8 Human Error in Aviation Maintenance

8.1 INTRODUCTION

Maintenance is an important element of the aviation industry worldwide, and in 1989 U.S. airlines spent around 12% of their operating costs on the maintenance activity [1, 2]. During the period from 1980 to 1988, the cost of airline maintenance increased from about $2.9 billion to $5.7 billion [3]. This increase is attributable to factors such as increase in air traffic and increased maintenance for continuing airworthiness of aging aircraft.

Needless to say, increase in air traffic and increased demands on aircraft utilization because of the stringent requirements of commercial schedules continue to put significant pressures on the maintenance activity for on-time performance. In turn, this has increased chances for the occurrence of human errors in aircraft maintenance operations [4]. A study conducted in the United Kingdom reported that the occurrence of maintenance error events per million flights has doubled during the period from 1990 to 2000 [5]. This clearly indicates that there is a need to eliminate or minimize the occurrence of such error events for reliable and safe flights.

This chapter presents various importance aspects of human error in aviation maintenance.

8.2 FACTS, FIGURES, AND EXAMPLES

Some of the facts, figures, and examples directly or indirectly concerned with the occurrence of human error in aviation maintenance are as follows:

- A study revealed that approximately 18% of all aircraft accidents are maintenance related [6, 7].
- As per Ref. [8] maintenance error contributes to 15% of air carrier accidents and costs the United States industry over $1 billion dollars annually.
- According to a Boeing study 19.1% of in-flight engine shutdowns are caused by maintenance error [8].
- A study reported that maintenance and inspection are the factor in approximately 12% of major aircraft accidents [9, 10].
- A study of 122 maintenance errors occurring in a major airline over a period of three years revealed that their breakdowns were: omission (56%), wrong installations (30%), incorrect parts (8%), and other (6%) [11, 12].

- An analysis of safety issues versus onboard fatalities among jet fleets worldwide during the period 1982–1991 identified maintenance and inspection as the second most important safety issue with onboard fatalities [13, 14].
- In 1979, 272 people were killed in a DC-10 aircraft accident due to improper maintenance procedures followed by maintenance personnel [15].
- In 1991, 13 people were killed in an Embraer 120 aircraft accident due to a human error during scheduled maintenance [4, 5].
- In 1988, the upper cabin structure of a Boeing 737-200 aircraft was ripped away during a flight because of structural failure, basically due to the failure of maintenance inspectors to identify over 240 cracks in the aircraft skin during the inspection process [5, 16].

8.3 CAUSES OF HUMAN ERROR IN AVIATION MAINTENANCE AND MAJOR CATEGORIES OF HUMAN ERRORS IN AVIATION MAINTENANCE AND INSPECTION TASKS

There are many factors that can impact performance of aviation maintenance personnel. Over 300 such factors/influences are listed in a document prepared by the International Civil Aviation Organization [17]. These factors/influences range from boredom to temperature. Some of the important reasons, directly or indirectly, for the occurrence of human error in aviation maintenance are time pressure; inadequate training, work tools, and experience; complex maintenance tasks, poorly written maintenance procedures, poor equipment design, outdated maintenance manuals, poor work layout, fatigued maintenance personnel, and poor work environment (e.g., temperature, humidity, lighting) [15,18].

There are many major categories of human errors in aviation maintenance and inspection-related tasks. Eight of these categories are incorrect assembly sequence (e.g., incorrect sequence of inner cylinder spacer and lock ring assembly), procedural defects (e.g., nose landing gear door not closed), wrong part (e.g., incorrect pitot-static probes installed), incorrect configuration (e.g., valve inserted in backward direction), missing part (e.g., bolt-nut not secured), defective part (e.g., worn cables, fluid leakage, cracked pylon, etc.), functional defects (e.g., wrong tire pressure), and tactile defects (e.g., seat not locking in correct position) [12, 19, 20].

8.4 TYPES OF HUMAN ERROR IN AIRCRAFT MAINTENANCE AND THEIR FREQUENCY

In 1994, a Boeing study examined a total of 86 aircraft incident reports with respect to maintenance error and reported 31 types of maintenance errors. These types, along with their frequency in parentheses, are: system operated in unsafe conditions (16), system not made safe (10), equipment failure (10), towing event (10), falls and spontaneous actions (6), degradation not discovered (6), person entered dangerous zones (5), unfinished installation (5), work not documented (5), did not obtain or use appropriate equipment (4), person contacted hazard (4), unserviceable equipment used (4), equipment not activated/deactivated (4), no appropriate verbal warning given (3), safety lock or warning moved (2), pin/tie left in place (2), not tested appropriately (2), equipment/vehicle contacted aircraft (2), warning sign or tag not used (2), vehicle driving instead of towing (2), wrong fluid type (1), access panel not closed (1), wrong panel installation (1), material left in engine/aircraft (1), incorrect orientation (1), equipment not installed (1), contamination of open system (1), wrong component/equipment installed (1), unable to access part or component in stores (1), necessary servicing not performed (1), and miscellaneous (6) [21].

8.5 COMMON HUMAN ERRORS IN AIRCRAFT MAINTENANCE ACTIVITIES

Over the years various studies have identified commonly occurring human errors in aircraft maintenance activities. One of these studies conducted by the United Kingdom Civilian Aviation Authority (UKCAA) over a period of three years has identified a total of eight commonly occurring human errors in aircraft maintenance, as shown in Figure 8.1 [12, 22].

8.6 AIRCRAFT MAINTENANCE ERROR ANALYSIS METHODS

Over the years, many methods have been developed in reliability and its associated areas that can be used to perform human error analysis in the area of aircraft maintenance. Three of these methods are presented below.

8.6.1 Cause-and-Effect Diagram

This diagram was developed by a Japanese man named K. Ishikawa in the early 1950s. It is also referred to in the published literature as an Ishikawa diagram or a

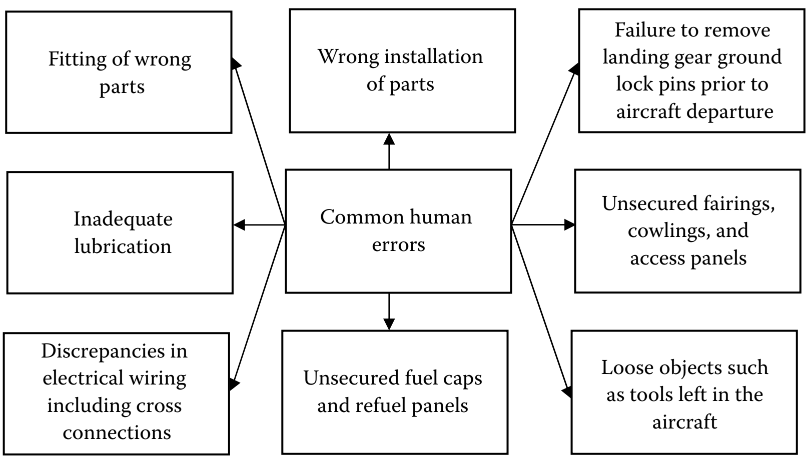

FIGURE 8.1 Commonly occurring human errors in aircraft maintenance.

fishbone diagram. The diagram can be a useful tool to determine the root causes of a specified aircraft maintenance error and generate appropriate relevant ideas.

Pictorially, the box on the extreme right-hand side of the diagram represents effect and the left-hand side represents all the possible causes that are connected to the centerline. In turn, usually each cause is composed of various subcauses. Usually, the following five steps are followed to develop a cause-and-effect diagram [8]:

- **Step 1:** Develop problem statement.
- **Step 2:** Brainstorm to identify possible causes.
- **Step 3:** Establish major cause categories by stratifying into natural groupings and process steps.
- **Step 4:** Develop the diagram by connecting all the causes by following the appropriate process steps and fill in the effect (i.e., the problem) in box on the right hand side of the diagram.
- **Step 5:** Refine cause categories/classifications by asking questions such as what causes this? And why does this condition exist?

There are many benefits of the cause-and-effect diagram. Some of the important ones are as follows:

- An effective tool for generating ideas
- An effective approach to present an orderly arrangement of theories
- A useful tool to identify root causes
- A useful approach for guiding further inquiry

Example 8.1

A study of aircraft maintenance facility reported the following six causes for the occurrence of human error in maintenance:

- Poor work environment
- Time pressure
- Complex maintenance tasks
- Poor equipment design
- Poor work layout
- Inadequate tools

Three subcauses of the cause "poor work environment" are temperature, humidity, and lighting. Draw a cause-and-effect diagram for the effect: human error in aircraft maintenance.

The cause-and-effect diagram for the example is shown in Figure 8.2.

8.6.2 Error-Cause Removal Program (ECRP)

This method was originally developed to reduce the occurrence of human error to some tolerable level in production operations [24]. It can also be used to reduce

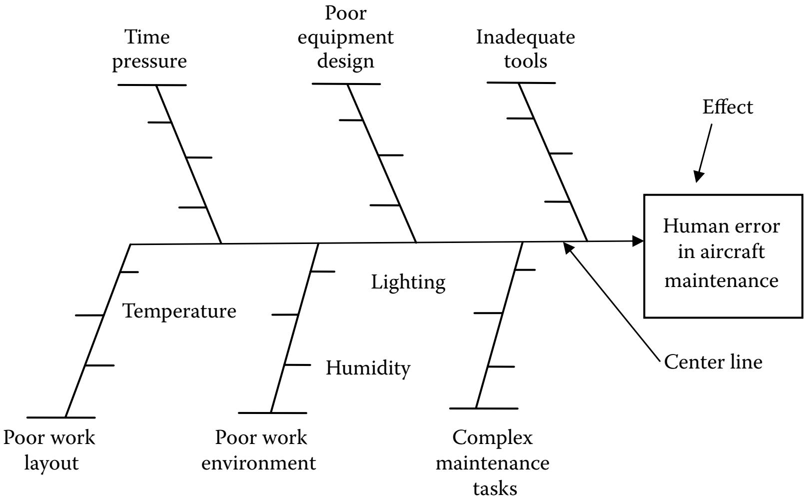

FIGURE 8.2 Cause-and-effect diagram for the occurrence of human error in aircraft maintenance.

human error in aircraft maintenance operations. The emphasis of this method is on preventive measures rather than merely on remedial ones. In terms of aircraft maintenance, ECRP may simply be described as the maintenance worker-participation program for reducing the occurrence of human errors.

More specifically, the ECRP is composed of teams of workers (e.g., aircraft maintenance workers) with each team having its own coordinator, who has special technical and group-related skills. Workers present their error and error-likely reports during team meetings held periodically. After appropriate discussions on these reports, recommendations are made for preventive or remedial measures. Team coordinators present the recommendations to management for appropriate actions.

The seven basic elements of the ECRP are as follows [24]:

- All people involved with the ECRP are educated about the usefulness of the ECRP.
- All maintenance workers and team coordinators are trained in data collection and analysis approaches.
- The efforts of the aircraft maintenance workers in regard to ECRP are recognized appropriately by the management.
- Human factors and other specialists determine the effects of changes made in, say, aircraft maintenance operations with the aid of the ECRP inputs.
- The most promising proposed solutions are fully implemented by the management.
- All proposed solutions are evaluated with respect to cost by various specialists including human factors specialists.
- Aircraft maintenance workers report and evaluate errors and error-likely conditions, in addition to proposing solutions to eradicate error causes.

Finally, three of the important guidelines concerning ECRP are as follows:

- Focus on data collection on items such as error-likely conditions, accident-prone conditions, and errors.
- Evaluate each work redesign recommended by the team with respect to factors such as increments in cost-effectiveness and job satisfaction, and the degree of error redaction.
- Restrict to the identification of work situations that require redesign for reducing the error occurrence potential.

8.6.3 Fault Tree Analysis

This is a powerful and flexible method often used in industry to perform various types of reliability-related analysis. The method is described in Chapter 4 and in Refs. [18, 20]. Its application to perform human error analysis in aviation maintenance is demonstrated through the example presented below.

Example 8.2

Assume that the subcauses of the cause "poor work environment" in Example 8.1 are poor lighting, high/low temperature, and distractions. Similarly, the subcauses of the cause "poor equipment design" are poorly written design specification, no formal consideration given to the occurrence of maintenance error in design specification, and misinterpretation of design specification.

Develop a fault tree for Example 8.1, for top event "Human error in aircraft maintenance" by considering the above subcauses and using fault tree symbols given in Chapter 4.

A fault tree for the example is shown in Figure 8.3.

Example 8.3

Assume that the probability of occurrence of events in the circles (i.e., $X_1, X_2, X_3, \ldots, X_8$) shown in Figure 8.3 is 0.02. For independent events, calculate the probability of occurrence of the top event T (i.e., human error in aircraft maintenance), and intermediate events I_1, (i.e., poor equipment design) and I_2 (i.e., poor environment).

Using Chapter 4 and Refs. [18, 20], and the specified data values, we obtain the values of I_1, I_2, and T as follows:

The probability of occurrence of intermediate event I_1 is given by

$$\begin{aligned} P(I_1) &= 1-\{1-P(X_1)\}\{1-P(X_2)\}\{1-P(X_3)\} \\ &= 1-\{1-0.02\}\{1-0.02\}\{1-0.02\} \\ &= 0.0588 \end{aligned}$$

where $P(I_1)$, $P(X_1)$, $P(X_2)$, and $P(X_3)$ are the probabilities of occurrence of events I_1, X_1, X_2, and X_3, respectively.

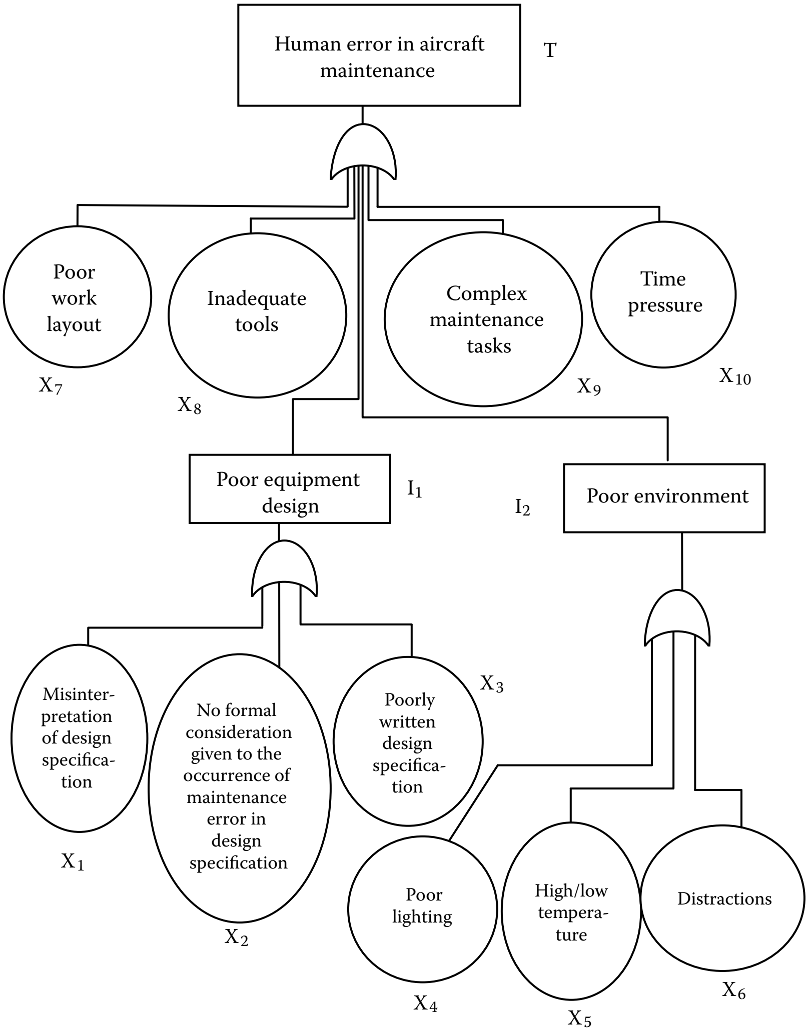

FIGURE 8.3 Fault tree for Example 8.2.

The probability of occurrence of intermediate event I_2 is expressed by

$$\begin{aligned} P(I_2) &= 1 - \{1 - P(X_4)\}\{1 - P(X_5)\}\{1 - P(X_6)\} \\ &= 1 - \{1 - 0.02\}\{1 - 0.02\}\{1 - 0.02\} \\ &= 0.0588 \end{aligned}$$

where $P(I_2)$, $P(X_4)$, $P(X_5)$, and $P(X_6)$ are the probabilities of occurrence of events I_2, X_4, X_5, and X_6, respectively.

By using the above specified and calculated values, Chapter 4, and Refs. [18, 20] we obtain

$$\begin{aligned} P(T) &= 1-\{1-P(X_7)\}\{1-P(X_8)\}\{1-P(X_9)\}\{1-P(X_{10})\}\{1-P(I_1)\}\{1-P(I_2)\} \\ &= 1-\{1-0.02\}\{1-0.02\}\{1-0.02\}\{1-0.02\}\{1-0.0588\}\{1-0.0588\} \\ &= 0.1829 \end{aligned}$$

where $P(T)$ is the probability of occurrence of event T.

Thus, the probabilities of occurrence of the top event T (i.e., human error in aircraft maintenance), intermediate event I_1 (i.e., poor equipment design), and intermediate event I_2 (i.e., poor environment) are 0.1829, 0.0588, and 0.0588, respectively.

8.7 MAINTENANCE ERROR DECISION AID (MEDA)

This important tool to investigate contributing factors to maintenance errors in aviation was developed by Boeing, along with industry partners such as Continental Airlines and United Airlines, in the 1990s [25–27]. MEDA may simply be described as a structured process for investigating the causes of human errors made by aircraft maintenance personnel. The philosophy of the process is shown in Figure 8.4 [26].

Four main objectives of the MEDA are as follows [27]:

- To highlight aircraft maintenance system-related problems that increase exposure to human error and decrease efficiency
- To provide the aircraft maintenance organization a better understanding of how human-performance-associated issues contribute to the occurrence of human error
- To provide the line-level aircraft maintenance personnel a standardized mechanism to investigate the occurrence of maintenance errors
- To provide an appropriate means of human error trend analysis for the aircraft maintenance organization

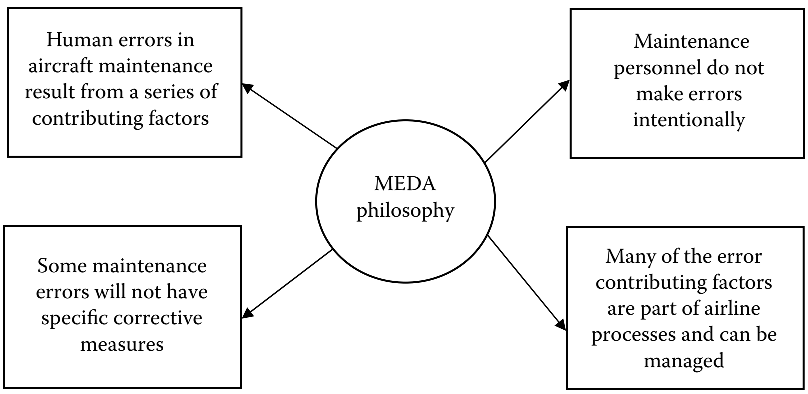

FIGURE 8.4 The philosophy of MEDA.

All in all, MEDA provides people associated with the aircraft maintenance activity a basic five-step process to follow: event, decision, investigation, prevention strategies, and feedback [25]. Additional information on these steps and on MEDA is available in Refs. [25–27].

8.8 USEFUL GUIDELINES FOR REDUCING HUMAN ERROR IN AIRCRAFT MAINTENANCE ACTIVITIES

Over the years, various guidelines have been developed for reducing human error in aircraft maintenance activities. These guidelines cover many areas as shown in Figure 8.5 [14, 20]. Two important guidelines concerning the area of design are as follows:

- Actively seek relevant information on human error occurrence during the maintenance phase, for providing effective inputs in the design phase.
- Ensure that equipment manufacturers give proper attention to maintenance-related human factors during the design phase.

Two guidelines in the area of tools and equipment are as follows:

- Review systems by which items such as lighting systems and stands are kept for removing unserviceable equipment from service and repairing it rapidly.
- Ensure the storage of all lockout devices in such a manner that it becomes immediately apparent when they are left in place inadvertently.

Some of the guidelines concerning risk management are to avoid performing simultaneously the same maintenance task on similar redundant units, review formally the effectiveness of defenses, such as engine runs, built into the system for detecting maintenance errors, and review the need to disturb normally operating systems to carry out rather nonessential periodic maintenance, because the disturbance may lead to a maintenance error.

A useful guideline in the area of communication is to ensure that proper systems are in place to disseminate important pieces of information to all individuals concerned with maintenance, so that repeated errors or changing procedures are considered with care.

Two particular guidelines in the area of training are as follows:

- Provide on a periodic basis training courses to all maintenance personnel with emphasis on company procedures.
- Consider introducing crew resourcement for personnel involved with the maintenance activity.

Some of the useful guidelines concerned with procedures are ensuring that standard work practices are being followed throughout aircraft maintenance operations,

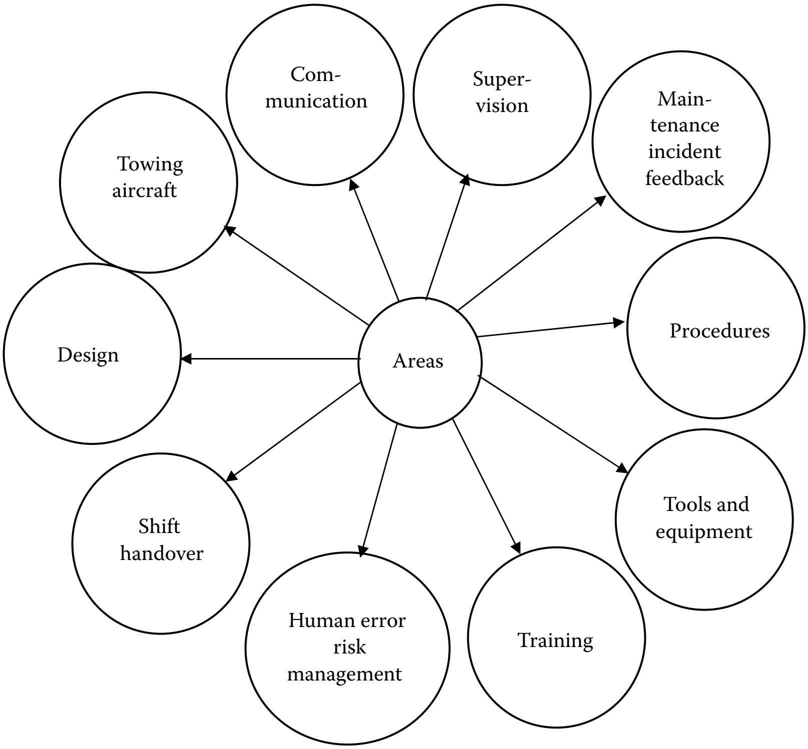

FIGURE 8.5 Areas covered by guidelines for reducing human error in aircraft maintenance activities.

reviewing maintenance work practices regularly to ensure that they do not vary significantly from formal procedures, and reviewing all documented maintenance procedures and practices periodically with respect to items such as accessibility, consistency, and realism.

A useful guideline in the area of supervision is to recognize that management and supervision-related oversights must be strengthened, particularly in the final hours of all shifts, as the occurrence of errors becomes more likely. Two particular guidelines pertaining to maintenance incident feedback are as follows:

- Ensure that all individuals associated with the training activity are provided proper feedback on the occurrence of human factors–related maintenance incidents regularly, so that appropriate corrective actions aimed at these problems are taken effectively.
- Ensure that all management personnel are given effective feedback on the occurrence of human factors–related maintenance incidents regularly, with proper consideration to the conditions that play an instrumental role in the occurrence of such incidents.

A guideline pertaining to the area of towing aircraft is to review the equipment and procedures used for towing to and from maintenance facilities on a regular basis. Finally, one particular guideline concerning shift handover is to ensure the effectiveness of practices associated with shift handover by considering factors such as communication and documentation, so that incomplete tasks are transferred correctly across all shifts.

8.9 CASE STUDIES IN HUMAN ERROR IN AVIATION MAINTENANCE

Over the years, many aircraft accidents directly or indirectly due to maintenance error have occurred throughout the world. Three such accidents are briefly described below.

8.9.1 Continental Express Embraer 120 Accident

This accident occurred on September 11, 1991, when a Continental Express Embraer 120 aircraft crashed in Texas, killing all persons on board, because the leading edge of the left horizontal stabilizer separated from the aircraft [1, 20, 28]. An investigation into the accident reported that the night prior to the accident some maintenance work, involving the removal of a screw from the upper left surface of the "T-tail" of the aircraft, was carried out. When the shift change occurred, the maintenance work was only partially accomplished and it was not documented at all.

The maintenance personnel of the incoming shift, being totally unaware of the partial accomplishment of the maintenance work, signed the Embraer 120 back into service. The National Transportation Safety Board (NTSB), in its final report on the accident, identified poor maintenance practices within the airline organization [29]. Additional information on the accident is available in Ref. [29].

8.9.2 Air Midwest Raytheon (Beechcraft) 1900D Accident

This accident occurred on January 8, 2003, when an Air Midwest Raytheon 1900D aircraft lost pitch control during takeoff and crashed in North Carolina, killing all persons on board (19 passengers and 2 crew members). Some of the factors that contributed to the cause of the accident were as follows [28]:

- The contractor's quality-assurance inspector's total failure to detect the wrong rigging of the elevator control system
- The operator's maintenance procedures and documentation and lack of oversight of the work being performed at the maintenance station
- The regulator's lack of oversight of the maintenance program of the operator

Additional information on the accident is available in Ref. [28].

8.9.3 British Airways BAC1-11 Accident

This accident occurred on June 10, 1990, when a British Airways BAC1-11 aircraft departed from Birmingham Airport in the United Kingdom to a destination in Spain, carrying 81 passengers and 6 crew members. During the aircraft's climb through 17,300 feet altitude, a cockpit windscreen was blown out. Consequently, the pilot in command was sucked out through the windscreen aperture [4].

The copilot immediately regained control of the aircraft and the other crew members held the pilot by the ankles until the safe landing of the aircraft. A subsequent investigation into the accident reported that the cause of the accident was the fitting of a replacement windscreen by maintenance workers using wrong bolts [4].

Additional information on the accident is available in Ref. [4].

8.10 PROBLEMS

1. Write an essay on human error in aviation maintenance.
2. List at least five facts and figures on human error in aviation maintenance.
3. What are the important reasons, directly or indirectly, for the occurrence of human error in aviation maintenance?
4. Discuss major categories of human errors in aviation maintenance and inspection tasks.
5. What are the commonly occurring human errors in aircraft maintenance?
6. Describe the error-cause removal program.
7. Describe the maintenance error decision aid (MEDA).
8. What are the useful guidelines to reduce human errors in the following areas of aircraft maintenance?
   - Tools and equipment
   - Shift-handover
   - Communication
9. Discuss two case studies concerned with human error in aviation maintenance.
10. Discuss the benefits of the cause-and-effect diagram.

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