Safety Regulation Group

Civil Aviation Authority

CAP 718

Human Factors in Aircraft Maintenance and Inspection

(previously ICAO Digest No. 12)

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24 January 2002

ISBN 0 86039 836 6

First Edition 24 January 2002
Reprinted April 2002

Enquiries regarding the content of this publication should be addressed to:
Human Factors, Aerodrome, Air Traffic and Licensing Standards Division, Safety Regulation Group, Civil Aviation Authority, Aviation House, Gatwick Airport South, West Sussex, RH6 0YR

The latest version of this document is available in electronic format at www.caa.co.uk, where you may also register for e-mail notification of amendments.

Published by TSO (The Stationery Office) on behalf of the UK Civil Aviation Authority.

Printed copy available from:
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Introduction

1.1 Aircraft maintenance is an essential component of the aviation system which supports the global aviation industry. As air traffic grows and the stringent requirements of commercial schedules impose increased demands upon aircraft utilization, the pressures on maintenance operations for on-time performance will also continue to escalate. This will open further windows of opportunity for human error and subsequent breakdowns in the system's safety net. There is no question that human error in aircraft maintenance has been a causal factor in several air carrier accidents. It is also beyond question that unless the aviation industry learns from these occurrences, maintenance-related safety breakdowns will continue to occur. From a Human Factors perspective, important truths have been uncovered during the investigation of these occurrences.

1.2 The objectives of this digest are to provide practical Human Factors guidance — based on those truths — to those concerned with aircraft maintenance and inspection and to introduce the non-specialist to Human Factors issues in aircraft maintenance and inspection. It is intended to show how human capabilities and limitations can influence task performance and safety within the maintenance and inspection environments. This digest also identifies sources of Human Factors knowledge and information. The target audience includes aircraft maintenance technicians/ engineers/mechanics, aircraft airworthiness inspectors, maintenance designers and planners, civil aviation and airline management personnel, operational personnel as well as those responsible for maintenance organizations.

1.3 Throughout the digest and consistent with the series of ICAO Human Factors digests, both the SHEL model and the Reason model are presented and repeatedly referred to in order to demonstrate the relevance of Human Factors to aviation safety and effectiveness. Information on aircraft accidents in which maintenance error has been identified is included to illustrate the issues discussed. The digest advocates the importance of information exchange, the sharing of experience in maintenance operations among operators and the safety benefits to be gained therefrom. The need to adhere to established maintenance procedures by all concerned is emphasized and the negative aspects of non-adherence are explained using real-life examples. New and improved training methods for aircraft maintenance personnel are briefly reviewed and possible advantages addressed.

1.4 This digest also discusses the safety and efficiency gains from the provision of proper facilities and work environment. Job design, reward systems and selection and training of staff are also examined, emphasizing these gains. Obviously, a job design that works for one organization does not necessarily work for another. This digest, therefore, stresses that each organization's culture must be considered separately if and when assigning work teams. It also introduces the reader to existing advanced job aids and to those expected to be available in the near future. The need to introduce new advanced technology vis-à-vis the gains to be had from their introduction — not only financially but, most importantly, in the enhancement of safety standards — is discussed. Although acknowledging advantages from advanced job aids, it nevertheless cautions that introduction of automation or new technology should take into consideration the capabilities and limitations of the operators who will use it. Automation should be designed to assist humans in performing their normal duties in a more efficient and **safe** manner.

1.5 This digest comprises the following:

- **Chapter 1** discusses Human Factors in aircraft maintenance and inspection.
- **Chapter 2** examines human error in aircraft maintenance and inspection.
- **Chapter 3** presents the issues affecting aircraft maintenance.
- **Chapter 4** considers teams and organizational issues in maintenance operations.
- **Chapter 5** deals with automation and advanced technology systems in aircraft maintenance.
- **Chapter 6** addresses the challenges for the future through error prevention considerations and strategies.
- **Appendix 1** provides a list of references and recommended reading.

1.6 This digest was produced with the assistance of the ICAO Flight Safety and Human Factors Study Group, developed from an initial draft prepared by Study Group Member Dr. William T. Shepherd. Other sources of reference include *Human Error in Aircraft Maintenance* by David A. Marx and R. Curtis Graeber, *Human Error* by Professor James Reason and ICAO Human Factors Digests No. 7 — *Investigation of Human Factors in Accidents and Incidents* and No. 10 — *Human Factors, Management and Organization*. Other digests in this series include:

- Digest No. 1 — *Fundamental Human Factors Concepts* (Circular 216);
- Digest No. 2 — *Flight Crew Training: Cockpit Resource Management (CRM) and Line-Oriented Flight Training* (LOFT) (Circular 217);
- Digest No. 3 — *Training of Operational Personnel in Human Factors* (Circular 227);
- Digest No. 4 — *Proceedings of the ICAO Human Factors Seminar* (Circular 229);
- Digest No. 5 — *Operational Implications of Automation in Advanced Technology Flight Decks* (Circular 234);
- Digest No. 6 — *Ergonomics* (Circular 238);
- Digest No. 7 — *Investigation of Human Factors in Accidents and Incidents* (Circular 240);
- Digest No. 8 — *Human Factors in Air Traffic Control* (Circular 241);
- Digest No. 9 — *Proceedings of the Second ICAO Flight Safety and Human Factors Global Symposium* (Circular 243);
- Digest No. 10 — *Human Factors, Management and Organization* (Circular 247); and
- Digest No. 11 — *Human Factors in CNS/ATM Systems* (Circular 249).

Chapter 1 Human Factors — Aircraft Maintenance and Inspection

1 Contemporary Maintenance Problems

1.1 There is no question that human error in aircraft maintenance and inspection has been a causal factor in several recent air carrier accidents. Whenever humans are involved in an activity, human error is a certain sequel. According to one source,[1] the number of maintenance concern accidents and incidents to public transport aircraft has increased significantly. This source defines maintenance concern as one which is not necessarily a maintenance error (it may be a design error) but one which is of concern to the maintenance personnel as frontline managers of technical problems in daily operations. The same source states that in the first half of the 1980s, there were 17 maintenance concern-related accidents and incidents, involving aircraft belonging only to Western operators and excluding all "routine" technical failures (engine, landing gear, systems, structure, component separations, ramp accidents, etc). All these accidents and incidents had serious consequences (fatal, serious damage, significant previous occurrences, significant airworthiness implications, etc). In the second half of the 1980s, the same source enumerates 28 accidents of maintenance concern, an increase of 65% over the first half of the decade. In the same period, traffic movements (flight departures, scheduled and non-scheduled) increased by 22%. In the first three years of the 1990s there were 25 accidents involving maintenance concerns. This compares with seven in the first three years of the 1980s.

1.2 Whether maintenance concern-related occurrences are a "new" phenomenon in aviation or whether they have always existed but have only recently been validated by statistics may be a matter of debate. Indeed, the awareness of the importance of maintenance to aviation safety may be the logical consequence of the gradual acceptance of broader, systemic approaches to aviation safety. Whatever the case may be, the increase in the rate of accidents and incidents involving maintenance concerns appears to be at least statistically significant. In the last ten years, the annual average has increased by more than 100% while the number of flights has increased by less than 55%.

1.3 Traditionally, Human Factors endeavours have been directed towards flight crew performance and, to a lesser extent, towards the performance of air traffic controllers. Until recently, available literature showed little consideration of the Human Factors issues which could affect aircraft maintenance personnel who inspect and repair aircraft. This has been a serious oversight, since it is quite clear that human error in aircraft maintenance has indeed had as dramatic an effect upon the safety of flight operation as the errors of pilots and air traffic controllers.

1.4 Aircraft maintenance and inspection duty can be very complex and varied in an environment where opportunities for error abound. Maintenance personnel — at least in the most developed aviation systems — frequently work under considerable time pressures. Personnel at the maintenance base and at the flight line stations realize the importance of meeting scheduled departure times. Operators have increased aircraft utilization in order to counteract the economic problems that plague the industry. Aircraft maintenance technicians are also maintaining a fleet that is increasing in age. It is not uncommon to find 20 to 25 year old aircraft in many airline fleets, including

1. TechLog — "Is There a Maintenance Problem." *AEROSPACE*, June 1993.

those of major operators. In addition, many operators intend to keep some of these aircraft in service in the foreseeable future, perhaps beyond the turn of the century. Engine hush kits will make some older narrow-body aircraft economically and environmentally viable. However, these aircraft are maintenance-intensive. The old airframes require careful inspection for signs of fatigue, corrosion and general deterioration. This places an increased burden on the maintenance workforce. It creates stressful work situations, particularly for those engaged in inspection tasks, because additional maintenance is required and because the consequences may be serious if the signs of aging, which are frequently subtle, remain undetected.

1.5 While maintenance of these aging aircraft is ongoing, new technology aircraft are entering the fleets of many of the world's airlines, thus increasing the demands on aircraft maintenance. These new aircraft embody advanced technology such as composite material structures, "glass cockpits", highly automated systems and built-in diagnostic and test equipment. The need to simultaneously maintain new and old fleets requires aircraft maintenance technicians to be more knowledgeable and adept in their work than they may have been previously. The task of simultaneously maintaining these diverse air carrier fleets will require a highly skilled workforce with proper educational background.

1.6 There is at present a growing awareness of the importance of Human Factors issues in aircraft maintenance and inspection. The safety and effectiveness of airline operations are also becoming more directly related to the performance of the people who inspect and service the aircraft fleets. One of the objectives of this digest is to bring to light Human Factors issues which are of significant importance to aviation safety. To facilitate a better understanding of the issue, two models,[1] widely used by ICAO to allow an organized, systemic approach to the comprehension of the Human Factors issues involved, will be discussed before progressing to the specific Human Factors issues involved in aircraft maintenance and inspection.

2 The SHEL Model

2.1 The "SHEL" model was first advocated by Professor Elwyn Edwards in 1972 and a modified diagram to illustrate the model was later developed by Capt. Frank Hawkins in 1975 (Figure 1-1). The component blocks of the SHEL model (the name being derived from the initial letters of its components: Software, Hardware, Environment, Liveware) are depicted with a pictorial impression of the need for matching the components. The following interpretations are suggested: liveware (human), hardware (machine), software (procedures, symbology, etc.) and environment (the conditions in which the L-H-S system must function). This block diagram does not cover interfaces which are outside Human Factors (e.g. between hardware-hardware; hardware-environment; software-hardware) and is intended only as an aid for understanding Human Factors.

2.2 **Liveware** (or the human) is at the centre of the model. Human is generally considered the most critical as well as the most flexible component in the system. Yet people are subject to considerable variations in performance and suffer many limitations, most of which are now predictable in general terms. The edges of this block are jagged, and so the other components of the system must be carefully matched with them if stress in the system and eventual breakdown are to be avoided. In order to achieve

1. A model is an abstract representation of a system, and it may be physical, mathematical, verbal, or a combination of these. A scale aircraft model in a wind tunnel is a physical model. Models perform three functions: they allow predictions to be made in cases where relevant data are not available; they guide research by suggesting experiments; and they provide a framework that helps to organize data. Most models attempt to describe and predict the behaviour of systems under normal operating conditions.

this matching, an understanding of the characteristics of this central component is essential. Examples of those important characteristics are as follows:

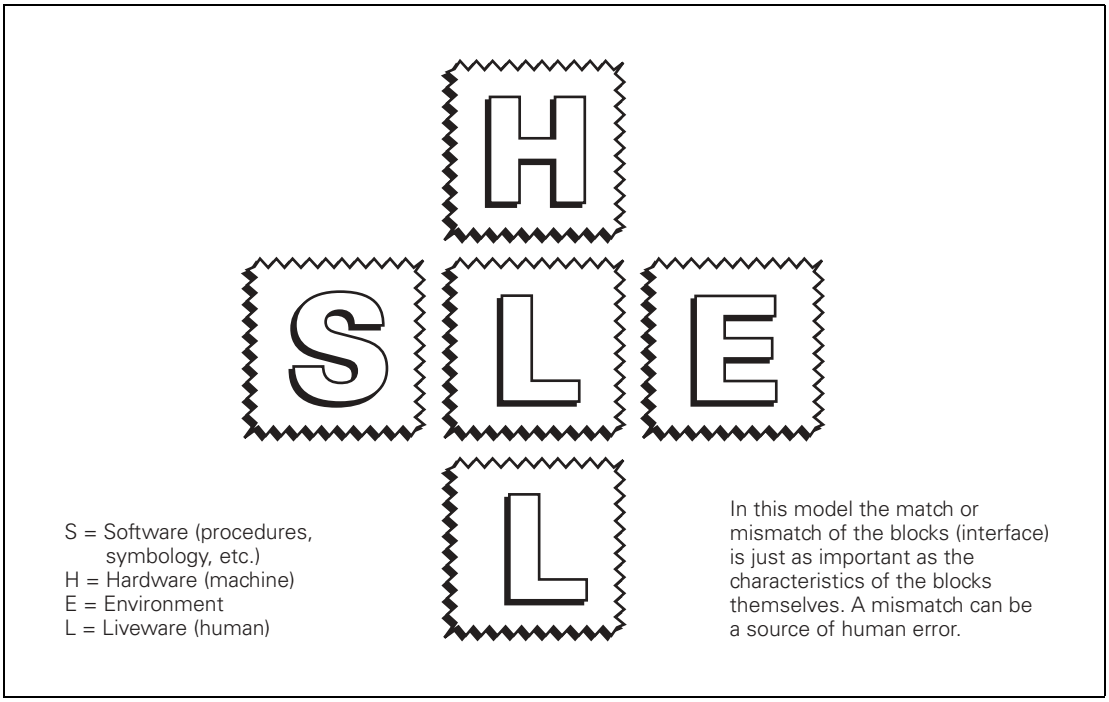

Figure 1 The SHEL Model (adapted from Hawkins, 1975)

Physical size and shape. In the design of workplace and equipment, a vital consideration involves body measurements and movements, which may vary according to factors such as age, ethnicity and gender. Human Factors inputs must be provided at an early stage in the design process, and data for these inputs are available from anthropometry, biomechanics and kinesiology.

Physical needs. People's requirements such as for food, water and oxygen are indicated in human physiology and biology.

Input characteristics. Humans possess various sensory systems for collecting information from the world external as well as internal to them, enabling them to respond to events and to carry out the required task. All senses may, however, be subjected to degradation for one reason or another, and the sources of knowledge include psychology and physiology.

Information processing. Again, these human functions have limitations. Poor instrument and alerting system design has frequently resulted from a failure to take into account the capabilities and limitations of human information processing. Factors such as stress, motivation and short- and long-term memory are involved. Psychology and cognitive sciences are the sources of background knowledge here.

Output characteristics. Once information is sensed and processed, decisions are made and/or messages are sent to muscles to initiate the desired response. Responses may involve a physical control movement or the initiation of some form of communication. Acceptable control forces and direction of movement have to be known, and biomechanics, physiology and psychology provide the background knowledge.

Environmental tolerances. Environmental factors such as temperature, vibration, pressure, humidity, noise, time of day, amount of light and G-forces

can affect human performance and well-being. Heights, enclosed spaces and a boring or stressful work environment can influence human behaviour and performance. Background information is available from medicine, psychology, physiology and biology.

2.3 Liveware is the hub of the SHEL model of Human Factors. The remaining components must be adapted to and matched with this central component.[1]

Liveware-Hardware. This interface is the most commonly considered when speaking of human-machine systems: the design of seats to fit the sitting characteristics of the human body; of displays to match the sensory and information-processing characteristics of the user; of controls with proper movement, coding and location. The user may not be aware of an L-H deficiency, even when it finally leads to disaster, because the great virtue of human adaptability may mask the effects of such a deficiency. However, the deficiency continues to exist and may constitute a potential hazard. Ergonomics deals mostly, although not exclusively, with issues arising from this interface.

Liveware-Software. This encompasses the interface between humans and the non-physical aspects of the system such as procedures, manual and checklist layout, symbology and computer programmes. The problems may be less tangible than those involving the L-H interface and consequently more difficult to detect and resolve (e.g. misinterpretation of checklists or symbology).

Liveware-Environment. The human-environment interface was one of the earliest recognized in aviation. Initially, measures taken were aimed at adapting the human to the environment (e.g. by using helmets, flying suits, oxygen masks and G suits). Later, attempts were made to alter the environment to match human requirements (e.g. by applying pressurization, air-conditioning and soundproofing). Today, new challenges have risen, notably ozone concentrations and radiation hazards at high flight levels, and the problems associated with disturbed biological rhythms and sleep because of high-speed transmeridian travel. Since illusions and disorientation are involved in many aviation occurrences, the L-E interface must also consider perceptual errors induced by environmental conditions (e.g. illusions occurring during approach and landing). The aviation system operates within the context of broad managerial, political and economic constraints. These aspects of the environment will interact with the human via this interface. Although the modifications to these factors are generally beyond the function of Human Factors practitioners, they should be considered and addressed by those in management with the ability to do so.

Liveware-Liveware. This is the interface between people. Flight crew training and proficiency testing have traditionally been conducted on an individual basis. If each individual crew member was proficient, then it was assumed that the team comprising those individuals would also be proficient and effective. This is not always the case, however, and for many years attention has been increasingly turned to the breakdown of teamwork. Flight crews function as groups and group interactions play a role in determining behaviour and performance. In this interface, one is concerned with leadership, crew co-operation, teamwork and personality interactions. Human Factors Digest No. 2 describes current industry approaches to deal with issues associated with this interface (i.e. CRM and LOFT programmes). Staff/management relationships

1. Some of the descriptions of the model tend to be flight crew-oriented. This is because the model was initially developed to address interface problems in the cockpit environment.

are also within the scope of this interface, as corporate climate and company operating pressures can significantly affect human performance. Digest No. 2 also demon-strates the important role of management in accident prevention.

3 The Reason Model

3.1 Figure 1-2 depicts a modified version of the Reason model of accident causation, showing the various human contributions to the breakdown of a complex system.[1] Since its introduction in 1990, several variations have circulated among the Human Factors and accident prevention specialists, including a revised model by Professor Reason himself in 1993. This digest discusses the 1990 version, as included in ICAO Human Factors Digests No. 7 and No. 10.

3.2 Professor Reason views the aviation industry as a complex productive system. One of the basic elements of the system is the **decision-makers** (high-level management, the company's corporate or the regulatory body) who are responsible for setting goals and for managing available resources to achieve and balance two distinct goals: the goal of safety and the goal of on-time and cost-effective transportation of passengers and cargo. A second key element is **line management** — those who implement the decisions made by upper management. For upper-management decisions and line management actions to result in effective and **productive activities** by the workforce involved, certain **preconditions** have to exist. For example, equipment must be available and reliable, the workforce has to be skilled, knowledgeable and motivated, and environmental conditions have to be safe. The final element, **defences** or safeguards, is usually in place to prevent foreseeable injury, damage or costly interruptions of service.

3.3 The Reason model shows how humans contribute to the breakdown of complex, interactive and well-guarded systems — such as commercial aviation — to produce an accident. In the aviation context, "well-guarded" refers to the strict rules, high standards, inspection procedures and sophisticated monitoring equipment in place. Because of technological progress and excellent defences, accidents seldom originate exclusively from the errors of operational personnel (front-line operators) or as a result of major equipment failures. Instead, they result from interactions of a series of failures or flaws already present in the system. Many of these failures are not immediately visible, and they have delayed consequences.

3.4 Failures can be of two types, depending on the immediacy of their consequences. An **active failure** is an error or a violation which has an immediate adverse effect. These errors are usually made by the front-line operator. A pilot raising the landing gear lever instead of the flap lever exemplifies this failure type. A **latent failure** is a result of an action or decision made well before an accident, the consequences of which may remain dormant for a long time. Such failures usually originate at the decision-maker, regulator or line management levels; that is, with people far removed in time and space from the event. A decision to merge two companies without providing training to standardize aircraft maintenance and flight operations procedures illustrates the latent failure type. These failures can also be introduced at any level of the system by the human condition, for example, through poor motivation or fatigue.

1. Reason, J. (1990) *Human Error.* Cambridge University Press, United Kingdom.

3.5 Latent failures, which originate from questionable decisions or incorrect actions, although not harmful if they occur individually, can interact to create "a window of opportunity" for a pilot, air traffic controller or mechanic to commit an active failure which breaches all the defences of the system and results in an accident. In such cases, the front-line operators become the inheritors of a system's defects because they are the ones dealing with a situation in which their actions, technical problems or adverse conditions will reveal the latent failures long embedded in a system. In a well-guarded system, latent and active failures will interact, but they will not often breach the defences. When the defences work, the result is an incident; when they do not, it is an accident

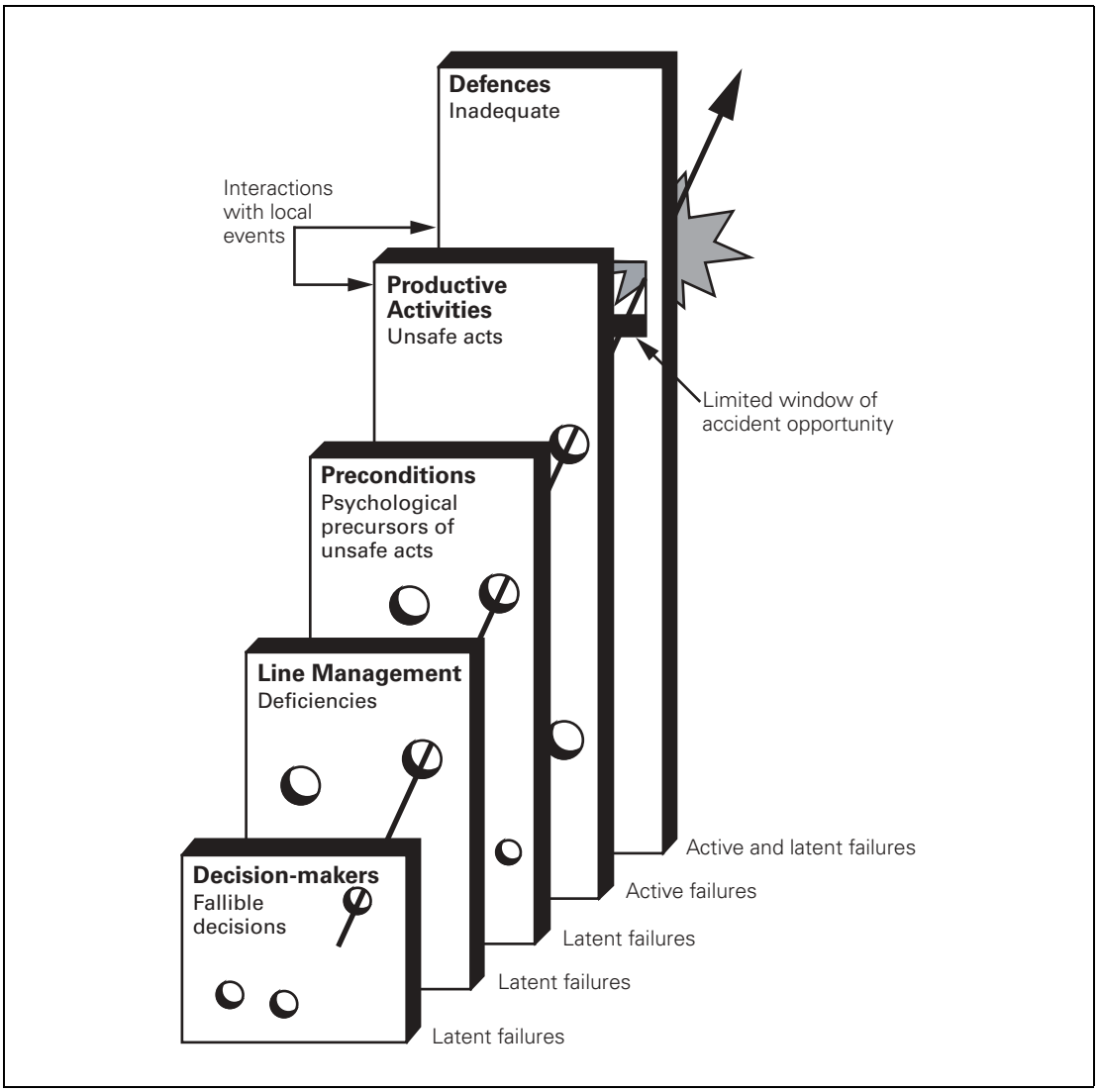

Figure 2 James Reason's Model of Accident Causation (modified version, 1990)

4 Human Error

4.1 Human error rather than technical failures has the greatest potential to adversely affect contemporary aviation safety. The Boeing Commercial Airplane Company recently analysed 220 documented accidents and found the top three causal factors to be:[1]

- Flight crews not adhering to procedures (70/220)
- Maintenance and inspection errors (34/220)
- Design defects (33/220)

4.2 The following quotation illustrates this point:

> "Because civil aircraft are designed to fly safely for unlimited time provided defects are detected and repaired, safety becomes a matter of detection and repair rather than one of aircraft structure failure. In an ideal system, all defects which could affect flight safety will have been predicted in advance, located positively before they become dangerous, and eliminated by effective repair. In one sense, then, we have changed the safety system from one of physical defects in aircraft into one of errors in complex human-centred systems." [2]

4.3 The increasing significance of human error is not unique to aircraft engineering. Hollnagel[3] conducted a survey of the Human Factors literature to identify the extent of the human error problem. In the 1960s, when the problem first began to attract serious attention, the estimated contribution of human error to accidents was around 20%. In the 1990s, this figure has increased fourfold to 80%. There are many possible reasons for this dramatic increase, but there are three which relate to aircraft engineering.

- The reliability of mechanical and electronic components has increased markedly over the past thirty years. People have stayed the same.
- Aircraft have become more automated and more complex. The current generation of Boeing 747-400s and Airbus A340s has duplicated or triplicated flight management systems. This may have reduced the burden on the flight crew but it has placed a greater demand on aircraft maintenance technicians, many of whom acquired their basic training in mechanical rather than computerized control systems. This suggests a mismatch of the Liveware- Hardware (L-H) and Liveware-Software (L-S) components of the SHEL model.
- Increased aviation system complexity creates the potential for organizational accidents in which latent procedural and technical failures combine with operational personnel errors and violations to penetrate or circumvent defences as the Reason model suggests. In short, complexity acts to shift the errors to other people.

1. Reason, J. (1993) *Comprehensive Error Management (CEM) in Aircraft Engineering*.
2. Drury, C.G. (1991) "Errors in Aviation Maintenance: Taxonomy and Control". Proceedings of the Human Factors Society 35th Annual Meeting, pp. 42-46.
3. Hollnagel, E. (1993) *Human Reliability Analysis — Context and Control.* Academic Press, San Diego, CA.

Chapter 2 Human Error in Aircraft Maintenance and Inspection (an organizational perspective)

1.1 Human error in maintenance usually manifests itself as an unintended aircraft discrepancy (physical degradation or failure) attributable to the actions or non-actions of the aircraft maintenance technician (AMT). The word "attributable" is used because human error in maintenance can take two basic forms. In the first case, the error results in a specific aircraft discrepancy that was not there before the maintenance task was initiated. Any maintenance task performed on an aircraft is an opportunity for human error which may result in an unwanted aircraft discrepancy. Examples include incorrect installation of line-replaceable units or failure to remove a protective cap from a hydraulic line before reassembly or damaging an air duct used as a foothold while gaining access to perform a task (among other failures, these examples also illustrate mismatches in the L-H interface of the SHEL model). The second type of error results in an unwanted or unsafe condition being undetected while performing a scheduled or unscheduled maintenance task designed to detect aircraft degradation. Examples include a structural crack unnoticed during a visual inspection task or a faulty avionics box that remains on the aircraft because incorrect diagnosis of the problem led to removal of the wrong box.[1] These errors may have been caused by latent failures, such as deficient training, poor allocation of resources and maintenance tools, time-pressures, etc. They may also have been caused by poor ergonomic design of tools (L-H flawed interface), incomplete documentation or manuals (L-S interface flaw), etc.

1.2 Several widely publicized accidents have had human errors in maintenance as a contributing factor. The American Airlines DC-10 accident in Chicago in 1979[2] resulted from an engine change procedure where the pylon and engine were removed and installed as a unit rather than separately. This unapproved procedure (a latent failure, probably with L-H and L-S mismatch involved) resulted in failure of the pylon structure which became evident when one of the wing-mounted engines and its pylon separated from the aircraft at take-off. The resulting damage to hydraulic systems caused the retraction of the left wing outboard leading edge slats and subsequent loss of control. In 1985, a Japan Airlines Boeing 747[3] suffered a rapid decompression in flight when an improperly repaired rear pressure bulkhead failed **(a** latent failure, probably with L-H and L-S mismatch involved). The subsequent overpressurization of the empennage and expansion of shockwave due to the explosive breakage of the spherical pressure bulkhead caused control system failure and the destruction of the aircraft with great loss of life. In April 1988, an Aloha Airlines Boeing 737[4] suffered a structural failure of the upper fuselage. Eventually the aircraft was landed with the loss of only one life. This accident was attributed to improper maintenance practices (latent failures) that allowed structural deterioration to go undetected.

1. Marx, D.A. and R.C. Graeber. (1993) *Human Error in Aircraft Maintenance*. Boeing Commercial Airplane Group, Seattle, Washington.
2. National Transportation Safety Board (1979) "Aviation Accident Report, American Airlines DC-10, Chicago." (NTSB/AAR-79/17). Washington, D.C.
3. Boeing 747 SR-100, JA8119, "Accident at Gunma Prefecture, Japan, on 12 August 1985". Report released by the Aircraft Accident Investigation Commission, Japan.
4. National Transportation Safety Board (1989). "Aircraft Accident Report, Aloha Airlines Flight 243". Boeing 737-200, N73711, Near Maui, Hawaii, 28 April 1988 (NTSB/AAR-89/03). Washington, D.C.

1.3 In a detailed analysis of 93 major world-wide accidents which occurred between 1959 and 1983, it was revealed that maintenance and inspection were factors in 12% of the accidents.[1] The analysis proposes the following significant causes of accidents and their presence in percentages:

Cause of Accident	**Presence (%)**
pilot deviation from standard procedures	33
inadequate cross-check by second pilot	26
design faults	13
maintenance and inspection deficiencies	**12**
absence of approach guidance	10
captain ignored crew inputs	10
air traffic control error/failure	09
improper crew response during abnormal conditions	09
insufficient or incorrect weather information	08
runway hazards	07
improper decision to land	06
air traffic control/flight crew communication deficiencies	06

1.4 In some accidents, where the error was attributed to maintenance and inspection, the error itself was a primary causal factor of the accident whereas, in other cases, the maintenance discrepancy was just one link in a chain of events that led to the accident.

1.5 The United Kingdom Civil Aviation Authority (UK CAA)[2] has published a listing of frequently recurring maintenance discrepancies. According to this listing, the leading maintenance problems in order of occurrence are:

incorrect installation of components
fitting of wrong parts
electrical wiring discrepancies (including cross-connections)
loose objects (tools, etc.) left in aircraft
inadequate lubrication
cowlings, access panels and fairings not secured
landing gear ground lock pins not removed before departure.

1. Sears, R.L. (1986) "A new look at accident contributions and the implications of operational training programs" (unpublished report). Quoted in Graeber, R.C. and D.A. Marx. *Reducing Human Error in Aviation Maintenance Operations.* (Presented at the Flight Safety Foundation 46th Annual International Air Safety Seminar. Kuala Lumpur, Malaysia, 1993.)
2. United Kingdom Civil Aviation Authority (UK CAA) (September 1992) "Maintenance Error". *Asia Pacific Air Safety.*

1.6 An analysis of 122 documented occurrences involving Human Factors errors with likely engineering relevance, occurring in the 1989-1991 time period in one airline, revealed that the main categories of maintenance error were:[1]:

Maintenance error categories	**Percentage**
omissions	56
incorrect installations	30
wrong parts	08
other	06

1.7 The majority of items often omitted are fastenings left undone or incomplete. The following example illustrates this point:

> An aircraft experienced vibration problems with the right engine for two weeks. The engineers had looked at the problem and, believing that it was the pneumatics, had swapped the pressure-regulating valves. However, just to be on the safe side, they sent an aircraft maintenance technician along to monitor the engine readings on a flight from Amsterdam to Kos carrying a full load of tourists. Departure was uneventful except for a brief rise on the vibration indicator of the right engine at about 130 knots. On cruise, the vibration indicator was bouncing up and down between 1.2 and 1.3, still within the normal range. However, there was a feeling of unfamiliar and strange vibrations. Ninety minutes into the flight, the vibration indicator registered 1.5, just below the amber range. Fifteen minutes later, the indicator was bouncing up into the amber range. The crew reverted to manual throttle control and descended to FL 290, slowly closing the throttle. The right engine vibration indicator suddenly shot up to 5.2 and a dull tremor shook the aircraft. Then the readings returned to the normal range and the vibration disappeared. The Captain, however, decided to declare an emergency and land in Athens where he felt he could get technical support that would not be available at Kos. With the engine now at idle thrust, the engine readings went back to the normal range and, as a result, the Captain decided to leave it well alone and not shut it down. On landing, the crew noticed some metal particles around the engine and discolouration on the blades that looked like oil.

1.8 When the report concerning the engine came out a few days later, it read:

> "... that the cause of the loose disc was the nuts being fitted only 'finger tight' to the LP1 (low pressure) and LP2 disc bolts and not being torqued up allowing axial movement in and out of the curvature, causing heavy rubs and out of balance. The nuts became successively loose allowing the bolts to come free until only the residual four remained."

1.9 The engine had been in for overhaul before the operator took delivery of the aircraft. There are 36 nuts and bolts that hold the LP1 and LP2 discs together. Apparently the technician working on them had finger tightened them and then decided to go to lunch. On his return he forgot to torque them as he had intended to do before he left for lunch. All but four of the bolts had fallen out and the remaining bolts only had 1/4 of an inch of thread left. Only the residual thrust held the engine together. Had the

1. Graeber, R.C. and Marx, D.A. (1993) *Reduced Human Error in Aircraft Maintenance Operations*.

crew elected to shut the engine down, the consequences would probably have been catastrophic.[1]

1.10 Incorrect installation of components and lack of proper inspection and quality control represent the most frequently recurring maintenance errors. Examples abound. Consider the following occurrences:

- On 5 May 1983, Eastern Airlines Flight 855, a Lockheed L-1011 aircraft, departed Miami International Airport en route to Nassau, the Bahamas. A short time after take-off, the low oil pressure light for No. 2 engine illuminated. The crew shut down the engine as a precautionary measure and the pilot decided to return to Miami. Shortly thereafter the remaining two engines failed following a zero oil pressure indication on both engines. Attempts were made to restart all three engines. Twenty-two miles from Miami, descending through 4 000 ft, the crew was able to restart the No. 2 engine and made a one-engine landing with the No. 2 engine producing considerable smoke. It was found that all three master chip detector assemblies had been installed without O-ring seals.[2]
- On 10 June 1990, a BAC 1-11 aircraft (British Airways Flight 5390) departed Birmingham International Airport for Malaga, Spain, with 81 passengers, four cabin and two flight crew. The co-pilot was the pilot flying during the take-off and, once established in the climb, the pilot-in-command handled the aircraft in accordance with the operator's normal operating procedures. At this stage both pilots released their shoulder harnesses and the pilot-in-command loosened his lap-strap. As the aircraft was climbing through 17 300 feet pressure altitude, there was a loud bang and the fuselage filled with condensation mist indicating that a rapid decompression had occurred. A cockpit windscreen had blown out and the pilot-in-command was partially sucked out of his windscreen aperture. The flight deck door blew onto the flight deck where it lay across the radio and navigation console. The co-pilot immediately regained control of the aircraft and initiated a rapid descent to FL 110. The cabin crew tried to pull the pilot-in-command back into the aircraft but the effect of the slipstream prevented them from succeeding. They held him by the ankles until the aircraft landed. The investigation revealed that the accident occurred because a replacement windscreen had been fitted with the wrong bolts.[3]
- On 11 September 1991, Continental Express Flight 2574, an Embraer 120, departed Laredo International Airport, Texas, en route to Houston Intercontinental Airport. The aircraft experienced a sudden structural breakup in flight and crashed, killing all 13 persons on board. The investigation revealed that the accident occurred because the attaching screws on top of the left side leading edge of the horizontal stabilizer were removed and not reattached, leaving the leading edge/ de-ice boot assembly secured to the horizontal stabilizer by only the bottom attachment screws.[4]

1.11 In following the organizational perspective, several questions, raised as a result of these occurrences, need to be diligently answered. To address problems exposed as a result of accident investigation findings, contributing Human Factors issues, individual as well as organizational, must be identified.

1. Summarized from "Finger-Tight at 290 (a tale of the unexpected)". Robin Rackham, *Log*, BALPA, August/September 1993.
2. National Transportation Safety Board. "Aircraft Accident Report, Eastern Airlines Inc., L-1011". Miami, Florida, 5 May 1983 (NTSB/AAR-84/04). Washington, D.C.
3. AAIB Aircraft Accident Report 1/92. "Report on the Accident to BAC One-Eleven, G-BJRT" over Didcot, Oxfordshire on 10 June 1990. London: HMSO.
4. National Transportation Safety Board (1992) "Aircraft Accident Report, Continental Express Flight 2574". In-Flight Breakup, EMB-120RT, N33701. September 1991 (NTSB/AAR-92/04). Washington, D.C.

1.12 In the case of the Eastern Airlines L-1011 aircraft, the National Transportation Safety Board (NTSB) concluded:

> "the master chip detectors were installed without O-ring seals because the mechanics failed to follow the required work card procedures, and because they failed to perform their duties with professional care expected of an A&P (airframe and powerplant) mechanic."[1]

1.13 Notwithstanding the conclusions of the NTSB, the findings and conclusions seem to have been limited to the notion of cause-effect relationships. Emphasis on factors such as multiple causation, mutual dependency and interaction of systems which are relevant to high-technology systems' safety was not as strong as it ought to have been to address both latent and active failures at their roots. It is the interaction of multiple failures, which are not expected to occur at the same time, rather than isolated individual actions, that explain why a particular accident or incident has occurred.

1.14 Chip detector installation was not a new task for the aircraft maintenance technicians at Eastern Airlines. The airline estimated that each technician involved had successfully performed over 100 chip detector changes. They were also in possession of a work card that specifically required the installation of the O-ring seals on the chip detector. They nevertheless failed to install the seals and thus the safety of the flight was seriously endangered. The investigation revealed that there were informal procedures not written on the work card but known to and adopted by most technicians in the maintenance and inspection departments. The records suggest that there were previous master chip detector installation problems and that the technicians were not routinely replacing O-ring seals on master chip detectors. This fact was known, at least, to one General Foreman who failed to take positive action to ensure compliance with the procedure as prescribed. One finding of the NTSB was that the aircraft maintenance technicians "had the responsibility to install O-ring seals"; however, a subsequent finding in the NTSB report states that "the mechanics had always received master chip detectors with 'installed' O-ring seals and had never actually performed that portion of the requirements of work-card 7204."[2] Latent organizational failure and L-S mismatches are obvious in this case.

1.15 Evidence available from organizational psychology confirms that organizations can prevent accidents as well as cause them. When viewed from an organizational perspective, the limitations of technology, training or regulations to counteract organizational deficiencies become obvious. Too often, safety promotion and accident prevention practices in the aviation industry have not taken into consideration the fact that human error takes place within the context of organizations that either foster or resist it.[3]

1. National Transportation Safety Board. "Aircraft Accident Report, Eastern Airlines Inc., L-1011". Miami, Florida, 5 May 1983 (NTSB/AAR-84/04). Washington, D.C.
2. Ibid. For detailed analysis of Human Factors issues in this particular incident, see Marx, D.A. and Graeber, R.C. (1993) *Human Error in Aircraft Maintenance*. Boeing Airplane Commercial Group, Seattle, Washington.
3. For a more detailed discussion on this subject, see *ICAO Human Factors Digest No. 10 — Human Factors, Management and Organization*. (1993)

1.16 The immediate cause of the BAC 1-11 aircraft accident identified by the investigation was that the replacement windscreen had been fitted with the wrong bolts. Causal factors listed were:

a) A safety critical task, not identified as a "Vital Point" (latent failure), was undertaken by one individual who also carried total responsibility for the quality achieved, and the installation was not tested until the aircraft was airborne on a passenger-carrying flight (latent failure).

b) The potential of the Shift Maintenance Manager (SMM) to achieve quality in the windscreen fitting process was eroded by his inadequate care, poor trade practices, failure to adhere to company standards and failure to use suitable equipment (L-H mismatch), which were judged symptomatic of a longer-term failure by him to observe the promulgated procedures.

c) The British Airways local management, Product Samples and Quality Audits had not detected the existence of the inadequate standards used by the Shift Maintenance Manager because they did not directly monitor the working practices of Shift Maintenance Managers (latent failure).[1]

1.17 The windscreen change was carried out some 27 hours before the accident. Statistics maintained by the operator show that 12 No. 1 windscreens, left or right, had been changed on their BAC 1-11s over the last year, and a similar number the year before. The Shift Maintenance Manager, who was responsible for the windscreen replacement on the accident aircraft, had carried out about six windscreen changes on BAC 1-11s while employed by the operator.

1.18 Though the local management of the airline was cited for not detecting the existence of the inadequate standards used by the Shift Maintenance Manager, the findings and conclusions still followed the obvious notion of cause-effect relationships. In considering those accidents caused by human error, it is evident that we tend to think in individual, rather than in collective, terms. As a result, solutions are directed towards the individual, the front-end operator, thus shielding latent organizational errors, which are, for the most part, the root causes of such accidents. More often than not, latent failures are left untouched, intact, waiting to combine with an unsuspecting front-line operator's active failure or error — the last in a chain of errors — and cause an accident involving the loss of human life and the destruction of property. The fact that errors do not take place in a vacuum and that human error takes place within the context of organizations which either foster or resist it has long been put aside in order to identify an individual fully responsible for what has transpired. Therefore, it is imperative that systemic and/or organizational failures are scrutinized in order to uncover system-wide, error-inducing conditions.[2]

1.19 The investigation of the Continental Express Flight 2574 accident revealed that the attaching screws on the top of the left side leading edge of the horizontal stabilizer had been removed and had not been reattached, leaving the leading edge/de-ice boot assembly secured to the horizontal stabilizer by only the bottom attachment screws. The probable cause statement read:

> "The National Transportation Safety Board determines that the probable cause of this accident was the failure of Continental Express maintenance and inspection personnel to adhere to proper maintenance and quality assurance procedures for the airplane's horizontal stabilizer deice boots

1. AAIB Aircraft Accident Report 1/92. "Report on the Accident to BAC One-Eleven, G-BJRT" over Didcot, Oxfordshire on 10 June 1990. London: HMSO *causal factors (emphasis added)*, pp. 54.
2. "From Individuals to Organizations" ICAO position paper delivered at the Algonquin College validation course on aviation Human Factors. February 1993.

> that led to the sudden in-flight loss of the partially secured left horizontal stabilizer leading edge and the immediate severe nose-down pitch-over and breakup of the airplane. Contributing to the cause of the accident was the failure of the Continental Express management to ensure compliance with the approved maintenance procedures, and the faiure of the FAA surveillance to detect and verify compliance with approved procedures."[1]

1.20 Although the report addresses latent failures as contributing factors to the occurrence, the emphasis in this statement is focused on the active failure of the maintenance personnel, making them the probable cause of the occurrence. In this and the previous cases, it is not difficult to see that "mechanic error" is replacing "pilot error" as the probable cause; this shifting of blame still brands a specific professional body as the sole entity responsible for the safety of the system and still fails to properly address systemic and/or organizational errors as the breeding grounds for human error in their real dimension. Over the last fifty years, ascribing "pilot error" as a probable cause of an occurrence failed to prevent accidents of similar causal factors. The reason is simple: human error takes place within the context of organizations. No accident, however obvious its causal factors seem to be, ever happens as a result of a single occurrence. A chain of latent failures is almost always present, depriving the last single error of the defence which could prevent it from becoming an accident. It is therefore imperative that causal factors in accidents are addressed in the organizational context in order to prevent them from occurring again and again. Aviation safety began to make optimal use of accident investigations lessons only after it had begun to address the organizational context of operations. These lessons are as applicable to errors committed in the maintenance base as they are to those committed in the cockpit or the ATC room. As is the case in the cockpit and ATC environment, accidents resulting from faulty maintenance or inspection reflect more on the organization than on the individual who is at the end of the line (Reason's model simplifies this notion).

1.21 In keeping with this line of thinking, a dissenting statement in this particular report suggests that the probable cause cited should have read as follows:[2]

> "The National Transportation Safety Board determines that the probable causes of this accident were (1) the failure of Continental Express management to establish a corporate culture which encouraged and enforced adherence to approved maintenance and quality assurance procedures, and (2) the consequent string of failures by Continental Express maintenance and inspection personnel to follow approved procedures for the replacement of the horizontal stabilizer deice boots. Contributing to the accident was the inadequate surveillance by the FAA of the Continental Express maintenance and quality assurance programmes."

1.22 The justification for this dissenting statement lies in the fact that the accident investigation report identified "substandard practices and procedures and oversights" by numerous individuals, each of whom could have prevented the accident. This includes aircraft maintenance technicians, quality assurance inspectors, and supervisors, all of whom demonstrated a "general lack of compliance" with the approved procedures. Departures from approved procedures included failures to solicit and give proper shift-change turnover reports, failures to use maintenance work cards as approved, failures to complete required maintenance/

1. National Transportation Safety Board (1992) "Aircraft Accident Report, Continental Express Flight 2574". In-Flight Breakup, EMB-120RT, N33701, September 1991 (NTSB/AAR-92/04). Washington, D.C.
2. Ibid. pp. 54. John K. Lauber, Member NTSB. "Dissenting Statement".

inspection shift turnover forms and a breach in the integrity of the quality control function by virtue of an inspector serving as a mechanic's assistant during the early stages of the repair work performed on the accident aircraft.

1.23 The investigation also discovered two previous maintenance actions on the accident aircraft, each of which departed from the approved procedures and involved employees different from those engaged in the de-icing boot replacement. The first event was the replacement of an elevator without the use of the required manufacturer-specified balancing tools. The second was the failure to follow specified procedures and logging requirements in response to an engine overtorque. Although these events were in no way related to the accident, the report indicates that they "suggest a lack of attention to established requirements for performing maintenance and quality control in accordance with the General Maintenance Manual (GMM)".

1.24 A detailed examination of the organizational aspects of the maintenance activities the night before the accident reveals a mélange of crossed lines of supervision, communications and control. The multitude of lapses and failures committed by numerous airline employees, discovered during the investigation, is not consistent with the notion that the accident resulted from isolated, as opposed to systemic, factors. Based on the record, the series of failures which led directly to the accident cannot be considered the result of an aberration by individuals but rather reflects on the customary, accepted way of doing business prior to the accident. Line management of an airline has the regulatory responsibility not only for providing an adequate maintenance plan (and we conclude that the GMM was, in most respects, an adequate plan) but for implementing the provisions of that plan as well. By permitting, whether implicitly or explicitly, such deviations to occur on a continuing basis, senior management created a work environment in which a string of failures, such as occurred the night before the accident, became probable.[1]

2 Human Error in the Maintenance Environment

2.1 There are unique characteristics which shape human error in the maintenance environment differently than in other operational environments, such as the flight deck or the ATC room. Push the wrong button or pull the wrong knob, issue a contradicting instruction, and the pilot or the controller will see the effects of the error before the aircraft completes its flight. If an accident or incident occurs, the pilot is always "on the scene" at the time of the accident or incident. If it is an air traffic controller who is involved, the ATC is nearly always on the scene or on real time. While this important characteristic may seem obvious for flight crew/ATC error, it does not always apply to aircraft maintenance error.

2.2 In contrast to the "real-time" nature of error in ATC and the flight deck, maintenance errors are often not identified at the time the error is made. In some cases the maintenance technician making the error may never know of the mistake because detection of the error could occur days, months or years after the error was made. In the case of the 1989 Sioux City DC-10 engine disk failure,[2] the suspected inspection failure occurred seventeen months before the aircraft accident.

2.3 When human error in maintenance is detected, usually through some system malfunction, we often know only the resulting aircraft discrepancy. What is rarely known is why the error occurred. In the realm of aircraft maintenance, there are no

1. Ibid. pp. 52-54 (an adaptation and emphasis added).
2. National Transportation Safety Board (1990) "Aircraft Accident Report, United Airlines Flight 232, McDonnell Douglas DC-10-10". Sioux Gateway Airport, Sioux City, Iowa, 19 July 1989 (NTSB/AAR-90/06). Washington, D.C.

equivalents to the cockpit voice recorder, the flight data recorder or the ATC tapes to preserve the details of the maintenance job performed. Additionally, maintenance self-report programmes have not progressed to the sophistication of those within the flight environment, such as the ASRS, CHIRP, etc. Thus, in most cases, the data to discuss maintenance error in terms of specific types of human error is simply not available. Errors are, therefore, discussed in terms of the aircraft discrepancy. Consider the following scenario: a New York-based line maintenance technician forgets to install an anti-vibration clamp on an engine-mounted hydraulic tube. Three months later, the tube suffers from fatigue in flight and causes the loss of a hydraulic system. Upon landing in London, aircraft maintenance technicians inspect the engine and find that the anti-vibration clamp was not installed. Do they know why? Most likely not since the error occurred three months ago in New York. Consequently a human error gets recorded as "clamp missing".

2.4 This unavailability of "scene-of-the-error" causal data represents a problem for an industry conditioned for decades to follow an approach to prevention and investigation strongly biased towards searching for some specific causal factor. Looking at the analysis of the causal factors of accidents and their percentage of presence discussed earlier, it can be seen that "pilot error" (the popular misnomer of human error committed by pilots) has been broken down into specific performance failures such as pilot deviation, improper crew response, improper decision, poor crew co-ordination, miscommunication with air traffic control, etc. In the same analysis, however, maintenance and inspection receives only one line: maintenance and inspection deficiencies. Notwithstanding all the other errors possible in the maintenance of a complex aircraft, every maintenance-related accident falls within that single line. Except for major accidents that are exhaustively re-created, identification of maintenance-related-error causal factors beyond this level is rarely seen.[1]

2.5 The maintenance- and inspection-error-related accidents of the BAC 1-11 and Embraer 120 aircraft are exceptions in that the accidents occurred soon after the active errors had been committed. This enabled the accident investigators to concentrate their efforts on site and to look closely into the activities of the individuals concerned as well as those of the organizations. The classic case of "displaced in time and space" was not a factor slowing, if not hindering, timely investigation of the occurrences. The opportunity to identify organizational errors, individual human error or error-inducing organizational practices was present, providing the chance to address accident-enabling practices at their source.

2.6 Statistics indicate that organizational or systemic errors within aircraft maintenance organizations are not limited to one organization or one region. In the three accidents analysed here, the behaviour of the organizations and the individuals within the organizations before the occurrences was similar. For example:

- maintenance and inspection personnel failed to adhere to established methods and procedures (active failure);
- those responsible for ensuring adherence to established procedures and methods failed to supervise not in 'one-offs' but in what were symptomatic of longer-term failures (active and latent failures);
- high-level maintenance management failed to take positive action to require compliance with procedures as prescribed by their respective organizations **(latent failures)**;

1. See Marx, D.A. and Graeber, R.C. (1993) *Human Error in Aircraft Maintenance*. Boeing Commercial Airplane Group, Seattle, Washington.

- maintenance work was performed by personnel who were not assigned to do the job but who, with good intentions, started the work on their own initiative (active failure fostered by the two previous latent failures); and
- lack of proper and/or positive communication was evident, extending the chain of error which led to the accidents (latent failure).

2.7 As indicated in 1.11, one of the basic elements of the aviation system is the decision maker (high-level management, companies' corporate or regulatory bodies) who is responsible for setting goals and for managing available resources to achieve and balance aviation's two distinct goals: safety and on-time and cost-effective transportation of passengers and cargo. When viewed through both the Reason and the SHEL models, it is not difficult to see why and where errors were committed.

Chapter 3 Human Factors Issues Affecting Aircraft Maintenance

1 Information Exchange and Communication

1.1 Communication is possibly the most important Human Factors issue in aircraft maintenance. Without communication among maintenance managers, manufacturers, dispatchers, pilots, the public, the government and others, safety standards would be difficult to maintain. In the maintenance realm there is an enormous volume of information that must be created, conveyed, assimilated, used and recorded in keeping the fleet airworthy. A frequently quoted example is the paper stack, supposedly exceeding the height of Mt. Everest, that the Boeing Aircraft Company produces annually in order to support its aircraft operators. Airlines literally have warehouses full of paper that contain the historical records of maintenance of their aircraft.

1.2 It is most important that maintenance information be understandable to the target audience. The primary members of this audience are the inspectors and technicians who undertake scheduled aircraft maintenance and diagnose and repair aircraft malfunctions. New manuals, service bulletins, job cards and other information to be used by this audience should be tested before distribution to make sure that they will not be misunderstood or misinterpreted. Sometimes maintenance information is conveyed through a less-than-optimum selection of words. Anecdotal evidence suggests a case where a certain maintenance procedure was "proscribed" (i.e. prohibited) in a service bulletin. The technician reading this concluded that the procedure was "prescribed" (i.e. defined, laid down) and proceeded to perform the forbidden action. These types of problems are becoming more prevalent now that air carrier aircraft are being manufactured all over the world. Sometimes the technical language of the manufacturer does not translate easily into the technical language of the customer and the result can be maintenance documentation that is difficult to understand. Since so much maintenance information is written in English, there is a strong case to be made for use of "simplified" English. Words that mean one thing to a certain reader should mean the same thing to every other reader. For example, a "door" should always be a door. It should not be referred to as a "hatch" or a "panel".

1.3 Communication with the aircraft manufacturer, as well as between airlines, can be crucial. If an operator discovers a problem in maintaining its aircraft that could degrade safety, then that problem should be communicated to the manufacturer and to other operators of the same aircraft type. This is not always easy to do. Industry cost control measures and competitive pressures may not place a premium on communication among airlines. However, civil aviation authorities can play an important role by encouraging operators under their jurisdiction to interact frequently with one another and the manufacturer of the aircraft they operate. A maintenance-related incident in one airline, if made known to other operators, could easily prevent an accident from happening. The accident record has no shortage of accidents that could have been prevented if incident information from airlines had been made known to the industry. The investigation of the American Airline DC-10 accident at Chicago in 1979 revealed that another airline, using the same unapproved engine change procedures, had discovered that the procedure caused cracks in the pylon attachment area and, as a consequence, had reverted to using the approved procedures. It is believed that if the airline had shared its experience with the other operators of similar aircraft, the accident at Chicago could have been prevented. However, for such co-operation to

succeed and flourish, information disseminated under such co-operation must be strictly used for accident prevention purposes only. The use or misuse of such information to gain a marketing advantage over the reporting airline can only result in stifling all safety-related interactions among operators.

1.4 Lack of communication within an airline's maintenance organization can also have a very serious negative impact on the airline's operation. The accidents discussed in Chapter 2 illustrate this problem. In all of those occurrences, lack of proper communication of action taken or action which needed to be taken was rampant, adding to the series of errors and, thus, the accident occurrences. Each investigation has revealed that a number of latent failures were evident and that there was a serious flaw in the L-L and L-S interfaces.

1.5 In the EMB-120 accident, the second shift supervisor who was responsible for the aircraft failed to solicit an end-of-shift verbal report (shift turnover) from the two technicians he assigned to remove both horizontal stabilizer de-ice boots. Moreover, he failed to give a turnover to the oncoming third shift supervisor and to complete the maintenance/inspection shift turnover form. He also neglected to give the maintenance work cards to the technicians so that they could record the work that had been started, but not completed, by the end of their shift. It is probable that the accident could have been avoided if this supervisor had solicited a verbal shift turnover from the two technicians assigned to remove the de-ice boots, had passed that information to the third shift supervisor, had completed the maintenance shift turnover form and had ensured that the technicians who had worked on the de-ice boots had filled out the maintenance work cards so that the third shift supervisor could have reviewed them (latent failure and L-L mismatch*)*.

1.6 The two technicians were assigned to the second shift supervisor by another supervisor, who was in charge of a C check on another aircraft. This supervisor was given a verbal shift turnover from one of the technicians after he had already given a verbal shift turnover to the oncoming third shift supervisor, informing him that no work had been done on the left stabilizer. He failed to fill out a maintenance shift turnover form and also failed to inform the oncoming third shift supervisor. He failed to instruct the technician to report to the supervisor who was actually responsible for the assigned task or to the oncoming third shift supervisor. Instead, he instructed the technician to report to a third shift technician, indicating what work had been accomplished. If this supervisor had instructed the technician to give his verbal shift turnover information to the second shift supervisor (responsible for the aircraft) or to the oncoming third shift supervisor and had instructed the technician to complete the maintenance work cards, the accident would most likely not have occurred *(*a series of latent failures and L-L flaw at all levels*)*.

1.7 A second shift Quality Control Inspector assisted the two technicians in removing the upper screws on both horizontal stabilizers, signed out on the inspector's turnover sheet and went home. An oncoming third shift Quality Control Inspector arrived at work early, reviewed the second shift Inspector's turnover sheet and recalled no entry. Unfortunately, the oncoming Inspector reviewed the shift turnover sheet before the second shift Inspector wrote on it "helped mechanic pull boots." In addition, the second shift Inspector failed to give a verbal shift turnover to the oncoming third shift Inspector. It is believed that if the second shift Quality Control Inspector had given a verbal shift turnover to the oncoming third shift Inspector and had reported any work initiated regarding removal of the upper leading edge screws on both stabilizers, the accident would most likely not have occurred. In addition, as an Inspector, he was a "second set of eyes" overseeing the work of the technicians. By helping remove the upper screws, he effectively removed himself from functioning as an inspector.

1.8 One of the technicians, who assumed responsibility for the work accomplished on the aircraft during the second shift, failed to give a verbal shift turnover, per the airline's maintenance manual, to the second shift supervisor (responsible for the aircraft), who had assigned him the task of removing the de-ice boots. In addition, he failed to solicit and fill out the maintenance work cards from the second shift supervisor before leaving at the end of his shift *(*again a series of latent failures and L-L mismatch*)*. It is further believed that, if the technician had given a verbal shift turnover either to the second shift supervisor responsible for the aircraft or to the oncoming third shift supervisor, who was working the hangar directly, and if he had solicited the maintenance work cards from the second shift supervisor, the accident would most likely not have occurred.

1.9 The accident investigation[1] revealed that there was a serious organizational flaw within the maintenance system of the organization. The paragraphs above each emphasize a failure of an individual but not the same individual; it is a group of individuals, i.e. an organization. The investigation further revealed that the action of these individuals or of a group of individuals was not a one-time slip. Two previous maintenance actions taken on the accident aircraft departed from approved procedure and involved employees different from those engaged in the de-icing boot replacement. Although the actions were in no way related to the accident, the investigation indicated that they "suggest a lack of attention to established requirements for performing maintenance and quality control in accordance with the General Maintenance Manual". The behaviour of the maintenance technicians, as revealed by the investigation, can only be explained as a manifestation of the existence of a corporate culture which condoned unapproved practices and which lacked norms that condemned such behaviour within the organization.[2] An attitude of disregard of maintenance procedures, organizational policies or regulatory standards involves more than individual human performance issues, since such behaviour does not develop overnight.

1.10 Communication was also an issue in the blown-out windscreen accident.[3] A Stores Supervisor, who had been on the job for about 16 years, informed the shift maintenance manager of the correct specification of the bolts used to fit that windscreen but failed to press the point (L-L mismatch). Communication which is weakly or unconvincingly conveyed is as good as no communication at all. This accident also illustrates a problem faced regularly by maintenance technicians, i.e. the pressure to make a gate time. Due to the high costs of aircraft, operators cannot afford the luxury of having back-up aircraft when maintenance cannot be completed on time. Scheduling of aircraft for service reflects a delicate balance between obtaining the maximum number of revenue flight hours and performing needed maintenance. Significant maintenance tasks must be accomplished quickly so that the aircraft can make its scheduled gate time. Passengers do not like maintenance delays and if they happen too often on an airline, business may be lost to a competitor. Aircraft maintenance technicians are keenly aware of this pressure and strive to accomplish their work in a timely manner. Clearly this can sometimes lead to compromised maintenance especially when, as so often happens, things do not go according to plan. Management's role is to ensure that their maintenance organizations are provided with adequate personnel and resources to prevent the type of work that results in degraded airworthiness. This problem, while not — strictly

1. National Transportation Safety Board (1992) "Aircraft Accident Report, Continental Express Flight 2574", In-Flight Breakup, EMB-120RT, N33701. September 1991 (NTSB/AAR-92/04). Washington, D.C.
2. For a detailed discussion on Human Factors and corporate or organizational culture, see ICAO Human Factors Digest No.10 — *Human Factors, Management and Organization* (Circular 247).
3. AAIB Aircraft Accident Report 1/92, "Report on the Accident to BAC One-Eleven, G-BJRT" over Didcot, Oxfordshire on 10 June 1990, London: HMSO.

speaking — a communication issue, highlights the importance of an open, two-way exchange within maintenance organizations. Airline management needs to develop procedures and ensure their application to prevent dispatch of non-airworthy aircraft. One of the best ways of facilitating this activity is to maintain an ongoing dialogue with maintenance staff, encouraging them to report hazardous situations or practices.

2 Training

2.1 Training methods for aircraft maintenance technicians vary throughout the world. In many States a common procedure is for a would-be technician to enrol in a relatively short-term (two-year) course of training at an aircraft maintenance technician training centre. These centres provide training in the skills required to pass examinations given by the civil aviation authority (CAA) for the Airframe and Powerplant (A&P) technician's licence or certificate. In addition, it is possible in many States to obtain certification through an apprenticeship-type programme whereby, over a period of years, individuals learn their craft using on-the-job training (OJT) methods.

2.2 In practice and as a general industry-wide trend, most graduates of A&P training institutes are not well prepared for the airline maintenance role. As students they spend a lot of their training time learning such skills as wood/dope/fabric repair and piston engine repair. These skills, while useful in maintaining the general aviation aircraft which abound, are not often needed in maintaining the fleet of complex, turbine-powered air carrier aircraft. Consequently, the airlines must provide a good deal of training for their maintenance staff. In some States, maintenance technician candidates have no prior training in training centres. In these cases, the airlines are required to provide practically all of the training.

2.3 Airline training should be a mix of structured classroom training as well as OJT. The problem with OJT is that it is difficult to manage, hence, the training outcomes can be expected to vary considerably. Often with OJT a more experienced technician demonstrates a maintenance procedure to a junior or less experienced person. The trainee is expected to assimilate the training and demonstrate this newly acquired knowledge to the satisfaction of the trainer. If all goes well the trainee is expected to successfully perform the task, unsupervised, in the future. On the other hand, the senior technician/trainer may not be an effective teacher or the training environment (outdoors, night-time conditions) may not be conducive to training. The student may not know enough about the system which is being used for training to ask questions that might make the difference between successful or unsuccessful training. Other problems include training to perform certain tasks which may be difficult to learn in one session. Successful accomplishment of such tasks is heavily reliant on operator skill as there is as much “art” as there is “science” in these tasks.

2.4 OJT should be controlled and supervised. Trainers should be instructed in training procedures that will optimize student learning. On-the-job trainers should be selected both for technical skills and for the motivation to train others. Maintenance shop managers should recognize that a good technician does not necessarily make a good instructor. Regardless of their personal capabilities to perform a given task, experienced technicians can be good or bad trainers and training outcomes can be expected to be similarly good or bad. The safety consequences are too obvious to require further elaboration. Trainees should be given graduated experiences so that, for example, they are trained in light scheduled maintenance work and move on to successively more difficult problems rather than start out immediately on heavy maintenance work. Records of OJT performance should be kept and remedial training provided as necessary. OJT should be scheduled as much as possible and should not be reliant on unpredictable aircraft malfunctions to provide training opportunities.

2.5 The growing complexity of modern air transport aircraft makes it necessary to provide more formal classroom-type training. With, for example, glass cockpits and sophisticated electronic systems, it is important to provide extensive classroom-based training on underlying system principles. This is difficult to do with OJT. Here, as well, it is very important that classroom instructors be extensively prepared for their task. It is not enough to simply dub a senior technician a teacher. In addition to being a subject matter expert, the instructor must also know how to teach, i.e. how to present information clearly, how to seek feedback from the students to ascertain that they are learning, how to determine problem areas and be able to provide remedial instruction. Most major airlines maintain training departments staffed with skilled instructors. However, this is not always the case with smaller carriers and in fact such departments are rarely seen in many commuter-type operations. In the meantime, commuter aircraft are also becoming as complex as aircraft operated by the major airlines. The challenge for these operators with limited resources is to develop methods to ensure that their maintenance technicians receive all the training required to maintain a fleet of modern aircraft. This may include taking maximal advantage of manufacturer-provided training and negotiating for follow-up training as part of an aircraft acquisition agreement.

2.6 Computer-based instruction (CBI) is found at some airlines depending on the size and sophistication of the training programme. However, most of the CBI currently in use would now be considered early or old technology. New training technologies are being developed which may complement or, in some cases, even replace OJT and classroom methods. Certainly these new training technologies would be expected to replace old-style CBI. Early CBI, which is still in use today, provides tutorial-type instruction usually followed by screen-presented multiple choice questions on the tutorial material. An incorrect answer keyed in by a student is typically met with a buzzer sound and the words "wrong answer — try again". The student can keep guessing until the right answer is chosen, but usually little or no remedial instruction is given with these systems.

2.7 Today's students have greater expectations from interactive computer systems including training systems. In many States including a number of developing States, secondary or high school students have already had some exposure to personal computers and to computer games available for home televisions. These devices do provide considerable feedback and performance rating features found in new technology training systems. Similarly, newer CBI systems offer training that adapts to the students' knowledge and skill. However, advanced technology CBI must have a reasonable degree of intelligence comparable to that of a human instructor. More than the instructions and feedback on what needs to be done or on how one is performing, new technology should be able to provide systemic tutoring. Systems capable of such endeavours are now available in some high-technology training establishments. These new systems are called Intelligent Tutoring Systems (ITS). The features that set ITS apart from the less proficient CBI systems are software modules that emulate students, subject matter experts and instructors. This is done

2.8 The primary components of an ITS are shown in Figure 3. At the centre of the figure is the instructional environment. For aviation maintenance training, this environment is usually a simulation. The expert model or module on the right of the figure must contain much of the same knowledge about a system or device that a human expert would possess. The student model at the bottom of the figure can be based on required student knowledge and on critical actions the student must take during interaction with the instructional environment. This model also contains a current file of students' actions as well as historical files describing students' preferred learning styles, previously mastered lessons and typical errors. The instructor or pedagogical

model on the left provides the subject matter expert's knowledge in a way that optimizes student learning. This module sequences instruction based on student performance and provides appropriate feedback, remedial instruction and suggestions for further instruction outside of the ITS environment as needed.

2.9 ITS have been found to be very effective for training in the diagnosis and maintenance of complex high-technology equipment. They have a number of advantages over traditional training methods including the capacity to provide "just-in-time" training or refresher training immediately before maintenance work is started. Also with ITS, training is under the students' control and can be scheduled, paced or repeated at the students' discretion. There is a feeling, in some circles, that these systems may prove to be too complex for widespread use. It is possible that these feelings spring from lack of experience with this technology rather than from an evaluation of technical and training staff capabilities. Operators and civil aviation authorities are urged to keep an open mind about the use of these new technologies lest they deprive their airlines of important capabilities which could have very significant safety implications.

3 The Aircraft Maintenance Technician

3.1 Due to the increasing complexity of new aircraft, maintenance is becoming a more critical function. In the early days of aviation, aircraft maintenance was considered a higher level of automotive maintenance not far removed from that of an automobile and similar skills could be successfully employed in either endeavour. Such consideration could not survive for long as aircraft technology quickly developed into a much more complex technology. Today aircraft maintenance technicians must know a good deal about system theory, be able to perform complex tests and interpret results, maintain structural elements that differ greatly from typical riveted aluminum structures and evaluate sensitive electronic and automated systems where a mistaken application of the simplest task can cause considerable loss in damage. Trends in aircraft and systems development clearly indicate that future aircraft technicians, in order to perform successfully, will need to be highly educated and trained to the level of a degree in engineering or its equivalent.

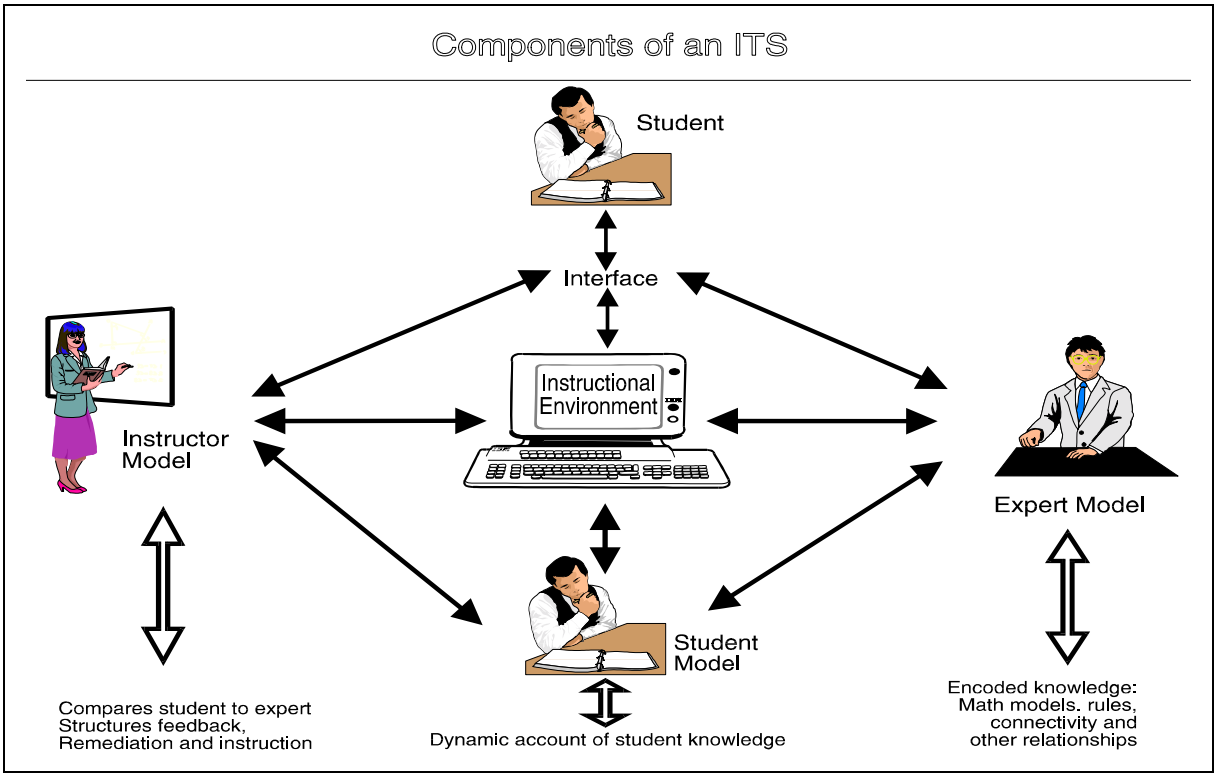

Figure 3 The components of an Intelligent Tutoring System
(Modified version from Polson & Richardson, Psotka et al., 1988)

3.2 Even though many, if not all, airlines today are experiencing few problems recruiting qualified maintenance personnel, this may not be the case in the future. Competition from other industries — possibly with better working conditions and more interesting work — and increasing demand for more people highly skilled in aircraft maintenance are a few of the reasons why airlines may find it more difficult to adequately staff their maintenance establishments in the future. For those facing this prospect, some thought should be given to possible actions to enhance future supplies of adequately trained maintenance personnel. Supporting quality secondary education in community schools and increasing awareness of the aircraft maintenance career among school-age groups are two relatively inexpensive means. Other methods include loan of equipment or instructors to A&P training schools, provision of training loans or grants to promising students in exchange for work agreements, development of more formal training or apprenticeship programmes and recruitment of maintenance talent from non-traditional groups such as women. Parenthetically, it is suggested that industry support and foster expanded computer education in secondary schools since, as the trend indicates, future maintenance activity may be heavily underpinned by computerized and automated systems even in those States that, at present, do not employ significant electronic support systems.

3.3 Aircraft maintenance is frequently performed at night. Physiologically and mentally we are most alert during daylight hours and prefer to rest or sleep at night. When job requirements disturb this pattern, work performance deficits can follow. This can certainly pose problems in aircraft maintenance where safety is vitally connected to error-free technician performance. In most maintenance-error accidents, like the ones discussed in this digest, the faulty maintenance work which contributed to the accident was performed during night shift working hours *(*inducing L-E interface flaw*)*. Operators should carefully examine work assignments for their effects on technicians and their work. Physically demanding tasks should not be followed by tedious work

requiring intense concentration. Management should be aware of the hazards of such activities as repetitive inspection of identical items such as rivets or turbine blades. A long history of research shows that operator vigilance declines rapidly on these tasks and error can easily follow. Similarly, use of certain types of equipment is associated with work error. Old-style inspection devices rely heavily on technicians' skill in manipulating equipment and in detecting and interpreting subtle instrument indications. Couple these difficulties with a fatigued technician and the probability for error increases dramatically. Shift supervisors need to be especially observant of technician fatigue and to oversee and perform follow-up checks of tasks to discover any resulting errors. Inspection during daylight hours of maintenance work accomplished the previous night could also go a long way towards reducing the probability of an error such as happened on the accident aircraft.

3.4 Technician health and physical status can also influence work performance. Aircraft maintenance and inspection activity can sometimes be physically demanding. Climbing over wings and horizontal stabilizers and working in uncomfortable positions and in cramped or confined spaces are common. These can be demanding especially for the maintenance technician who is overweight, sick or poorly conditioned and could result in work being skipped, uncompleted or improperly performed. The need for good vision and sometimes for normal colour vision is important as well. Older people frequently need vision correction in the form of glasses or contact lenses. At present, there are no medical requirements for aircraft maintenance technicians. As is the case with many people, technicians may not attend to visual deficiencies on time, especially when we consider the fact that lacking periodic examinations, detection of gradual visual deficiency is difficult until vision has deteriorated significantly. Moreover, the technician may experience job insecurity and therefore avoid reporting failing eyesight.

3.5 Currently it is rare to find an operator or administration that requires regular medical screening of technicians to detect disorders that may impair their work performance. However, due to the increasing correlation between aviation safety and maintenance technician performance, it may be timely to consider implementing regular medical screening of aircraft maintenance technicians.

4 Facilities and Work Environment

4.1 To understand human error in maintenance, it is essential to understand the responsibilities and working environment of the aircraft maintenance technician. Work environment can have a strong effect on technician performance. While it is desirable to have ideal work conditions such as well lighted, comfortable hangars for aircraft maintenance work, such is not likely given the cost of building and operating these facilities at every airport served by airlines. Consequently, a lot of aircraft maintenance is performed under less-than-ideal-conditions including outdoor, night work in inclement weather.

4.2 One of the most important work parameters in aircraft maintenance is lighting. It is very difficult to provide adequate lighting for all aspects of maintenance work including inspection and repair. Poor ambient illumination of work areas was identified as a significant deficiency during the investigation of the accidents discussed in this digest. In the BAC 1-11 aircraft accident, an adequately lighted working area may have made it possible for the shift maintenance manager to see the excessive annulus of unfilled countersink which was easily discernible when viewed under good lighting conditions *(*L-E mismatch*)*. In the EMB-120 accident, a third shift inspector had gained access to the top of the horizontal stabilizer to assist with the installation and inspection of the de-ice lines on the right side of the horizontal stabilizer. He later

stated that he was not aware of the removal of the screws from the left leading edge assembly of the horizontal stabilizer and in the dark outside the hangar, he did not see that the screws were missing from the top of the left side leading edge assembly (L-E mismatch).

4.3 A great deal of lighting for specific tasks is provided by hand-held torches or flashlights. The advantages of these lights are that they are portable and require no set-up time. Disadvantages include lack of brightness and the fact that they usually encumber one hand, sometimes forcing maintenance work or inspection activity to be performed with the one remaining hand only. One frequently noted problem in several observed maintenance hangars is poor area lighting. Often hangar area lighting is provided by ceiling-mounted units. These hard-to-reach units are frequently dust- or paint-coated and burnt-out bulbs sometimes go unreplaced for long periods of time. In addition, the number and placement of these units are sometimes insufficient to provide good area lighting conditions. Area lighting in hangars should be at least in the order of 100 to 150 foot-candles to provide adequate lighting.

4.4 Maintenance and inspection tasks performed beneath aircraft structures and within confined spaces pose difficult lighting problems. The structure shades work points from area lighting and, similarly, cramped equipment compartments will not be illuminated by ambient hangar lighting. Special task lighting should be provided for these situations. Task lighting needs a range from 200 to 500 foot-candles, depending on the task. Affordable portable lighting units which can be positioned near work areas or attached to adjacent structures for the performance of specific tasks are available in various sizes and ranges. The use of such lighting systems could help alleviate some of the problems which may result from a liveware-environment mismatch.

4.5 Outdoor, night-time maintenance activity demands careful attention to lighting needs. A great deal of aircraft maintenance is performed under these conditions. There is an unfortunate tendency to rely on flashlights or ambient lighting from open hangar doors for this work because adequate portable lighting is either unavailable or time-consuming to obtain and set up. Management must be aware of the importance of providing and requiring the use of adequate area and task lighting. It is not a trivial issue. Adverse occurrences, resulting, at least partly, from lack of adequate lighting, are often identified in many accident investigation reports.

4.6 Noise is another important work environment factor. Aircraft maintenance operations are usually intermittently noisy due to activities such as riveting, machinery operation inside hangars, or engine testing or run-up on ramps. Noise can cause speech interference and can also have health implications. Loud or intense noise tends to result in heightened response of the human autonomic nervous system. One of the results can be fatigue. Perhaps more important is the effect of noise on hearing. Regular exposure to loud noise can result in permanent hearing loss. Lower-intensity noise can cause temporary hearing loss which can have safety implications in the workplace. Missed or misunderstood communication resulting from noise interference or hearing loss can have serious consequences. Actions that can be taken by operators to deal with noise problems include controlling noise sources by enclosing or insulating machinery, isolating noisy activities so that fewer people are exposed, providing workers with hearing protection and requiring its use, reducing engine run-up or testing to the minimum acceptable and measuring noise levels in work areas. Noise monitoring can identify where problems exist, thereby enabling management to take corrective actions. The serious consequences of noise exposure should be stressed so that the workers see the need for hearing protection and for controlling noise wherever possible. Exposure to noise levels above 110 dB should not exceed twelve minutes in an eight-hour period and continuous exposure to 85 dB

noise levels requires hearing protection. Both noise and light levels can be easily measured with relatively inexpensive hand-held meters. These are tasks that can be accomplished by the operator's health or safety departments or by supervisors who have been trained in the use of this equipment.

4.7 Toxic materials in aircraft maintenance have become more prevalent with the advent of more sophisticated aircraft that use composite materials in their structure or other hazardous substances such as tank sealants or structural bonding chemicals. Some non-destructive evaluation methods such as x-rays are also potentially hazardous. Employees should be informed of and trained on the hazards associated with handling toxic materials. They should be instructed in proper handling methods and provided with protective devices such as protective clothing, rubber gloves and goggles.

4.8 There are other hazards associated with aircraft maintenance. Chief among these is working on stands or other work platforms including movable buckets or "cherry-pickers" as they are sometimes called. As large transport aircraft structures stand several tens of feet from the ground, a slip or fall from a work platform can cause very serious injury. Makeshift work stands and carelessly positioned ladders on slippery hangar floors should be avoided at all costs. Properly designed and used work support systems will, in the long run, be cost-effective because of reduced work error and fewer worker injuries.

4.9 The above information on noise, toxic materials, work stands and platforms is a good example of where and how a Liveware and Environment (L-E) interface flaw can occur in the maintenance shop. Although it addresses maintenance technicians' health and safety considerations, it has obvious implications for aviation safety. It is evident that technicians whose performance is impaired because of lack of health and personal safety provisions will be more likely to commit error affecting the over-all safety of aircraft operation. This is of great concern because, as a general rule, the effects of human error in maintenance are manifested far displaced in time and location.

Chapter 4 Teams and Organizational Issues in Aircraft Maintenance

1 Team Work

1.1 The importance of team work in aircraft maintenance cannot be overstressed. As aircraft and their systems become more complex, a greater emphasis on technical specialties (e.g. sheet metal/structures, electrical/electronics, hydraulics) is emerging. An unfortunate parallel trend is to organize the technical specialists into distinct departments or "functional silos", which tends to inhibit team work and communication.

1.2 A great deal of effort has been expended in recent years on the study of cockpit teamwork. These studies have resulted in training programmes with the familiar name of Cockpit (or Crew) Resource Management (CRM).[1] The results of this research support the conclusion that safety is enhanced when cockpit crews function as integrated, communicating teams rather than as a collection of individuals pursuing independent courses of action. The same conclusion might be assumed in the aircraft maintenance realm. Some airlines are either planning or are already providing CRM-type training in their maintenance organizations. This training, like its cockpit counterparts, emphasizes communication, leadership, assertiveness, decision making and stress management, skills that are important to team operations. At least one airline has shown an improvement in important operating variables such as on time departures and job injuries after providing specially designed CRM training to its maintenance personnel.[2]

1.3 Another example of the benefits of a team approach to aircraft maintenance comes from the U.S. Air Force (former) Tactical Air Command. This organization originally employed a "dispatch" maintenance system where specialty technicians (e.g. hydraulic, electronics, etc.) could be dispatched to work on any of the aircraft stationed on a given base. A centralized organization called "Plans and Scheduling" directed all maintenance activity. All maintenance requests were passed to a sub-unit called "Job Control" which interpreted the requests, made decisions on who or what shop to dispatch and notified the appropriate organization to perform the work. Under this system the dispatched technician sometimes brought the wrong tools or parts or discovered on reaching the aircraft that he was the wrong technician for the job because Job Control was not tightly coupled with the system and frequently made wrong decisions. Technicians had no unit identity. They could be dispatched by Job Control to work on any of the aircraft assigned to a Wing. A team organization was not employed.

1.4 The results of this organizational scheme were apparent in a continuing decline in aircraft readiness. Units that had initially averaged 23 sorties a month per aircraft were averaging 11.5 sorties ten years later. Corrective action was clearly needed. As a first step, a team organizational structure was instituted. The 72 aircraft in a wing were assigned to three separate 24-aircraft squadrons. The maintenance technicians were divided into groups and assigned to one of the squadrons, and only those people

1. For a full discussion about CRM, refer to ICAO Human Factors Digest No. 2 — *Flight Crew Training: Cockpit Resource Management (CRM) and Line-Oriented Flight Training (LOFT)* (Circular 217).
2. Robertson, M., Taylor, J., Stelly, J. and Wagner, R. (March 1994) "Maintenance CRM Training". Assertiveness attitudes effect on maintenance performance in a matched sample. WEAAP Conference. Dublin. See also Stelly, J. and Taylor, J. (1992) "Crew Coordination Concepts for Maintenance Teams". Proceedings of the 7th International Symposium on Human Factors in Aircraft Maintenance and Inspection. Washington D.C.

assigned to a given squadron worked on their squadron's aircraft. A decentralized leadership structure was adopted with several levels of authority and responsibility. Goals and standards were established including a sortie requirement for each aircraft. The newly created maintenance teams were given the responsibility of ensuring aircraft readiness. Of course they were also provided with the required resources (parts, supplies etc.) to get their jobs done. Competition among the squadrons was fostered with sortie goals and squadron performance posted in prominent places. Technician status was boosted a number of ways. The technician was identified as a key player and not an anonymous cog in a wheel. Considerable effort was expended to establish a sense of unit identity and "ownership" in the structure of the organization.

1.5 The results were dramatic. Within a relatively short time, utilization rates improved by 43%, and aircraft readiness increased 59%. On-time departure rates increased from 75% to over 90%. These and other performance improvements show that organizational factors in the workplace can have a strong influence on aircraft maintenance. The structure of an organization can impede or facilitate productivity. Teamwork, responsibility and especially leadership are key performance factors. Leadership at the working level seems to be encouraged by a decentralized structure. Competition and team identity are also important ingredients. Allowing the technicians to participate in decision processes will help to identify them as valuable contributors and foster interest in team results. By maintaining a distinct group of technicians who know each other and know one another's capabilities, team pride and performance are encouraged. The desired results, of course, are enhanced maintenance quality and a technician workforce that enjoys its work.

1.6 Observations made in a number of international air carrier maintenance facilities seem to indicate that an organizational concept similar to the "dispatch" system once used by the U.S. Air Force is prevalent. Distinct departments or shops with separate lines of accountability and limited goals are common. Individual rather than team performance is encouraged. Adaptability in response to unusual events is very important in aircraft maintenance, but can be disrupted by poor performance in one shop or department. Lack of team identity can lead to indifferent worker attitudes with predictable results. If individual technicians conclude that diligence will be for naught because of others' poor performance, then it is likely that diligence will become more and more rare over time.

1.7 Establishment of maintenance teams should be planned; it is not enough to simply separate people into groups and label them teams. Principles of job design should be employed when creating work teams. Space limitations prevent a detailed discussion in this digest on these principles; however, Appendix 1 contains a list of recommended readings on this and other subjects. Well-designed teams can result in improvements in work performance and employee satisfaction, and poor team design can lead to effects in the opposite direction. Without proper management and regular evaluation of team performance, negative results are likely. For example, if work teams are given total autonomy on their productivity levels, then low productivity may result. Also, non-monitored groups can make poor decisions and sometimes inter-and intra-group conflicts can emerge. There may be a need to redefine goals and objectives as well as a need to exchange or replace team members for a variety of reasons as suggested above. This, of course, is a management function and well beyond the objectives of this digest for detailed consideration.

1.8 Current thinking in job design focuses on what is called the motivational approach. The intention is to create jobs that are challenging, meaningful and motivating. Employees should feel their work is important and productive. They should participate

in decisions and have input into the methods used to accomplish their jobs. Research has shown that jobs requiring mental acuity are more motivating and satisfying. The work team concept seems to fit in especially well in this regard because there is a need for continuing interaction and communication among team members which stimulates thought and innovation. There is typically a certain amount of competition among team members for the leadership role which can be a positive force enhancing team performance.

1.9 Today, many industries, ranging from heavy manufacturing, like automobile assembly, to strictly service industries such as advertising firms, are implementing work teams. There is reason to believe that the team approach can be successfully and fruitfully employed in aircraft maintenance and the previously cited U.S. Air Force example supports this belief. However, careful planning and management are required to create and maintain effective work teams. The potential payoffs of well-functioning teams are improved productivity as well as greater job satisfaction. Both of these are difficult to obtain simultaneously when dealing with individual jobs.

1.10 Some of the most important aspects to consider for work team design and management include job design, reward systems, selection and staffing, and training.[1]

2 Job Design

2.1 Proper job design can have an important effect on working productivity. While this fact has been recognized for some time, considerable research is still required to determine the optimum structure for jobs in particular occupational settings. As there are different approaches to job design, the optimum job design may require trade-offs among these approaches. Current attention is shifting from issues of the individual worker to issues focusing on work groups as a basic unit, especially in manufacturing and related industries.

2.2 One of the most important aspects of job design, based on a team concept, is to provide for self-management. To the extent possible, a team should have responsibility for its own activities, including such matters as making decisions about scheduling and employee assignments and participating in the selection of new team members. The principal responsibility of management is to provide resources so that the team operates smoothly. Participation by all team members is another aspect to be considered. There should be equal sharing of the burden and jobs should be designed so that employee interaction is required. There should also be task significance — team members should feel that their contribution is important.

2.3 Moving to a team concept in aircraft maintenance is not easy. It may also not be suitable to all maintenance organizations. However, if implemented, team design must be carefully worked out and team performance regularly observed. What works in one airline may not work well in another. Each company's culture must be considered when designing work teams. The potential for worker satisfaction and for improved output appears to be sufficiently high with well-structured teams to be worth the effort to carefully examine this concept.

1. For a complete explanation of these concepts, read Campbell, R.J. (January 1992) "Measurement of Workforce Productivity". Proceedings of the Fifth Federal Aviation Administration Meeting on Human Factors Issues in Aircraft Maintenance and Inspection — The Work Environment in Aviation Maintenance. Washington, D.C.

3 Reward Systems

Team structure should provide for interdependent feedback and rewards. There should be a mechanism to identify individual performance as well as an individual's contribution to team performance. If the only output measure available is that of the total team, the contribution of specific individuals to team performance cannot be objectively defined. In that case, some employees may not do their share of the work. If everyone's performance is assessed and related to team productivity, all members of the team then feel that they have a common responsibility and will benefit accordingly.

4 Selection and Staffing

Work teams should have membership skill diversity. For example, an aircraft maintenance team should not consist solely of powerplant or electronics specialists. The team should have a variety of the skills necessary to accomplish a number of tasks that comprise a work objective. Completion of landing gear maintenance, for example, may involve several specialties including hydraulic, electrical and rigging skills.

5 Training

5.1 Team members should be trained for their roles. This training is necessary especially for newly formed groups of people who were accustomed to working as individual technicians. The training should include methods of group decision making, development of interpersonal skills and working with other teams. Team members should also receive technical cross-training so that they can fill in for absent team members. In this way the team's productivity will not be overly impaired if a team member cannot perform.

5.2 Finally, work teams should consist of people who express a preference for team work. There are as many people who prefer to work alone as there are who like the team approach. This consideration is particularly important when and if one is attempting to establish self-managing teams. To succeed, such teams require members who are interested in the increased responsibilities accompanying team work.

Chapter 5 Automation and Advanced Technology Systems

1 Automation and Computerization

1.1 Technology in industry is increasing at a rapid pace and this is no less true in aircraft maintenance. Clearly, world-wide industry is entering an electronic era where more and more processes, operations and decisions are controlled by computers and advanced technology systems. In aircraft maintenance and inspection, a great deal of automation is currently in place but is usually somewhat removed from the technicians performing the actual work on aircraft. Generally speaking, information management is the area that has benefited most from applications of automation. All sorts of planning and reporting are now accomplished electronically. Other activities such as tool and inventory control, computer-aided design of tools and tracking of service bulletins and airworthiness directives are also done with computers, at least at the maintenance shops of the major air carriers.

1.2 Most aircraft manufacturers either have or are developing electronic versions of their maintenance manuals. In this case, rather than searching through paper pages in a manual, a technician can seek the information he needs with a tape or disc and a computer or video monitor. Some sort of artificial intelligence is incorporated in some of these systems so that by use of a few key words, the information system will automatically display the pertinent parts of the maintenance manual that may be needed by the technician for a particular maintenance assignment. More advanced versions of these systems allow the technician to use a "mouse" or a pointing device to point to desired information items on a screen-displayed menu and then, with a push of a button, gain access to the maintenance manual information.

2 Advanced Job Aid Tools

2.1 Other technologies providing automated information which may find their way into civil aircraft maintenance applications are under development. One noteworthy example is the Integrated Maintenance Information System or IMIS. This system embodies a great deal of computer-derived technology that helps technicians diagnose aircraft and system malfunctions and perform required maintenance. The system is highly portable and can be carried to the malfunctioning aircraft much like any other tool a technician might need. IMIS has a liquid crystal display (LCD) and can provide enlarged views, parts lists, technician specialties required to repair a system, sequenced test and maintenance procedures and a host of other information that, for the most part, resides in printed information such as maintenance manuals and parts catalogue. The system can even be plugged into a specialized maintenance bus on the aircraft and automatically receive information on the status of aircraft systems. This in turn can be used to provide the technician with system evaluations and required remedial actions. IMIS is a good example of a job aid that can provide strong support to maintenance technicians. One of its best features is its portability because it saves a great deal of time that would normally be spent travelling back and forth between the aircraft and information sources such as technical libraries. This time can instead be fruitfully applied to the task the technician is best equipped to perform: maintaining the aircraft.

2.2 New technology computers have become smaller and smaller and some incorporate features such as handwriting recognition. This latter capability could be particularly useful in filling out the numerous reports and forms that are required in aircraft maintenance. By some estimates, technicians spend 25% of their time on paperwork, time that could be better spent on aircraft maintenance. If such a system had been in place and available to the technicians working on the EMB-120 aircraft discussed earlier, the accident might possibly have been prevented because work performed and work yet to be accomplished would have been filed properly and on time, making it clear to the incoming shift what work still needed to be completed. By automating the filing process to the extent possible and further automating the information filing activity into larger computer storage facilities, recording errors can be avoided, and great savings in clerical manpower can be obtained. Funds that are currently spent on these ancillary maintenance tasks could be devoted to actions that would have more direct safety pay-offs such as providing further training. Furthermore, aircraft maintenance technicians would have more time to perform their tasks, leading to a less hurried, and hence less error-prone, work environment.

2.3 Recently developed "pen" computers seem to be ideally suited for these tasks. The "pen" is actually a stylus which can be used to write on the computer screen. The stylus can also be used to select items from screen-displayed menus, thus permitting the technician to quickly zero in on stored information required for maintenance. The pen computer, not much larger than this digest, can be used in conjunction with storage media such as compact discs to store and provide access to an enormous volume of information. The entire maintenance manual for an aircraft and additional information such as airworthiness directives, service bulletins, job cards and specialized inspection procedures can be quickly made available to the aircraft maintenance technician next to the aircraft. When the technician has completed the maintenance job, he can call up the required forms to document his work, filling them out on the screen with the stylus or an integral keyboard on the computer, and can store this information or dump it directly onto a mainframe computer. The automation technology needed to perform these kinds of activities exists today and is currently being tested. There is little question that this type of job-aiding automation, which is neither overly complex or expensive, will find its way into the aircraft maintenance workplace in due course. The training, experience and technical talent needed at present to carry out the tasks of an aircraft maintenance technician are more than sufficient to successfully use these automated job aids. It is reasonable therefore to expect this type of automation in aircraft maintenance to be implemented globally.

2.4 Introducing further and advanced automation in aircraft maintenance, it should be noted that automation, unless designed with the capabilities and limitations of the human operators in mind, can be a source of a different set of problems hindering rather than assisting the aircraft maintenance technician. Inevitably, such automation cannot serve the interests of safety or efficiency in aircraft maintenance. For this reason, it is appropriate to recognize that automation devices designed and manufactured to assist a human operator must of necessity be designed in accordance with the principles of human-centred automation.[1] Such a consideration will help ensure that advanced automated aids will serve the purpose they are designed for, without creating an overwhelming set of new and additional problems for the maintenance organization.

1. For a detailed presentation on *human-centred automation,* see ICAO Human Factors Digest No. 11 — *Human Factors in CNS/ATM Systems* (Circular 249).

2.5 Other automated job aids are found on new transport aircraft. These systems have the capability to assess the status of on-board equipment such as engines and electronic systems. When an in-flight equipment malfunction is encountered on these aircraft, the information (problem) is automatically stored and telemetered to the aircraft maintenance base without any input from the flight crew. On landing, aircraft maintenance technicians can be standing by with required spare parts to quickly remedy the problem and get the aircraft back into service. Obviously, not every device or system on the aircraft can be evaluated this way, but a great deal of diagnostic or test time can be saved when major systems malfunction on aircraft which have such built-in test equipment (BITE). The major safety pay-off of such a system is that maintenance problems are identified and corrected early in their development stage, thus relegating the solving of maintenance problems through trial and error to the history books. One of the big advantages of BITE is that aircraft system malfunctions are identified at a very early stage before they become a threat to the safety of the aircraft and its occupants. Another advantage is that flight crew members may be advised of and consulted on a developing maintenance problem, thus enhancing their decision-making capabilities to ensure the continued safe operation of the aircraft based on actual and timely facts.

2.6 The technician's task is complex and varied and is performed at several different physical locations. Actual maintenance activity involves frequent access to confined or difficult-to-reach spaces and a broad range of manipulation of tools, test equipment and other devices. Maintenance work differs from that of pilots or air traffic controllers who perform more predictable activities at a single workstation, either a cockpit or an ATC console. Because of these differences it would be very difficult, if not impossible, to automate much of the work of the aircraft maintenance technician. Rather, most automation related to maintenance tasks will likely consist of improvements in diagnostic support systems. Closely allied with these job-aiding systems are computer-based training systems which were discussed in Chapter 4.

2.7 This chapter presented a summary on automation and advanced job aid tools currently or soon to be available to assist aircraft maintenance technicians in accomplishing their tasks. There are other concepts under development at this time such as automated devices that will traverse an aircraft's external structure and inspect it for cracks, corrosion, damaged rivets and other flaws, significantly assisting the work of an inspector. Other ideas under study involve automation of human expertise. A large percentage of the airline maintenance workforce in the United States is now or will soon be ready to retire. This group has a tremendous body of knowledge on aircraft maintenance and inspection methods that will be lost when these individuals retire from the active workforce. If this expertise can somehow be captured, properly arranged and provided to the junior, less experienced workforce, then aircraft safety, at least from the maintenance experience point of view, will be retained and enhanced and great savings in cost and time will be realized. Some airlines are already working on this concept.

Chapter 6 Error Prevention Considerations and Strategies

1.1 It has often been advanced that no accident, however obvious its causal factors seem to be, ever happens in isolation. Analysis emanating from broadened perspectives that focus on safety deficiencies in systems rather than on individuals has allowed the identification of deficiencies at several stages of the aviation system. The aircraft maintenance shop is such an organization where focusing on system deficiencies rather than on individual errors would, in time, significantly minimize occurrences resulting from human error in maintenance. Considering the potential for failures and other shortcomings, human error in aircraft maintenance has been remarkably managed. Lessons learned over the past ninety years of aviation have rapidly made their way into the methods of aircraft and maintenance systems design. However, from the occasional occurrences, there appears to be significant potential for improvement.

1.2 The complexity of maintenance error can range from errors as simple as a single aircraft maintenance technician forgetting to torque a finger-tightened screw to errors that cause a system-wide failure as in the accident investigations discussed in Chapter 2. In the cases of a significant breakdown of the maintenance system, not only was the primary maintenance task misperformed but many levels of defence (such as those which are discussed in the Reason Model) had to be penetrated in order for the error-tolerant maintenance system to break down so significantly.

1.3 In between these two extremes are the systematic errors that can be more readily traced back to some deficiency in the design of the aircraft or the management of the maintenance process. The maintenance community has become adept at dealing with these errors through redesign and process change. For example, units such as gauges, communication and navigation units, etc., which do not require taking the aircraft to the maintenance hangar for replacement (line replaceable units), are currently being designed with different size or shape electrical and fluid connectors so that cross-connection errors upon reassembly are eliminated. On the operational side, several aircraft maintenance departments have established sophisticated systems to ensure that work started on one shift is properly turned over to the next shift.

1.4 Errors, such as nuts and bolts not torqued, lockwire not installed and access panel not secured, continue to frustrate designers and maintenance managers because they are associated with such simple pieces of equipment that redesign of the equipment or maintenance system seems impractical, if not impossible. These errors may not always be life-threatening; however, their operational and economic impact continues to be very significant. An example of such an error is when a maintenance technician forgets to torque a screw or nut that he has installed finger-tight. What appropriate change can be introduced, in the way aircraft maintenance is performed to prevent such an error from occurring or to help reduce the error rate? Remove all nuts and screws from the aircraft? Require duplicate torquing for all nuts and screws on the aircraft? Regardless of the economic environment faced by manufacturers or commercial airlines, neither of these changes would have much chance of implementation. These errors are not so much the result of system deficiencies, but more a reflection of inherent limitations in the technology of both aircraft design and maintenance systems. Theoretically, to reduce removal and installation errors, aircraft would need to be designed with just a few components, rather than the three to four million parts currently found in large commercial jet transport. However, today's

technology requires the use of nuts and lockwire on aircraft. As a result, sooner or later, due to improper execution of a maintenance task, each of these parts will inadvertently be left off a departing aircraft.[1]

1.5 Graeber and Marx suggest that, in order to take the next significant step in maintenance error reduction, three issues should be addressed:[2]

1.5.1 **Maintenance data should be organized in a form that will allow study of the human performance aspects of maintenance:**

1.5.1.1 Much of the work in the theory of human error revolves around the classification of error. For the cognitive psychologist, there are many classification schemes from slip/lapse/mistake, to errors of commission and omission, to skill-based, rule-based and knowledge-based errors, to systematic and random errors. Each of these classification schemes is applicable to errors in any context, including aircraft maintenance. While these classifications impart order to what otherwise could appear as meaningless errors, they have, for the most part, not been used within the aircraft maintenance community. The problem for those in the "real world" of maintenance is that establishing the type of error provides little practical help in determining the underlying cause.[3] Unless the relevance between theoretical error classifications and the real-world management of maintenance error is made obvious, the distinction between slips, lapses and mistakes is of little help to the maintenance community.

1.5.1.2 Another approach to error classification which has been embraced by the aviation industry is to focus on cause or contributing factors. This is how the industry arrived at the statistics showing the high percentage of accidents attributable to human error in the flight deck. While appropriate for equipment failure, this approach has significant limitations when applied to human error. In 1991, Boeing conducted a study of maintenance-related accidents occurring during the previous ten years. After reviewing available data, analysts assigned contributing factors to the accident under each of the seven broad categories of performance-shaping factors listed below:

- tasks and procedures;
- training and qualification;
- environment/workplace;
- communication;
- tools and test equipment;
- aircraft design; and
- organization and management.

1.5.1.3 In an attempt to guard against the temptation to place blame, the maintenance technician was deliberately excluded from these categories. The over-all result, however, was a subjective list of causes placed under one or more of the seven performance-shaping categories. Consequently, placing "blame" emerged as one of the undesirable, and unavoidable, aspects of each accident. Two significant issues emerged from this analysis:

a) Can particular biases that analysts are likely to bring to an investigation due to experience, training or expertise be controlled? For example, would a maintenance

1. From Marx, D.A. and Graeber, C.R. (1994) *Human Error in Aircraft Maintenance*. In McDonald, N., Johnston, N., and Fuller, R. (Eds.), *Aviation Psychology in Practice*. Aldershot — Ashgate Press.
2. Ibid.
3. Barnett, M.L. (1987) *Factors in the Investigation of Human Error in Accident Causation*. College of Maritime Studies. Warsash, Southampton, United Kingdom.

instructor be more likely to identify training as a deficiency in a particular accident or incident?

b) Would the maintenance community embrace a study that relies heavily on subjective assessment?

1.5.1.4 Both of these questions point to the need for improved human performance data collection and investigation techniques that provide an observable framework, minimize the need for subjective assessments and are understood and endorsed by aircraft designers and maintenance managers.

1.5.1.5 The answer to the first question has been extensively discussed in ICAO Human Factors Digest No. 7 — Investigation of Human Factors in Accidents and Incidents (Circular 240) and Digest No. 10 — Human Factors, Management and Organization (Circular 247). It often seems that investigations into human performance simply trace error back to the careless and unprofessional work habits of the individual involved. Traditionally during investigation of accidents, backtracking occurs until all conditions pertinent to the accident are explained by abnormal but familiar events or acts. If an aircraft component fails, a component fault will be accepted as the prime cause if the failure mechanism appears "as usual". Human error is familiar to the investigator: to err is human. Therefore, the investigation quite often stops once the person who erred is identified.

1.5.1.6 Digest No. 7 proposes an approach to improve our human performance investigations and to eliminate these premature judgements against the human operator. While not attempting to discount individual responsibility regarding mishaps, the approach advanced by Digest No. 7, and furthered by Digest No. 10, suggests that system safety is best served if attention is focused on those elements within the system that are manageable. What is going on inside the heads of the maintenance workforce — as well as other operational personnel — is often the hardest factor to manage. Thus, to conduct analyses that will help improve the system, attributes of maintenance error that do not simply point to the maintenance technician involved and do not require subjective assessments of deficiency must be investigated. Factual threads among accidents, incidents and events that will allow members of the maintenance community to work together must be researched to improve the over-all margin of safety standards of the whole system.

1.5.1.7 The UK CAA study discussed in Chapter 2, listing the top seven maintenance problems in order of occurrence, represents an approach that relates to the maintenance process or behavioral task rather than to the actual human error or causal factor. At the highest level of maintenance processes, for example, we may identify errors associated with:

- equipment removal;
- equipment installation;
- inspection;
- fault isolation/troubleshooting;
- repair; and
- servicing.

1.5.1.8 Classifications of maintenance error based upon the process or task involved can provide tangible near-term benefits. For example, the Aloha Boeing 737 structural failure in 1987 led to heightened awareness of the Human Factors associated with visual structural inspection.[1] As a result, the United States Federal Aviation Administration has spent a significant portion of its maintenance Human Factors research funding on visual inspection issues.

1.5.1.9 A more in-depth analysis of this approach for analysing and classifying human error in aircraft engine troubleshooting has proved beneficial to the design of maintenance training systems.[2] In the case of the Aloha Boeing 737 accident, the errors were classified according to information-processing steps within a particular task of troubleshooting. The basic categories were observation of system state, choice of hypotheses, choice of procedures and execution of procedures.

1.5.1.10 This process of behaviourally oriented classification avoids the pitfalls associated with the cause or contributing factors approach discussed earlier. There is less "blame" placed within this classification scheme as compared to the previous approaches discussed. Rather than reacting defensively, most people will view this type of analysis as generating simple facts, pointing the way for improvements within the process.

1.5.1.11 In addition to error classification, prevention strategies can also be classified. Classification of error prevention strategies in maintenance is important because it helps to increase the visibility of tools that may be utilized by manufacturers and maintenance managers in the management of human error in maintenance. Three classes of strategies to manage human error in the maintenance of aircraft are proposed. Each of these classes is defined in terms of its method for controlling error:

a) **Error reduction.** Error reduction strategies are intended to intervene directly at the source of the error itself. Examples of error reduction strategies include improving access to a part, improving the lighting in which a task is performed and providing better training to the maintenance technician. Most error management strategies used in aircraft maintenance fall into this category.

b) **Error capturing.** Error capturing assumes the error is made. It attempts to "capture" the error before the aircraft departs. Examples of error-capturing strategies include post-task inspection, verification steps within a task and post-task functional and operational tests.

c) **Error tolerance.** Error tolerance refers to the ability of a system to accept an error without catastrophic (or even serious) consequences. In the case of aircraft maintenance, error tolerance can refer to both the design of the aircraft itself as well as the design of the maintenance system. Examples of error tolerance include the incorporation of multiple hydraulic or electrical systems on the aircraft (so that a single human error can only take out one system) and a structural inspection programme that allows for multiple opportunities to catch a fatigue crack before it reaches critical length.

1.5.1.12 Of the three classes of prevention strategies, only error reduction addresses the error directly. Error-capturing and error tolerance strategies are directly associated with system integrity. From a system safety perspective, human error in maintenance does not directly or immediately cause an aircraft to be unsafe. Until maintenance technicians are working on aircraft in-flight, this will always be the case. It is the

1. National Transportation Safety Board (1989) "Aircraft Accident Report, Aloha Airlines Flight 243", Boeing 737-200, N73711, Near Maui, Hawaii, April 28, 1988 (NTSB/AAR-89/03). Washington, D.C.
2. Johnson, W.B. and Rouse, W.B. (1982) *Analysis and Classification of Human Errors in Troubleshooting Live Aircraft Power Plants*. IEEE. Transactions on Systems, Man and Cybernetics.

aircraft being dispatched with a maintenance-induced problem that is cause for concern.

1.5.2 **The gap between the maintenance community and psychology as it applies to aviation should be narrowed:**

1.5.2.1 Over the past fifteen years, the pilot community and psychologists working in the industry have spoken an increasingly common language. Significant Human Factors work related to the flight deck has been accomplished through the interdisciplinary teaming of pilots, engineers and psychologists. Concepts such as mode error and Crew Resource Management have become common ground on which psychologists and the operational community can work together to improve system safety.

1.5.2.2 With few exceptions, however, aircraft designers, manufacturers, maintenance technicians and psychologists are still worlds apart. Looking at the L-1011 chip detector example, the question to be asked is whether psychologists would have been able to identify better intervention strategies than those undertaken by the operator. Human Factors Digests No. 7 and No. 10 point out that much of the Human Factors effort to date, especially in aviation, has been directed at improving the immediate human-system interface. Error reduction has been at the heart of Human Factors activities. The chip detector mishap, though, was just one of the everyday errors that involve relatively simple components of the aircraft that have little chance of being changed. Digests No. 7 and No. 10 contend that the most productive strategy for dealing with active errors is to focus on controlling their consequences rather than striving for their elimination.

1.5.2.3 In pursuit of reducing maintenance-caused accidents, psychologists must move beyond the individual human-machine interface issues to a collective systems analysis approach. For example, there are two major steps within error analysis. The first step, "contributing factors analysis", is concerned with understanding why the error occurred. For example, identifying why the aircraft maintenance technician forgot to torque the bolt he finger-tightened can be studied from a conventional behavioural/cognitive psychology perspective. The second major step, "intervention strategies analysis", is concerned with identifying the aircraft or maintenance system changes that should occur to effectively address the maintenance error.

1.5.2.4 Developing the strategies to address future occurrences of maintenance error requires skills that often extend beyond the Human Factors engineer or psychologist. To develop specific intervention strategies requires an understanding of system constraints, criticality of the error and its resulting discrepancy, as well as error management practices unique to aircraft maintenance.

1.5.3 **Methods and tools should be developed to help aircraft designers and maintenance managers address the issue of human error in a more analytical manner:**

1.5.3.1 Since the beginning of aviation, the maintenance community has continuously contributed to the improvement of the safety and effectiveness of flight operations. This has largely been accomplished without assistance from "foreign" disciplines, such as psychology. The design of the human interface of a sophisticated on-board maintenance system is a task that requires greater analytical skills and knowledge about human cognitive performance than those acquired through years of experience as a maintenance engineer. However, as Human Factors practitioners increase their involvement in maintenance error analysis, the fact that the bulk of error analysis and management today, as it will be in the future, is performed by aircraft designers, manual designers, maintenance trainers and maintenance managers must not be lost. Thus, the maintenance community must look to sources of external,

interdisciplinary support as a resource to help understand the inherent capabilities and limitations of the aircraft maintenance technician. As a resource, external sources should focus on the development of sound methods and tools that can be transferred to the design and operational environments. Through better methods and tools, the goal of improved error management will be achieved in a more rapid and systematic manner.

1.5.3.2 The investigation of Human Factors in accidents has clearly shown that addressing systemic or organizational shortcomings (latent failures) rather than individual errors (active failures) will positively contribute to significantly minimizing human error occurrences. Appreciation of this finding has led many safety organizations to pay increasing attention to organizational and cultural factors, both as accident-causal and accident-preventive factors. Better understanding of these factors will lead to a better understanding of human error in the organizational context. Human Factors Digest No. 10 maintains that knowledge gained in the understanding of management and organizational factors, both as causal and preventive factors, can be successfully used to face the challenges of the future in minimizing human error in the air transport industry.

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