INTRODUCTION

On April 28, 1988, at 13:46, a Boeing 737–200 … operated by Aloha Airlines … experienced an explosive decompression and structural failure at 24,000 feet … Approximately 18 feet from the cabin skin and structure aft of the cabin entrance door and above the passenger floor line separated from the airplane during flight. … The National Transportation Safety Board determines that the probable cause of this accident was the failure of the Aloha Airlines maintenance program to detect the presence of significant disbonding and fatigue damage which ultimately led to failure of the lap joint at S-10L and the separation of the fuselage upper lobe. (NTSB, 1989, Executive Summary)

The structural failure and separation of a large piece of cabin structure was a shocking event to the public and industry alike, and the Federal Aviation Administration (FAA) immediately established the Aging Aircraft Program of research to look more closely at metal fatigue damage. However, the probable cause raised by the National Transportation Safety Board (NTSB) took issue with the operator’s maintenance and inspection processes including the training and qualifications of mechanics and inspectors. In the words of the then FAA Associate Administrator,

… the airplane was inspected and an airworthiness action performed just a few months before it had the tragic inflight episode. Then, just recently we found another airplane, with another airline, which had about 50,000 to 55,000 cycles and had developed a major crack and a number of smaller ones. This airplane also had been inspected earlier, with its cracks discovered only as it was going in for repainting. So here we have two airplanes… for which somehow the system did not work. We have professionals involved in engineering and professionals involved in maintenance and yet cracks developed undetected. … We must develop an improved approach to the inspection process and, more important, it must be an organized approach. We need to take a technological approach, break the process into its components, and then examine each component to see if we can build a body of knowledge that will apply. (Broderick, 1990, p. 4)

The Aloha accident led to some major realizations. Accident causes distinguished “aircraft” from “maintenance and inspection” factors, but knowledge about the human reliability of maintenance and...
inspection processes was limited. This was a wakeup call to fully acknowledge the critical role of maintenance and inspection in flight safety. It was obvious that poorly performed maintenance and inspection could result in rework, aircraft damage, and injury to maintainers. But the chain of events leading to inflight accidents and incidents was not clear. In many cases, inspection and maintenance errors were latent conditions that did not cause immediate damage; failure might not occur for days, weeks, or ever. The complicated relationship between the latent nature of maintenance errors and adverse outcomes required systematic investigation and the establishment of principles and data that could lead to effective strategies for correcting, preventing and managing maintenance risks.

This chapter will chronicle the journey of the community of operators, regulators, and researchers who embarked upon the task of identifying critical human factors of maintenance and inspection, establishing a database and research tools, developing practical strategies for reducing the risks of maintenance and inspection errors, and understanding its critical role in preserving flight safety. We will take a historical perspective, developing a timeline that is largely driven by key events such as accidents and regulatory/government actions and initiatives. Part 1 focuses on how the field of maintenance human factors was built, beginning in the late 1980’s. Part 2 describes the development of methods and tools for meeting the maintenance human factors challenges identified. Finally, Part 3 updates the original chapter by focusing on issues that have persisted or emerged since 2010.

PART 1: BUILDING THE FOUNDATION OF MAINTENANCE HUMAN FACTORS

Following the landmark Aloha accident, the FAA called a meeting of aviation industry representatives to discuss problems associated with aging aircraft. Much of this meeting addressed issues of hardware, metal fatigue, and corrosion, but there was growing interest in understanding the contribution of human factors to aviation safety. In October 1988, the FAA called an industry meeting that marked the beginning of a systematic review of Human Factors in Aircraft Maintenance and Inspection. From 1988 to 1999, the FAA sponsored 13 annual industry meetings that covered a wide range of human factors topics (see Table
In addition to these meetings, the FAA began a program of research to investigate issues and recommendations generated by the community at large. The community included regulators, operators, union organizations, manufacturers, accident investigators, and researchers from both civil and military institutions. Soon, participants were coming from countries outside the United States eventually leading to a joint working agreement among the FAA, CAA-UK, and Transport Canada for the meetings from 1998 to 2006.

The timeline in Table 21.1 shows key events (e.g., accidents, incidents, and government actions) that influenced industry meetings, research and guidance documents. For example, the Aloha accident (in the left-hand column), resulted in the series of FAA Industry meetings that identified Human Factors issues in Maintenance and Inspection (listed in the right-hand column). The same community of researchers, regulators, and operators worked together to conduct the relevant research to develop and implement human factors solutions. They also began to capture its knowledge and lessons learned in guidance materials (e.g., ATA Specification 113).

By the mid-1990s, a realization that collecting and analyzing incident data (in addition accidents) could provide further insights; this prompted the development of event databases. With the use of investigation and error analysis tools, human factors issues could be identified on the basis of trends in actual data. The FAA renewed its plan to continue the research program and industry meetings and at the same time NASA, motivated by its own maintenance issues, began extending the human factors principles, research and training to space operations (e.g., shuttle processing).
Identifying Human Factors in the Maintenance and Inspection Work Domain

The series of FAA industry meetings beginning in 1988 generated many useful recommendations. While some of the changes were directed at the industry and regulator level (e.g., better communication of information and development of an industry-wide database), an equally important objective was to build knowledge at the ground level. Where exactly were maintenance and inspection tasks failing? What factors contributed to maintenance and inspection errors or non-compliance? Similar to researchers of “pilot error” who were moving away from a “blame the pilot” mentality by investigating root causes, the maintenance community began to systematically consider the numerous latent and underlying factors that could affect maintenance and inspection performance. The first five FAA/industry meetings met this challenge by focusing on the physical work environment, ergonomic factors, documents, procedures and training, in addition to individual factors such as fatigue, worker qualifications and skills.

Scarcely had the program gotten started when on July 18, 1989, United Flight 232 crash landed at Sioux City, Iowa, capturing the spotlight. At flight level 370, there had been a catastrophic failure of the #2 tail-mounted engine of the DC-10, which led to loss of the three hydraulic systems that powered the flight controls. The flight crew experienced severe difficulties controlling the aircraft, which subsequently crashed during an emergency landing at Sioux City Gateway Airport. Although there were 111 fatalities, 175 passengers and 10 crew members survived.

The National Transportation Safety Board determines the probable cause of this accident was the inadequate consideration given to human factors limitations in the inspection and quality control procedures used by United Airlines engine overhaul facility which resulted in the failure to detect a fatigue crack originating from a previously undetected metallurgical defect located in a critical area of the stage 1 fan disk that was manufactured by General Electric Aircraft Engines. (NTSB, 1990, Executive Summary)

Again the probable cause traced back to human factors limitations in inspection and quality control procedures. Although the accident became famous for the skilled teamwork of the flight crew in
executing the emergency landing and the extraordinary preparedness of ground personnel in helping survivors, it was a painful reminder to the maintenance community that human factors associated with inspection processes, could downgrade inspector performance and lead to catastrophic consequences. Again, the Safety Board raised the issue of human factors and inspector reliability, just as it had with the Aloha accident the year before. Acknowledging that the FAA had begun its series of industry meetings, the urgency of these activities was reinforced. In addition, the Safety Board reiterated the need for an FAA research program that would not only build a solid understanding of human factors but could focus on emerging technologies (e.g., Non-Destructive Inspection tools) that could simplify, automate, or enhance the inspection process.

A Focus on Training

The Aloha and Sioux City investigations led the NTSB to issue two training recommendations to the FAA, namely:

A-89–56: Require formal certification and recurrent training of aviation maintenance inspectors performing nondestructive inspection functions. Formal training should include apprenticeship and periodic skill demonstration.

A-89–57: Require operators to provide specific training programs for maintenance and inspection personnel about the conditions under which visual inspections must be conducted. Require operators to periodically test personnel on their ability to detect the defined defects. (NTSB, 1990, p. 88)

In addition to recommending better technical training, the emphasis on human factors promoted the training of team skills similar to the CRM training that flight crews had come to accept. While flight crew CRM was a concept that had been developed at the end of the 1970s, it was implemented as classroom awareness training and integrated into line-oriented flight training by the end of the 1980s. But the work of maintainers and inspectors differed in significant ways from pilots’ work including their organizational structure, coordination with multiple work groups, documents and procedures. The maintenance community took great care to adapt team training to fit their own tasks, organizations, and workplace.
The flight crew was already immersed in a proactive error management program—mostly focused on interpersonal communication and teamwork—called Cockpit [later called Crew] Resource Management (CRM). The maintenance community adapted the relevant portions of this CRM program to meet the perceived needs of their aircraft maintenance professionals and called such programs Maintenance Resource Management (MRM). (Patankar & Taylor, 2008, p. 62)

Maintenance Resource Management (MRM) training had immediate appeal because it was largely directed toward “protecting” the maintenance technician and inspector from human error. For many training practitioners, MRM was synonymous with Human Factors. Topics within the MRM training curriculum often included what is known as the “Dirty Dozen “ which was developed in Canada and popularized world-wide. The “Dirty Dozen” are: (1) Lack of Communication, (2) Complacency, (3) Lack of Knowledge, (4) Distraction, (5) Lack of Teamwork, (6) Fatigue, (7) Lack of Resources, (8) Pressure, (9) Lack of Assertiveness, (10) Stress, (11) Lack of Awareness, and (12) Norms (Dupont, 1997).

At this early phase of MRM development and implementation, the topics were somewhat generic and quite similar to the topics discussed in classroom CRM. However, MRM practitioners established credibility and relevance by interpreting these concepts within the context of maintenance and inspection tasks. For example, in maintenance operations, relevant roles in the workplace could involve mechanics, lead mechanics, company inspectors, FAA inspectors, supervisors, maintenance control, stores, and engineering. On the ramp, pilots and ramp agents could be involved. Often communications were needed to transfer information from one shift to the next. These could be face-to-face, or written on a task card or shift turnover form, thus accomplishing two functions, documenting and communicating. In short, maintenance tasks and work environments could present some unique human factors challenges as described here:

In the early days of flight, pilots endured noise, wind and extreme temperatures as an accepted part of aviation. Maintenance technicians must still contend with the elements in ways that few airline pilots are required to do. A maintenance worker may be required to perch high above the ground, perhaps in rain and darkness, communicating by hand signals through deafening noise. … Maintenance is different in other
ways as well. An air traffic controller can unplug from the console at the end of the day, knowing that the
day’s work is finished. When the flight crew leaves the aircraft at the end of a flight, the chances are that
any mistakes they made affected that flight only (unless they damaged the aircraft). But when maintenance
personnel head home at the end of their shift, they know that the work they performed will be relied on by
crew and passengers for days, weeks or even years into the future. (Hobbs, 1995, p. 4)

In the U.S. Navy, MRM training was never a standalone program; rather it was integrated into a more
comprehensive safety program, a forerunner of safety management systems that have been growing in
use since the mid-2000s. Components of the integrated MRM training were: (1) discussion of safety data
from their own organizations, (2) best practices benchmarking with emphasis on operational risk
management, and (3) safety climate assessment (Schmidt & Figlock, 2001). This approach showed that
MRM training could be a highly effective safety management mechanism for providing safety feedback
to the workforce and developing preventive strategies for the future. It also could include built-in metrics
for monitoring attitudes, risk and safety improvements.

Maintenance Accident Investigation

In spite of the surge of industry interest in maintenance human factors, the primary data source was
accident data. For example, Boeing statistics that covered the period between 1959 and 1989, indicated
that of the 109 accidents with known causes (excluding sabotage and military action), 69.7% were
attributed to cockpit crew as primary cause. In contrast, maintenance and inspection during this timeframe
was very small at 3.7%, which was even lower than airport/ATC at 4.6% and weather at 7.3% (Boeing,
2003). While these were relatively small percentages, accident analyses pointed to the possibility of
severe consequences tied to maintenance and inspection. Within only two more years, September 11,
1991, another accident involving maintenance occurred— Continental Express Flight 2574. This accident
was examined in great depth by the maintenance community for two reasons. First, it highlighted the
difference between “procedures as written” and “procedures as performed;” where many factors such as
communication across shifts, or the delineation between technician and inspector roles introduced
nonstandard ways of performing procedures. Second, it introduced the concept of organizational culture;
that individual actions were performed in the context of organizational norms and practices

Organizational Factors and Safety Culture

On the day of the accident, Continental Express Flight 2574, an Embraer 120 operating under Part 135, experienced a sudden in-flight loss of a partially secured left horizontal stabilizer leading edge, leading to immediate severe nose-down pitchover, breakup of the airplane, and subsequent crash near Eagle Lake, Texas.

… probable cause of this accident was determined to be 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 that led to the sudden in-flight loss of the partially secured left horizontal stabilizer leading edge and the immediate severe nose-down pitchover and breakup of the airplane. Contributing to the cause of the accident was the failure of Continental Express management to ensure compliance with the approved maintenance procedures, and the failure of FAA surveillance to detect and verify compliance with approved procedures. (NTSB, 1992, Executive Summary)

One NTSB member gave a dissenting opinion that stated probable cause should be: (1) the failure of the company to establish a corporate culture, which encouraged and enforced adherence to maintenance and quality assurance procedures, and (2) the consequent string of failures of the personnel to adhere to the approved procedures for replacement of the horizontal stabilizer deice boots. This opinion indicated the growing appreciation for what was to be called the “safety culture” of an organization. This concept was often explained according to James Reason’s “Swiss Cheese” model which illustrated how failed organizational barriers fit into an event occurrence with adverse consequences (Reason, 1990). The aviation maintenance community found Reason’s model compelling because it depicted safety as a system and interpreted individual actions of maintainers and inspectors in the context of local workplace conditions and within an organization that reflected management decisions, organizational processes, corporate culture, and so on. The complex network of organizational roles and responsibilities, regulations, and procedures was a daily occurrence for maintainers and inspectors, in contrast with the seeming autonomy of pilots’ actions. Furthermore, the ambiguity of roles and oversight responsibilities
pertaining to the use of contract maintenance was becoming a concern as outsourcing became more prevalent. But even during those less complicated times, another accident pointed to organizational and oversight failures that contributed to a catastrophic outcome.

On May 11, 1996, ValuJet Flight 592 (DC-9–32) crashed into the Everglades about 10 minutes after takeoff from Miami International Airport. This outcome resulted from a fire in the airplane’s class D cargo compartment that was initiated by the actuation of improperly carried oxygen generators. The NTSB concluded that three organizations had contributed to the accident: (1) the contract repair station, SabreTech to properly prepare, package, and identify unexpended chemical oxygen generators, (2) the operator, ValuJet, to properly oversee its contract maintenance program to ensure compliance with maintenance, maintenance training, and hazardous materials requirements and practices, and (3) the FAA to require smoke detection and fire suppression systems in class D cargo compartments (NTSB, 1997, Executive Summary).

_Maintenance Error Analysis_

As accident investigations were providing a window into the causes and contributing factors of human error events, the maintenance community began to evaluate their own smaller events and close calls. Such an approach would help to structure event databases from which trends could be determined and corrective actions could be developed. Whether implemented on a company basis or industry-wide, a standard system for collecting maintenance error information was needed for identifying current key issues and for developing and tracking interventions. By the mid-1990s serious efforts toward developing maintenance error investigation and analysis tools were developed. These efforts greatly enhanced the maintenance community’s understanding of human error in maintenance and inspection and provided a shared terminology. Often incorporated was Reason’s model that differentiated latent factors and failed barriers from active errors.
One of these tools, Boeing’s Maintenance Error Decision Aid (MEDA), provided a guide for collecting information about an event and the factors that contributed to its occurrence (Rankin & Allen, 1996). It provided a taxonomy and standard definitions of the elements of the event model. Due to the ability of Boeing to collaborate with their airline customers, MEDA allowed Boeing to determine the number of in-flight shut downs that were due to maintenance error and whether some airlines had more problems with human error than others (Rankin, 1999, Rankin & Sogg, 2003). In Europe, similar tools such as the Aircraft Dispatch and Maintenance Safety (Russell, Bacchi, Perassi & Cromie, 1998, McDonald, 1998) and company-developed tools such as British Airways’ MEI (Maintenance Error Investigation) tool also followed a structured approach to investigation and analysis of error events.

At roughly the same time, the Human Factors Accident Classification System (HFACS) was developed by the U.S. Naval Safety Center to analyze pilot errors. The framework was subsequently adapted for maintenance events and called HFACS-Maintenance Extension (ME). It was field tested by the Navy to ensure that the four error categories: Supervisory Conditions, Maintainer Conditions, Working Conditions, and Maintainer Acts would be relevant and appropriate for use in maintenance operations (Schmidt, Schmorrow & Hardee, 1998). In the Navy implementation of HFACS-ME the tool was used to aid the mishap investigation process and to develop corrective actions. In addition, the safety results fed into Human Factors training, providing data that pointed out key safety issues and content for the training course itself.

**Maintenance and the US National Database**

The NASA Aviation Safety Reporting System (ASRS) was designed to provide a nation-wide repository of event data, thus giving aviation personnel a vehicle for reporting unsafe occurrences and hazardous situations. In 1996, ASRS introduced a specialized maintenance reporting form in order to encourage the reporting of maintenance incidents. Because participation was voluntary it could capture close calls as well as events that were not required to be reported, and because it collected reports nationwide, trends or
patterns that may not have been apparent within a single organization could be revealed. The use of the ASRS database as a source for establishing industry baselines and for identifying new issues is discussed in Part 2.

**Government Reviews: Maintenance Human Factors and Aviation Safety**

*White House Commission on Aviation Safety and Security.* Although there was, by now, increased awareness about maintenance human error and aviation safety, the 1997 White House Commission on Aviation Safety and Security reinforced this linkage. In the released report, a National Goal was established to reduce the fatal accident rate by 80% in 10 years (White House Commission on Aviation Safety and Security, 1997). According to Boeing projections, the accident rate would be unacceptably high if increases in travel doubled in twenty years. In response to these concerns, NASA developed its Aviation Safety Program (2000) which included a focus on Maintenance Human Factors (see Part 2).

*FAA Strategic Program Plan.* When the White House Commission Report came out, the FAA established a new Strategic Program Plan (FAA, 1998) which included the research of maintenance and inspection safety issues in order to develop practical solutions “specifically designed to reduce maintenance errors” (FAA, 1997, Executive Summary).

Planned activities covering seven primary areas are listed below:

1. **Maintenance Resource Management (MRM)**—guidelines, training and reference materials for MRM through extensive cooperation with the airline industry (Federal Aviation Administration, 2000),
2. **Maintenance Error Reduction**—proactive reduction of maintenance errors by developing maintenance error reporting systems and self-disclosure programs,
3. **Job Task Analysis in Aviation Maintenance Environments**—an objective basis for structuring the maintenance curriculum and supporting of regulatory changes,
4. **Maintenance and Inspection Training**—improvements for maintenance training curriculum and new technologies for training delivery systems,
5. **Job Aids for Maintenance and Inspection**—electronic performance systems for inspectors, job aids to help design ergonomically efficient procedures, electronic checklists for auditing suppliers, design aids for document writers to ensure that procedures follow human factors conventions, software tools
for tracking the repair and return of aircraft parts back to service.

6. Information Dissemination—research products disseminated through conferences and Web sites
7. Communication and Harmonization—coordination with international organizations, regulators, and airlines.

**Maintenance Human Factors in Space Operations**

During the mid- to late 1990s the FAA and ever-growing maintenance human factors community were meeting regularly, conducting research, and steadily cultivating maintenance human factors knowledge, resources and solutions. The surge in awareness and knowledge reached the NASA space program where the space shuttle ground processing workforce could instantly identify with the issues being raised. Shuttle processing technicians, inspectors and engineers from Kennedy Space Center joined the aviation maintenance community and presented their human factors needs and initiatives at the 12th FAA/CAA/Transport Canada Symposium held in London (Kanki, Blankmann-Alexander & Barth, 1998).

In addition, NASA coordinated several workshops that brought the aviation maintenance and shuttle processing communities together to share information and discuss human factors issues. Three workshops during 1997–1998 focused on: (1) Analysis of Errors, (2) Human Factors Training, and (3) Procedures and Work Instructions.

**NASA Shuttle In-Flight Anomaly** In 1999, the NASA Space Shuttle ground operations experienced their own human error event that resulted in a serious in-flight anomaly.

During the launch of STS-93 in July, 1999, two serious in-flight anomalies occurred. The first occurred five seconds after lift-off when a primary and back-up main engine controller on separate engines dropped offline due to a power fluctuation. Post-flight inspection revealed a single 14 ga. polyimide wire had arced to a burred screw head. The second anomaly was a liquid oxygen low-level cutoff 0.15 seconds before the planned Main Engine Cut Off (MECO). Post flight inspection of the affected engine indicated that a liquid oxygen post pin had been ejected and had penetrated three nozzle coolant tubes, causing a fuel leak and premature engine shut-off. (National Aeronautics and Space Administration, 2000, p. 8)

While the second anomaly could be considered a “design” issue resulting in “internal FOD (foreign object debris),” the first anomaly (on which we will focus), describes a wire chafing event that only could have
resulted from collateral damage incurred during ground processing. An orbiter has more than 300 miles of wires such as those shown in the cable tray inside Columbia’s payload bay (see Figure 21.2). The damaged wire was located in the aft left-hand mid-body lower wire tray which is normally covered. Records indicated that the last time covers were removed was four years earlier during a maintenance down period. Since there was no evidence of generic chafing, the root cause was determined to be work-induced collateral damage. Contributing to the maintenance error was the inconsistent specification of wire protection application. This event again highlights how maintenance errors may be latent (four years) and hidden from detection (unopened cable trays).

**Insert FIGURE 21-2  Space Shuttle STS-93 in-flight anomaly caused by wire damage (Courtesy: NASA).**

The shuttle fleet was grounded until inspections of all four shuttles were conducted, analysis of the root cause and contributing factors was completed. Immediate corrective actions included:

- Extensive wiring inspection, repair, and additional wire protection to critical wiring,
- Redefinition and standardization of wire inspection criteria,
- Maximum feasible separation of redundant systems (redundancy of circuits had been compromised by placement in the same wire bundle).

In addition to immediate actions, a wide range of other factors, including organizational issues (e.g., reduced NASA oversight, reduction in workforce), procedures that encouraged workarounds, metrics that discouraged the reporting of maintenance errors, and lack of standardization and communication across maintenance organizations. Additionally, major issues in risk management philosophy and practices lead to an overreliance on past successes. As in aviation maintenance, risk management tended to be understood as “design risk,” typically addressed during the certification phase. Unfortunately, this perspective overlooks the daily operational risks that can potentially compromise flight safety even though they are hidden from obvious view and may lie dormant for years.
**Key Industry Guidance**

In just over ten years the aviation maintenance community was documenting many lessons learned. An industry working group (ATA Maintenance Human Factors Subcommittee) developed the ATA Spec 113 to pool their collective knowledge and experiences. In many respects this document provides a good summary of the first ten years of maintenance human factors programs. The original release of the document was in January 1999 and subsequent revision in 2002 (Air Transport Association, 2002).

**ATA Specification 113: Maintenance Human Factors Program Guidelines.** ATA Spec 113 provided guidance to operators for developing a maintenance human factors program. It provided definitions of maintenance human factors terms followed by a discussion of where maintenance human factors programs could be placed in an organization. At the time, companies were scoping and placing their programs to fit their organizational structure and needs, and not according to one set way.

The document described the current state of the art of maintenance human factors programs. While Maintenance Resource Management (MRM) was one important element, additional elements such as maintenance error management and ergonomics were called out, as well as the interaction of program elements with each other. For instance, the data generated from error management systems might suggest ergonomic improvements or procedure modifications. Best practices of the day provided training program guidance including details about conducting a needs assessment prior to the design phase, components of a basic curriculum, validation of a prototype program, and steps toward implementing, and evaluating the program. Guidance for developing error management and ergonomics programs was similarly described in a step-by-step manner. A later revision included guidance on how to calculate Return on Investment (ROI) in order to present a compelling business case to management.

**PART 2: DEVELOPING METHODS AND TOOLS TO MEET NEW CHALLENGES**
After 10 years of Human Factors conferences, industry working groups, supporting research and the development of guidance materials, Maintenance Human Factors programs appeared to have achieved some momentum. The White House Commission on Aviation Safety and Security set a goal of decreasing fatal aviation accidents including maintenance induced mishaps. But the next decade started with an aircraft accident that played out yet another variation on the maintenance error theme.

On January 31, 2000, just north of Anacapa Island, California, Alaska Airlines, Flight 261 crashed into the Pacific Ocean. The crew and passengers were killed and the airplane was destroyed by impact forces.

The National Transportation Safety Board determines that the probable cause of this accident was a loss of airplane pitch control resulting from the in-flight failure of the horizontal stabilizer trim system jackscrew assembly’s acme nut threads. The thread failure was caused by excessive wear resulting from Alaska Airlines’ insufficient lubrication of the jackscrew assembly. Contributing to the accident were Alaska Airlines’ extended lubrication interval and the Federal Aviation Administration’s (FAA) approval of that extension … which allowed the excessive wear of the acme nut threads to progress to failure without the opportunity for detection. Also contributing to the accident was the absence on the McDonnell Douglas MD-80 of a fail-safe mechanism to prevent the catastrophic effects of total acme nut thread loss. (NTSB, 2002, Executive Summary)

Since the probable cause was failure of lubrication and inspection of the jackscrew, it could not be tied to a specific error event; rather, a non-action building over time set up the failure conditions for the accident. Numerous contributing factors were cited, including the jackscrew assembly overhaul procedures, design, and certification of the MD-80 horizontal stabilizer trim control system, Alaska Airlines’ maintenance program, and the FAA’s oversight of Alaska Airlines, thus reinforcing the need to research human factors issues related to procedures, workplace, organizational factors and oversight.

**NASA Aviation Safety Program: Maintenance Human Factors**

During the same year, the NASA Aviation Safety Program (NASA AvSP) was being planned guided by more than forty high priority safety areas. Some were generic human factors topics such as: Human
Metrics and Models for Evaluation, Training and Skill Proficiency, and Organizational Culture for Safety.

In addition, maintenance-specific areas included:

- Maintenance Teamwork Procedures and Roles/Responsibilities
- Maintenance Training
- Maintenance Task Procedures


The NASA AvSP (renamed Aviation Safety and Security Program (AvSSP) after the terrorist events of 9/11 in the United States) Maintenance Human Factors (MHF) goals were: to provide guidelines, recommendations and tools directly to maintenance personnel and managers, through a better understanding of human error and human reliability, and to develop interventions that would enhance safety and operational effectiveness. The program approach emphasized operational partnership with aviation operators through four phases of research:

1) Identification of safety needs
2) Development of methods and tools
3) Development of human factors interventions
4) Validation of product implementation in operations

The FAA program of research had provided a 10-year foundation of research and industry involvement, so the NASA program easily complemented existing work by focusing on remaining industry-identified issues and expanding the research focus to address longer term goals, for example, methods and tools to solve maintenance safety needs, and developing interventions that included forward-looking new technologies.

Identification of Safety Needs

A fundamental challenge to working in maintenance human factors was the general lack of human factors data. Reason’s concepts and various taxonomies for classifying and analyzing maintenance error events
provided a common vocabulary and model for discussing and understanding maintenance human error. But the challenge of actually building databases that could be easily summarized and acted upon would take time and there needed to be a shift from reactive to proactive systems that collected and analyzed lower-level events and close-calls that could be precursors of accidents. One way to address this was the development of voluntary reporting systems, similar to the NASA ASRS program, but ones that could be maintained on a company basis.

In 2002, the FAA published *Advisory Circular 120–66B: Aviation Safety Action Program*, (Federal Aviation Administration, 2002) guidance that could help maintenance organizations develop their own in-house voluntary reporting. While the FAA’s Aviation Safety Action Program (ASAP) had already gained some success with the pilot community, there was no guarantee that maintenance personnel would trust the system enough to disclose events that would have led to punishment in the past.

During this timeframe, significant international progress was being made. For instance, maintenance human factors guidance was developed to be consistent with the European Aviation Safety Agency (EASA) Part-145 Human Factors and Error Management Requirements. A comprehensive guidance document was completed in 2003 by the CAA-UK, the *Civil Aviation Publication 716, Aviation Maintenance Human Factors (EASA/JAR145 Approved Organisations)*, (Civil Aviation Authority, 2003). During the same year, the International Civil Aviation Organisation published the *Human Factors Guidelines for Aircraft Maintenance Manual* (International Civil Aviation Organisation, 2003).

In spite of newly available, comprehensive guidance materials, a continuing challenge was the nature of maintenance errors themselves. As accidents and incidents showed, maintenance errors could lie undetected for an indefinite period of time. In other cases, errors were discovered in the course of performing other maintenance tasks, and as a matter of course, technicians fixed them without documenting the error. It would be difficult to know how to prevent future risks if they were never documented.
A Focus on Procedural Error. One area that seemed to defy solution, was procedural error as evidenced in the Air Midwest Flight 5481 accident that occurred on January 8, 2003. The Beechcraft 1900D with 19 passengers and 2 crew, lost pitch control during takeoff and crashed killing all on board. Probable cause was determined to be the incorrect rigging of the elevator control system compounded by the airplane’s center of gravity, which was substantially aft of the certified aft limit.

Contributing to the cause of the accident were (1) Air Midwest’s lack of oversight of the work being performed at the … maintenance station; (2) Air Midwest’s maintenance procedures and documentation; (3) Air Midwest’s weight and balance program at the time of the accident; (4) the Raytheon Aerospace’s quality assurance inspector’s failure to detect the incorrect rigging of the elevator control system; (5) the Federal Aviation Administration’s (FAA) average weight assumptions in its weight and balance program guidance at the time of the accident; and (6) the FAA’s lack of oversight of Air Midwest’s maintenance program and its weight and balance program. (NTSB, 2004, Executive Summary)

While probable cause was traced to individual actions, the contributing factors assigned responsibility to numerous organizations: the operator, maintenance contractors, manufacturer and regulator. Specific procedure-related recommendations were based on an examination of current task documents, revealing inadequacies in both the operator’s detailed inspection work card and the manufacturer’s Aircraft Maintenance Manual. In each case, it was felt that document inadequacies contributed to the failure of the mechanic, quality assurance inspector, and foreman on site, to detect the maintenance errors (i.e., incorrect rigging of the elevator control system). The deficiencies led to tightening the requirements on procedures and maintenance manuals for manufacturers and operators of Part 121 aircraft. For example, Part 121 air carriers were required to implement a program in which air carriers and aircraft manufacturers review all work card and maintenance manual instructions for critical flight systems and ensure the accuracy and usability of these instructions so that they are appropriate to the level of training of the mechanics performing the work.

In addition to these requirements, the NTSB report noted that many of the air carrier deficiencies should have been identified through their Continuing Analysis and Surveillance System (CASS) program. This was also the case in the Alaska Airlines Flight 261 accident earlier, and the FAA was working on a
revision of the original CASS Advisory Circular to include human factors. In April, 2003, the enhanced Advisory Circular, *AC 120–79: Developing and Implementing Continuing Analysis Surveillance System* (Federal Aviation Administration, 2003) was published.

**Procedural Error Research.** FAA research had already shown that some procedural errors were due to poorly written procedures and the Document Decision Aid was developed to help document writers follow human factors guidance (Drury, Sarac & Driscoll, 1997). Analyses of manufacturer documents provided another angle on procedural error. Hall reported that outdated information, as well as access, readability, portability and training issues contributed to procedural errors (Hall, 2002). Others found through field interviews and surveys, that manufacturer procedures were usually seen as accurate, but sadly lacking in usability (Chapparo & Groff, 2002). Surveys of maintenance personnel on their use of procedures established that procedural errors were often cases of procedural non-compliance (Hobbs and Williamson, 2000; McDonald, Corrigan, Daly, and Cromie (2000).

The yet untapped NASA ASRS maintenance database quickly became a valuable resource. An analysis of procedural error incidents confirmed that the causes of procedural error came from a variety sources; sometimes the procedure itself was incorrect, incomplete, ambiguous, or contained conflicting information; sometimes the error was due to procedure usability or the norms and safety culture governing its use (Patankar, Lattanzio, Munro & Kanki, 2003; Kanki, 2005).

**Development of Methods and Tools**

Maintenance Human Factors was still a relatively new research domain that lacked methods and tools, particularly in the area of process, task and risk analysis, so these were topics were in the NASA MHF program. Such generic tools would not only aid the research community but could be adapted for use by
human factors practitioners in assessing how specific processes and tasks can lead to errors and increased risk.

*Risk and Process Modeling Tools.* Probabilistic risk assessment (PRA) was not new to the designers of technical systems. To the operational manager, however, traditional PRA did little to combat human errors or shed light on latent errors. The development of socio-technical probabilistic risk assessment (ST-PRA) is a method that models human processes in technical systems. They can help both researcher and practitioner identify the error potential of certain processes and to develop interventions that can be shown to reduce the likelihood of error outcomes (Marx & Westphal, 2008). In addition to aerospace applications, ST-PRA has been used in the medical field as a means to manage a variety of risks ranging from specific outcomes such as surgical site infections, to systemic failures in long term care facilities (AHRQ, 2010).

Process modeling tools have been extremely useful for systems engineers and researchers, but may also be useful to human factors practitioners who are faced with error-prone processes or the need to build in error capture controls (Eiff & Suckow, 2008). In addition to revealing process traps and inefficiencies, process maps also clarify the interactions and dependencies among organizations. For example, research focusing on the aircraft inspection process from touchdown to takeoff has provided sights into the hierarchy of organizations involved in detecting and assessing aircraft damage (further discussed in Part 3). Process modeling indicates communication and decision points among workgroups as well as when and in what order these processes take place. Among other things, it provides a graphical framework for identifying areas of increased risk and which organizations are involved. (Kanki, Hobbs, Huang & Twining 2010; 2012))

*Development of Human Factors Interventions*

*MRM Training Evaluated.* Among the interventions addressed by the MHF program was Maintenance Resource Management (MRM) Training as it had been implemented by U.S. operators since the late
1980s. Ten years of development and implementation had shown there to be considerable industry-wide variation. Thus, this research focused on training effectiveness (both short and long term) by means of metrics that could be collected from programs that were just starting as well as those that had been running for many years. The researchers dealt with organizations on an individual basis giving each personalized assessments of their programs. After a large database was established, both longitudinal changes over time and variations across programs could be analyzed. Four generations of MRM training marked the evolution of training that started as an adaptation of CRM (Cockpit Resource Management), to other variations that better served the unique needs and culture of the maintenance community (Taylor & Patankar, 2001). The four variations included:

1. CRM-based Training in Communication Skills and Awareness.
2. Training that Directly Addressed Communicating and Understanding Maintenance Errors.
4. Integrated, behavior-based MRM programs.

Problems in information transfer. In response to known problems in maintenance shift turnovers, experiments systematically compared multiple communication modes (Parke & Kanki, 2008) resulted in recommendations for performing effective turnover briefings. Another project focused on improving the communication between airline mechanics and pilots via the Maintenance Log (Munro, Kanki & Jordan, 2004). Because the Maintenance Log is often the primary means of communicating critical information between pilots and mechanics, this survey-based research focused on identifying the underlying issues to be resolved.

Advanced Display Technologies. The development of advanced technologies was intended to meet longer term objectives but technologies advanced so quickly that what was a long-term product in 2005 was overtaken by similar innovations. For example, a form of video-mediated technology to promote collaboration (e.g., technicians or inspectors with engineering support) was developed, tested, evaluated,
and demonstrated in an operational setting (Majoros, 2008). While successfully completed during the MHF program timeframe, today’s technologies have already evolved into a new set of information technologies, many related to mobile phone technologies and Internet access for shared resources and applications. Nevertheless, the demonstration of the collaboration-supported interactions between engineers, technicians, and inspectors was valuable because the organization could see how an inefficient process could be improved. In the context of geographically distributed locations, video-mediated collaborations can help resolve a variety of communication, procedural, and technical issues in a more timely and effective way.

*Virtual reality (VR) technologies.* It was known that aircraft inspectors gain the depth of their skill through long years of on-the-job experience that supplemented traditional training. Thus, researchers developed a type of VR accelerated training to leverage this type of experiential learning (Bowling, Khasawneh, Kaewkuekool, Jiang & Gramopadhye, 2008). Analyzing a variety of measures (e.g., performance and process measures) showed that the VR training provided most benefit for detailed inspections under non-time-constrained conditions. Another promising direction examined was the use of VR technology with expert inspectors and novices working together, to some extent, simulating and accelerating the on-the-job experience. Given the recent gains in VR technology, these sorts of applications should be feasible. However, changes to the visual inspection task due to increasing composite aircraft structures have directed inspection in a different direction (see Part 3).

*Validation and Implementation of Products*

The fourth element of the research approach was to validate and implement products in operations with metrics that are operationally relevant. Since products could be methods or tools, human factors interventions such as training or process improvements, or technologies such as video-mediated devices or virtual reality training, validation of products were achieved in a variety of means. For example, performance metrics were developed to test for the benefit of improved procedures, the use of
communication aids for shift turnover and VR training. In the case of MRM training, a family of metrics was developed. At the individual level, short-term and long-term metrics—both attitudinal and behavioral—were developed and systematically collected for 15 companies over many years. At the organizational level, return-on-investment metrics were developed and safety data was tracked. In some cases, prototypes were developed and evaluated (e.g., video-mediated collaboration tool) or analysis tools (e.g., risk, process analysis) were demonstrated in actual operations.

While demonstration of products was easily achieved, implementation on a continuing basis was more difficult. Post-9/11, the air transport industry in the US imposed demanding, security requirements that left many operators under extreme economic strain. Cutbacks, layoffs, and other drastic measures were taken in order to stay in business. New projects were put on hold and, due to security policies, access to operations was more difficult for researchers. Even the FAA industry meetings became infrequent. Since MRM had been a stand-alone program, it was vulnerable to management changes and cuts in resources. However, other human factors products, particularly those that were tools and methods to support improvements (e.g., procedures, risk assessment, process mapping) could be maintained as best practices. Fortunately, many of the human factors principles and lessons learned had already been incorporated into guidance documents and integrated into ongoing programs such as the Continuing Analysis and Safety Surveillance and Safety Management Systems (Federal Aviation Administration, 2006). Implementation of human factors in maintenance was severely tested but the basic knowledge and tools were documented and available.

PART 3: PERENNIAL ISSUES AND NEW CHALLENGES

**FAA work on fatigue**

*Introduction*
Aviation maintenance personnel face an increasing risk of fatigue due to the need to work during circadian lows, the potential for long and unregulated duty times, and the sleep disruption that can result from these working conditions (Hackworth et al., 2007; Johnson, 2008; Johnson, Mason, Hall & Watson, 2001). Many maintenance tasks, particularly those involving intense visual attention, communication, or a heavy reliance on memory are particularly susceptible to fatigue.

Fatigue risk management principles

In recent years, comprehensive fatigue risk management approaches have been adopted in aviation and road transport, supplementing, or in some cases replacing, older Hours of Service approaches. Fatigue Risk Management Systems (FRMSs) are promoted by the International Civil Aviation Organization (ICAO, 2016), the Federal Aviation Administration (2010), the European Aviation Safety Agency (EASA, 2009) Transport Canada (2007), the Civil Aviation Safety Authority of Australia (CASA, 2009), and agencies in the road and rail transport industries (Australian National Transport Commission, 2004; Gertler, Popkin, Nelson & O’Neil, 2002). The FAA has defined FRMS as: … a data driven and scientifically based process that allows for continuous monitoring and management of safety risks associated with fatigue-related error. It is part of a repeating performance improvement process. This process leads to continuous safety enhancements by identifying and addressing fatigue factors…” (FAA, 2010, p. 3). Aviation maintenance has been slow to adopt the FRMS approach. Nevertheless, fatigue risk management is receiving increasing attention in the maintenance sector, as evidenced by the recent activities of the FAA (2016).

Most of the fatigue risk management approaches in industry have been designed for continuous control tasks such as driving a vehicle or operating an aircraft. In such tasks, one of the major fatigue-related threats is an unwanted sleep episode, in the form of either an extended period of sleep or a microsleep. In maintenance, falling asleep at work is not the main hazard created by fatigue. Rather, a fatigued
maintainer is at increased risk of maintenance errors and lapses due to the impact of fatigue on mental functioning (Hobbs, Williamson & Van Dongen, 2010)

In a report sponsored by the FAA, Hobbs, Avers and Hiles (2011) described three broad objectives for fatigue risk management in maintenance operations. This approach was subsequently integrated into an FAA Advisory Circular (FAA, 2016). As shown in figure X, each of three approaches can be considered as a layer of defenses in Reason’s “Swiss Cheese” model.

Insert Figure 21.2 Three approaches to fatigue risk management in maintenance (From Hobbs, Avers & Hiles, 2011).

(1) Reduce fatigue

First, efforts can be directed at reducing the level of fatigue experienced by personnel at work. This is the approach most commonly referred to when considering fatigue risk management. Hours of Service limits, and the re-design of shift schedules are common approaches intended to meet this objective.

Regulatory limits to hours of service. The only hours of service limit currently applying to aviation maintenance in the US is FAR part 121.377, which requires that a person performing maintenance be relieved of duty for at least 24 hours in any seven consecutive days, or the equivalent within a calendar month. This limitation, however, only applies to personnel maintaining aircraft operated by airlines.

EASA and the UK CAA do not specify hours of service limitations for maintenance personnel, however the UK CAA commissioned Folkard (2003) to develop comprehensive guidelines for best practices. In addition to Folkard’s original report, his guidelines are included in the CAA advisory document for part 145 operators (CAA, 2003), and a guidance document for maintenance organizations released by ICAO (2003).

Five key items from the Folkard guidelines are:
- 12 hour limit on shift duration
- No shift should be extended beyond 13 hours by overtime
- At least 11 hours break between shifts
- Work break every 4 hours
- A month’s notice of work schedules should be provided

As Folkard notes, predictability in work schedules enables staff to plan their work and non-work obligations to ensure that they arrive at work well rested.

The nonprofit International Federation of Airworthiness (IFA) has also published non-binding recommendations for maintenance duty periods (Jauregui & Hosey, 2007). The IFA recommendations are broadly similar to those of Folkard, however extended shifts are limited to 16 hours, and the seven day workweek is limited to 72 hours.

*Scientific scheduling models.* In recent years, several software models have been developed to quantify the level of fatigue expected on various shift patterns (Mallis, Mejdal, Nguyen, and Dinges, 2004). Software models have advantages over hard hours of service limits as they can take into account circadian variations in alertness and sleep obtained to produce an estimate of the fatigue level of an individual or an estimate of the fatigue that may result from a particular shift pattern. In some cases, hours of service and the scientific design of work schedules using software modeling have been seen as competing solutions, yet the two approaches can be implemented together. Hours of service limits can set the outer bounds of duty times, while scientific design of shift schedules can be useful in designing schedules within these bounds.

The provision of educational material to employees is one of the few methods available to address the personal lifestyle factors that contribute to fatigue. The FAA has released extensive material on fatigue risk management for maintainers, available via the FAA human factors in Maintenance website: [www.faa.gov/about/initiatives/maintenance_hf/](http://www.faa.gov/about/initiatives/maintenance_hf/). The maintenance guidance material for EASA Part 145 (EASA, 2003) includes fatigue as one of the topics that should be covered in human factors training for
employees of Part 145 maintenance organizations. EASA Part 66 also includes fatigue awareness among the topics that should be covered in initial training of maintenance personnel. The UK CAA has produced two advisory publications on maintenance human factors designed to meet the EASA requirements. CAP 715 (CAA, 2002) is a companion document to EASA part 66 and provides educational material on sleep, fatigue and shiftwork suitable for personnel obtaining their initial maintenance certification. The related CAP 716 (CAA, 2003) is a companion document to EASA part 145, and provides extensive information on fatigue, this time targeted at the needs of Part 145 operators and personnel.

In some cases, an employee’s fatigue at work will be a symptom of an underlying medical condition, such as insomnia or sleep apnea. In these cases, medical attention will be required to address the root cause of the problem. A comprehensive fatigue risk management system must include measures to identify at-risk employees, and ensure that they receive appropriate medical treatment.

(2) Reduce or capture fatigue-related errors

Second, interventions can be put in place to break the link between fatigue and performance decrements. This may involve reducing the probability that a fatigued maintainer’s performance will be degraded by fatigue or capturing such decrements once they have occurred.

Tasks performed during the window of circadian low, or by maintainers who are otherwise fatigued, may require additional countermeasures to detect the presence of error. These additional defenses can include independent inspections, functional checks, and formalized self-checks. Transport Canada is one of the few organizations to propose task-based approaches to risk mitigation in maintenance. Transport Canada recommends the following “fatigue-proofing” strategies directed at tasks that may be susceptible to fatigue (Transport Canada, 2007):

- close supervision
- working in pairs or teams depending on the task
- task rotation
- checklists
- support for new personnel by experienced personnel
• communication/briefings at shift hand-overs

Functional checks, such as engine runs or pressure checks, are one of the most useful means of uncovering maintenance errors on systems that involve moving parts or actuators (Reason & Hobbs, 2003). An accident involving a Beech 1900 occurred after maintenance personnel on the night shift made an error when rigging the elevator control system. The task card for the procedure contained no requirement for measurements of elevator deflection at the completion of the task, a step that may have detected the earlier error (NTSB, 2004). The NTSB has recommended that the FAA should require such checks to be performed after all maintenance on critical flight systems or components. Such checks would be particularly critical after maintenance on night shift.

The International Civil Aviation Organization has also made reference to task related interventions to counter the effects of fatigue. ICAO recommends breaking down lengthy repetitive tasks into smaller tasks, with breaks in between, and making appropriate additional checks on work performed by night shift (ICAO, 2003).

Task scheduling interventions. Although airlines sometimes have informal practices concerning the time of day at which maintenance tasks are scheduled, most operators do not appear to take the fatigue susceptibility of a maintenance procedure into account when scheduling tasks.

The following types of tasks are likely to be most susceptible to fatigue:

• Tasks that are monotonous or boring
• Inspection tasks
• Familiar tasks and those that can be performed “automatically” with minimal need for attention
• Tasks that rely on prospective memory
• Task requiring intense concentration for periods of more than 5 minutes without a chance for a break
• Tasks performed in a darkened environment, such as specialized inspections
• Those in which incorrect task performance is not clearly obvious.
In a report prepared for Transport Canada, Rhodes, Lounsbury, Steele & Ladha, (2003), recommended that if a maintenance task is to be performed during the window of circadian low (between 03:00 and 06:00), it should be checked by rested personnel. They also identified maintenance tasks that should be avoided during times at which fatigue effects are known to occur, including troubleshooting, testing, and calibration.

While AMTs may have limited discretion in the timing of tasks throughout their shift, the appropriate scheduling of tasks to minimize the impact of fatigue is the responsibility of supervisors and planning personnel. It is critical therefore, that such personnel have an awareness of the impact of fatigue on human performance.

Several regulatory authorities have acknowledged that production planning has an important role to play in managing the impact of fatigue on work quality. Section 145.A.47 (b) of EASA part 145 states “The planning of maintenance tasks, and the organizing of shifts, shall take into account human performance limitations”. The UK Civil Aviation Safety Authority advises that maintenance personnel should plan to avoid complex tasks during the window of circadian low (CAA, 2002).

(3) Minimize the consequences of fatigue-related errors

A last line of defense against fatigue in maintenance is to minimize the consequences of un-captured fatigue-related performance decrements. This approach is subtly different to the interventions described in the preceding section, as the intention is not to prevent or correct error, but to ensure that if errors do occur, they are less likely to result in significant safety consequences. An example would be task scheduling that avoids assigning work on flight control systems at 02:00 in the morning, instead assigning work on cabin interiors or cleaning. The maintainer may still make a fatigue-related error, however if so, it will occur on a less critical task.

Additionally, if a task that must be performed overnight involves a disassembly stage followed by an assembly stage, it may be appropriate to schedule the disassembly for the time of maximum fatigue, and
the assembly for a time at which fatigue is less likely. Of course, in many cases such an arrangement will not be feasible, due to the need to meet early morning flight schedules.

The progressive restriction of work responsibilities is an additional strategy to minimize the consequences of fatigue-related errors (Dawson, 2000). This involves progressively limiting the responsibilities of the maintenance performer as their level of fatigue increases. For example, the International Federation of Airworthiness has proposed that the certification and inspection authority of maintenance personnel should be limited when they have been on duty for longer than 12 hours (Jauregui & Hosey, 2005). An illustrative approach is shown in figure X.

**INSERT Figure 21.3 Example of a progressive restriction on work responsibilities with increasing fatigue risk.**

A potential complication with the progressive restriction of work responsibilities is that by removing responsibilities from personnel who are judged to be at risk of fatigue, we may create unanticipated negative consequences. Most importantly, it may increase the workload of the remaining staff.

**Management of fatigue risk interventions**

The FAA Advisory Circular on maintenance fatigue (FAA, 2016) makes it clear that interventions designed to control the risk of fatigue-related maintenance incidents cannot be made at the level of the AMT or inspector alone, but require a coordinated fatigue risk management approach at all levels of the organization requiring at least the following elements.

*Company policy.* Whatever approach to fatigue risk management is applied, it is clear that commitment from all levels of the organization is essential. Upper management have a responsibility to state a clear policy on fatigue, including how fatigue related incidents will be dealt with under a just culture policy. Supervisors and middle-level managers have a responsibility to ensure that the fatigue management
policy is applied in day-to-day operations. A formal statement of the organization’s policy towards fatigue can make it clear that the program has high-level management support.

*Incident reporting and analysis system.* An incident reporting and investigation system must be able to identify fatigue related incidents and near-misses. Because personnel may not be able to judge their own level of fatigue, subjective assessments alone cannot be relied on to determine if an incident was fatigue related. Maintenance activities typically occur over an extended time period, which can make it difficult to establish the time at which an error occurred and evaluate the likely fatigue level of the personnel involved.

*Risk assessment.* Fatigue risk management is about ensuring that risk remains within acceptable limits. From time to time, an increased exposure to fatigue will be necessary to meet operational needs, but in these cases, the increased risk must be evaluated and determined to be tolerable.

*Evaluation and improvement.* Fatigue risk management systems require periodic evaluation and adjustment as experience is accumulated (Transport Canada, 2007). The Civil Aviation Safety Authority of Australia provides a checklist to assist its inspectors in the evaluation of FRMS (Civil Aviation Safety Authority, 2004). CASA expects a review to occur within each 13 month period, and to include representatives from management and employees. The review is also an opportunity to update the system in light of current research.

Finally, individual aviation maintenance technicians and inspectors are ultimately responsible for the quality of their work. They must have a good understanding of fatigue and its effects, must strive to arrive for duty well-rested, and must have access to strategies to deal with workplace fatigue when it arises.

*Technology-driven changes in maintenance and inspection*

*Composite materials in aircraft primary structure*
A major shift in maintenance and inspection processes was set in motion by the increasing use of composite materials in primary aircraft structures. In line with wider industrial trends, the manufacturers of aircraft were increasing the use of composite materials such as lightweight winglets made of graphite-epoxy materials, carbon fiber reinforced plastics (CFRP) used in elevators, rudders, ailerons, and spoilers, and Glass Fiber Reinforced (GLARE) metal laminates utilized in fuselage skins. Composite materials provided the promise of great financial benefits including weight savings, increased strength, resistance to corrosion, aerodynamic efficiency, and reduced maintenance costs. But new challenges would emerge as well.

For more than 70 years, aircraft manufacturers and operators had been gaining experience in the maintenance, inspection and repair of predominately metallic aircraft. A long service history and a knowledge base of standards and best practices had accumulated and manufacturers, regulators, and operators drew from them with confidence. The failure modes of metallic structures had been studied extensively as well as the human factors of inspection (Drury, 1999). In contrast, the introduction of advanced composite aircraft presented many unknowns. The aviation industry knew they would need to grow their experience with composite structure, and develop standards and general guidance material to help with the transition. Industry groups (notably, the SAE Commercial Aircraft Composite Repair Committee and the A4A NDT Annual Forum) with the support of researchers and developers of related technologies provided important venues for sharing ideas, experience, best practices as well as problems they were experiencing.

New types of aircraft damage. One of the consequences of using composite primary structure was the introduction of a new type of severe damage created by anomalous ground or flight events (such as ramp impacts, hail and lightning) (Ilcewicz, 2011). “Blunt impacts can be defined as impact sources that can affect large areas or multiple structural elements, while potentially leaving little or no externally visibly detectable signs of damage. . .” (Kim et al., 2012, p. 5). Clearly these types of damage were not actually “new” but the risks or potential hazard to aircraft were greatly increased due to the difficulty of detecting
damage in composite structure. Ramp damage is notable because of its prevalence, the variety of ways it can occur, and the number of organizations and vehicles that can be involved. Damage events can occur when the aircraft is parked and when it is moving, during all times of the day and affecting nearly every part of the aircraft. (Kanki and Brasil, 2009).

**INSERT** Figure 21.4 A typical ramp/gate area shows a large variety of vehicles that can contribute to a wide range of damage locations (From Kanki, Hobbs, Huang & Twining, 2011)

*Human Factors in the Ramp Environment.* Some of the most obvious changes in the tasks carried out by operational personnel involved perceptual elements such as the detection of dents and delamination. However, detailed inspections do not typically occur on the ramp between flights. Ramp agents and other non-maintenance personnel (e.g., baggage handlers, fuelers, caterers), and even pilots during the walk-around may have the best awareness that a hazardous event has occurred on the ramp. Their reporting of such events is critical in order to trigger an unscheduled inspection and assessment of damage. It should be obvious that reporting of such events is critical but it may also be compromising depending on how the damage occurred. For example, if a fueler hit the aircraft by accident, his report may cost him his job. If there is no visible damage, he may be even less motivated to report. As a reminder, maintainers and inspectors were still learning about how best to detect composite structure damage; non-maintenance personnel were seldom trained on these new complexities, if at all.

*Limitations of visual inspection.* With the concerns of damage detectibility in mind, the European Aviation Safety Agency sponsored a program of research on the visual inspection of composite structure conducted by Baaran (2009). In the US, Kim and his team (Kim, et al. 2012; DeFrancisci, Chen & Kim, 2010, 2011; Haplin & Kim, 2009) followed their lead by conducting experiments that used larger structures and inflicted damage that emulated realistic hazard scenarios including: wide area high energy blunt impact (e.g., ramp damage, Foreign Object Debris), high velocity ice/hail impact (in-flight and ground hail/ice conditions), and low velocity blunt drop-weight impact (e.g., dropped tools, Ground
Support Equipment). Focusing on damage morphology, they developed models that characterized impact threats and identified key factors that produce maximum damage with minimum visual detectibility. This provided the scientific evidence that current inspection processes would need to change.

**Evolving inspection approaches.** Although 80-90% of inspections of composite structures were visual (Waite, 2007), three fundamental inspection approaches included: 1) unaided visual, aided by flashlights, mirrors, magnifiers, 2) tap testing, manual or automated, and 3) non-destructive inspection technologies pertinent to composites, such as ultrasonics, thermography, radiography and in some applications, eddy current techniques (Abrate, 1998). On the ramp, the use of tap testing and NDI technologies were time-consuming, and simply inappropriate for the fast paced, noisy and crowded ramp environment.

Non Destructive Testing (NDT) had been an important element of aircraft maintenance programs, particularly for aging (metallic) aircraft (Piotrowski, 2007, p. 69). A comprehensive study of various non-destructive inspection (NDI) tools conducted by Sandia Labs (Roach, 2012), reviewed the strengths and limitations of the various techniques, and highlighted the need for judicious use of NDI tools. For example a portable ultrasound tool may be effective in detecting delamination or subsurface cracking parallel to the surface over small areas, but may not be practical for scanning large areas. Training would have to be far more than knowing how to operate a NDI tool; it would have to ensure that NDI operators use the appropriate tool, proper technique and correct interpretation of data. Again, technology existed but was the maintenance and inspection requirements and processes would need an overhaul to accommodate the new risks inherent in composite primary structure.

**Sensors and Structural Health Monitoring (SHM)**

In some respects, the increasing use of permanently-placed (on-board) sensors can be seen as a special form of NDI. Rather than bringing the sensor equipment to the aircraft, the sensor is already situated at the location of interest. New sensor technologies and structural health monitoring systems can potentially help to address some of the current NDI (including visual) limitations. The concept of using on-board
sensors to collect inflight data is not new. Since the 1950’s, flight data recorders (FDR) on-board aircraft had been evolving, and all turbine-engine-powered transport category airplanes manufactured after August 19, 2002 were required to have at least 88 recorded parameters (FAA, 2011). But sensors are not without problems. Mounted sensors can become detached, or affect the airflow; embedded sensors, once cured, remain in the host material, but a failed or faulty embedded sensor may be very difficult to remove or repair once installed. Manufacturers, researchers, regulators and industry groups appreciated the potential benefits of sensor technologies and sensor systems but there was not yet a clear and compelling business case for operators to make the investment. At the 2011 International Workshop on Structural Health Monitoring, representatives from Embraer presented five requirements for SHM to be successful: technical feasibility, consistent business case, approval in a certification process, compatibility with continued airworthiness requirements, and acceptability by operators (Santos, 2011). Since that time progress has been made in all areas:

- Technical feasibility: Smart Structures use of NDI principles coupled with in-situ distributed sensors for rapid, remote, real-time condition assessments are overcoming many of the technical barriers. For example, sensors with a fail-safe feature will prevent acquisition of faulty data from a damaged or failed sensor.

- Acceptance by operators: Operators differ with respect to what is an acceptable business case, and is conditional on specific sensor solutions. For example, in a survey of 450 participants, reported by Roach (2017), many respondents (64.4%) felt that SHM solutions were viable with fuselage pressure bulkheads, and fuselage frames and stringers; much fewer respondents (34.1%) felt SHM usage with fuselage doors and control surfaces were viable, and very few (12.6%) felt SHM solutions were viable for power train. Clearly there lacks complete industry-wide agreement, but compelling demonstrations of the efficacy of specific sensor systems have been demonstrated.
• Compatibility with requirements: scheduled maintenance requirements and inspection intervals are developed and accepted by the operator, manufacturer and regulator based on a standard decision logic called MSG-3. The MSG-3 document has been revised many times for many reasons (ATA, 2011), most recently to allow sensor and SHM systems to be an approved part of maintenance and inspection requirements. Guidelines, standards, training and information sharing initiatives have been lead by several international industry groups.

In theory, structural health monitoring provides a proactive approach that allows aircraft operators to move away from a scheduled maintenance program to a condition based maintenance program. As Roach and Neidigk (2011) state, “The use of in-situ sensors for real-time health monitoring of aircraft structures can be a viable option to overcome inspection impediments stemming from accessibility limitations, complex geometries, and the location and depth of hidden damage. (p. 39)” In addition to these human factors considerations, scheduled maintenance runs the risk of performing unnecessary procedures and thus, the risk of human error. As it pertains to composite structures, it provides a path toward reducing the dependence on visual inspection which is known to be unreliable with blunt impact damage. When internal damage can exist with little or no exterior visibility, there must be greater emphasis on reporting hazards. As mentioned earlier, this pressures personnel who may not have the motivation or training to report reliably. It is clear that sensor systems have the potential to provide human factors benefits in hazard detection, damage detection and damage assessment both in flight and on the ground.

Structural Health Monitoring (SHM) is a still evolving field and there will be a long development, certification and validation process before SHM will be trusted by operators on a large scale. Until that happens, embedded sensors used in scheduled inspections can essentially be seen as permanently installed NDI systems with similar human factors elements such as communication, decision-making and

1 The Aerospace Industry Steering Committee on Structural Health Monitoring and Management (AISC-SHM) which operates as a technical committee within the SAE Aerospace Division (G-11 SHM) and the Air Transport Association MSG- 3 SHM working group
interpretation. As hybrid systems evolve (mixed “metallic” and “composite” fleet), changes in current inspection processes will need to be carefully reviewed and understood in order to appropriately capture the skills, judgments and experience that technicians, inspectors and engineers bring to the job. For example if raw data goes directly to the engineer, the valuable experience of technicians and inspectors may be bypassed. Often this knowledge is only apparent as unspoken and undocumented best practices. In the beginning, SHM will run in parallel with current NDI inspection at least until a successful flight history database is built. Structural health monitoring may rely to some extent on human involvement to gather data, transmit it to the analysis system, and interpret the results. Worden, Farrar, Manson and Park (2007) noted that SHM works by statistically comparing two system states, such as comparing current conditions with a baseline. It can be expected that there will be noise in the system, from which the signal must be extracted.

Eventually NDI equipment will come with preprogrammed software to help with the interpretation of the results, and so too must SHM systems. But as Crowder (2011) has noted, “The key to Situational Awareness is not simply collecting and disseminating data, but it is actually getting the right information to the right user at the right time” (p. 1333). Just as a FOQA uses a Ground Data Replay and Analysis System (GDRAS) to transform flight-recorded data into a usable format for processing and analysis (FAA, 2004) structural health monitoring systems also require software in order to prepare data for analysis. This software may need to capture, filter, store, combine and present sensor data in an easy-to-interpret manner. The importance of data definition and interpretation cannot be overstressed; validated criteria must be carefully established for sensor data to be used effectively and should be standardized industry-wide. Improperly programmed algorithms, parameters, or filters may decrease the system probability of detecting damage, overloading the system with trivial events, and undermining the confidence of the operators.

**SUMMARY**
The state of the art and state of the practice of maintenance human factors have shown impressive progress largely due to active collaborations of manufacturers, operators, regulators and researchers. In an industry where organizations must work together to make progress in parallel, it is an effective strategy. Industry partners have identified key human factors issues in maintenance and inspection, studied many of these issues and delivered operational solutions. Researchers were welcomed into the operational workplace in order to understand the nature of maintenance and inspection processes, procedures and norms. International collaboration and military participation also contributed to the conversation, knowledge base, and momentum. Even though the maintenance community itself goes through active and inactive phases, it is important to sustain two fundamental concepts: maintenance error/risk management and the relationship of maintenance error to safety of flight.

While different forms of maintenance error may trend over time, tools for characterizing maintenance error events are available, as well as guidance for developing human factors programs and the organizational pre-requisites for instilling a safety culture. Technological advances may promise great benefits but they may also result in changes to well established processes. Organizations themselves may change as companies merge and outsource parts of their work.

Accident investigations may have initiated the discussion of maintenance human factors, but the expanding focus from individuals to workplace, to organizations, and finally to the system of operators, third party vendors, manufacturers and regulators has resulted in a more complete understanding of root causes, contributing factors, and safety culture issues. Error analysis methods that identify systemic problems as well as local issues can result in more effective and long-lasting corrective actions. But in order to be proactive, an organization needs to be able to track its own safety data. Maintenance human factors programs have put great emphasis on the collection of safety information whether it is through a national voluntary reporting system or through company-specific reporting programs; in either case, this type of knowledge base helps an organization identify and manage their risks.
Continued vigilance to guard against maintenance and inspection failures has twofold significance. First, maintenance and inspection errors have consequences within technical operations (e.g., repair and rework, component damage, personal injury). In addition, accidents have provided dramatic and devastating proof that maintenance and inspection errors may also negatively impact flight operations. Using a global harmonized accident classification scheme (IATA, 2017), IATA reported that 2012-2016 accidents (including non fatal accidents) pointed to latent conditions involving maintenance operations (SOP’s and checking) as well as maintenance operations training. We cannot trace these latent conditions directly to maintenance errors, but in 11% of the 375 5-year total accidents, maintenance events (aircraft repairs on ground, maintenance log problems, maintenance errors) constituted a threat in the accident scenario. In an earlier IATA Safety Report (2003), the contribution of maintenance and technical failures was found to be 26% of 92 accidents worldwide. But the “accident scenarios … are … often a combination of the precipitant technical failure and the handling of the technical failure by the flight crew” (IATA, 2003). As human error in maintenance compromises aircraft reliability, the hazard potential for flight crews increases. Conversely, a reduction in maintenance error provides a safeguard to airworthiness and flight operations. While flight crews must be prepared for emergency situations, effective maintenance, and inspection can ensure that many of those situations will never happen.

**Concluding Remarks**

The foundation of Maintenance Human Factors knowledge and programs was established in a relatively short timeframe. The development of longer term concepts and adaptable generic methods and tools was also begun. But the most critical lessons were learned when organizational changes and economic uncertainty threatened the continued support of maintenance human factors in operations and research. The availability of a knowledge base and tools cannot overcome the lack of an organizational will to
value a safety culture. In sum, the prerequisites for managing maintenance error risks in ground and flight safety are the following:

1. In spite of economic strain and organizational challenges, organizations must uphold a safety culture in order to ensure that safeguards to maintenance and inspection errors are in place, and personnel have an avenue for reporting safety concerns without fear of reprisal;

2. A reporting culture makes it possible to collect and analyze data that forms a basis for developing effective corrective actions and proactive interventions. Although types of error may shift from one type to another, an error management system can help an organization remain current with their safety needs and to have a less reactive, more proactive safety management system;

3. Establishing an error management database is essential for tracking the effects of future changes such as technology changes in aircraft, in tools and in organizational responsibilities.

Like the field of human factors in general, maintenance human factors issues will always be a challenge even as workforce, workplace, regulations and technologies change. Therefore it is crucial to keep the knowledge base active and growing, and to be sure that the maintenance community has a voice in the aviation safety enterprise. We should not need another accident to remind us that promoting the effective management of maintenance error enhances safety of flight.

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