, following the critical incidents technique developed by Flanagan (1954). Interviews will follow a standard structure and all reports will be treated confidentially. All incidents will have involved the reporter, either as a participant or observer. Workers will be free to nominate any incidents from the past. It is likely that there will be systematic biases in recall related to when the incident occurred. The time elapsed since the incident occurred will be recorded to enable such biases to be studied. The incident anecdotes will be recorded, transcribed and coded onto a database. It is hoped that at least 50 critical-incident reports will be gathered.

3.1.3 Data analysis

Events and factors which preceded the anomaly will be coded using the Williamson and Feyer (1990) classification system and the Reason model.

With the assistance of experienced maintenance personnel, the severity of potential consequences of the anomaly will be assessed and the maintenance task at the time of the anomaly will be categorised according to Air Transport Association (ATA) chapter. (The internationally recognised ATA system assigns a chapter number to each major part of an aircraft.) Unsafe acts will be categorised according to:

- the violation/error distinction;
- the omission/commission/substitution distinction; and
- the level of cognitive control (SRK) framework.

3.2 Diary study

3.2.1 Participants

As for method one. After initially operating the system at one airline, it is planned to extend the participant pool to other airlines.

3.2.2 Data collection

All maintenance workers will be provided with pocket-sized notebooks in which they will be invited to record details of work anomalies. This system has been used successfully in Worksafe Australia research conducted by Williamson and Feyer (1990). Strict confidentiality provisions will operate and the information gathered will not be used for disciplinary purposes. The reliability of selected reports will be checked by telephoning the reporter; however, this will only be possible when the reporter has chosen to provide contact details.

3.2.3 Data analysis

As for method one.

3.3 Analysis of existing databases

3.3.1 Participants

Major Australian airlines, the US National Transportation Safety Board (NTSB) database and ICAO's statistics section.

3.3.2 Data collection

Australian and overseas accident investigation databases will be interrogated for information on maintenance-related air transport accidents.

In-company databases of maintenance anomalies will be interrogated and analysed.

3.3.3 Data analysis

As for method 1, to the extent that the information allows.

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