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# A review of human error in aviation maintenance and inspection

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**Abstract**

Aviation safety depends on minimizing error in all facets of the system. While the role of flightdeck human error has received much emphasis, recently more attention has been directed toward reducing human error in maintenance and inspection. Aviation maintenance and inspection tasks are part of a complex organization, where individuals perform varied tasks in an environment with time pressures, sparse feedback, and sometimes difficult ambient conditions. These situational characteristics, in combination with generic human erring tendencies, result in varied forms of error. The most severe result in accidents and loss of life. For example, failure to replace horizontal stabilizer screws on a Continental Express aircraft resulted in in-flight leading-edge separation and 14 fatalities. While errors resulting in accidents are most salient, maintenance and inspection errors have other important consequences (e.g., air turn-backs, delays in aircraft availability, gate returns, diversions to alternate airports) which impede productivity and efficiency of airline operations, and inconvenience the flying public. This paper reviews current approaches to identifying, reporting, and managing human error in aviation maintenance and inspection. As foundation for this discussion, we provide an overview of approaches to investigating human error, and a description of aviation maintenance and inspection tasks and environmental characteristics.

**Relevance to industry**

Following an introductory description of its tasks and environmental characteristics, this paper reviews methods and tools for identifying, reporting, and managing human error in aviation maintenance and inspection. 

*Keywords:* Aviation; Maintenance; Inspection; Human factors; Human error

## 1. Introduction

In the opening remarks of the 1995 FAA Aviation Safety conference, US Secretary of Transportation, Federico Peña, challenged the airline industry to meet the goal of zero accidents. Given the complexity of the aviation system, this goal is

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ambitious. Trends in the airline industry and the aviation environment exacerbate the difficulty of achieving this goal. Maintenance costs, passenger miles flown, and the number of aircraft have all exceeded the overall growth of the aviation maintenance technician (AMT) work force (Air Transport Association, 1994). Also, as the US commercial aviation fleet ages, aircraft require more inspection and maintenance. The concurrent trends of increased maintenance and inspection workload, and decreased work force seem to forecast increasing safety issues associated with human errors in maintenance and inspection.

Fortunately, technological advances have buffered, to some degree, the effects of these trends. Fail-safe systems, improved hardware, better software design, better maintenance equipment and methods, and other technological advancements, have improved safety and, in some ways, reduced maintenance and inspection workload. While it is tempting to think of such technological advancements as necessarily improvements to overall safety, one must consider that innovations also require the humans in the system to acquire new skills and knowledge, and may induce additional opportunities for human error. The focus of improving aviation maintenance and inspection has been traditionally to improve the technology used in these tasks. Because this focus introduced additional human error concerns, more recent attempts to improve aviation safety have focused on reducing inspector and repair personnel error (Reason and Maddox, 1995). Managing human errors has become a critical aspect of the aviation industries drive towards increasing the safety and reliability of the commercial aviation system. As evidence of this focus, human error was a major theme in the aircraft maintenance and inspection workshop held during the 1995 National Aviation Safety conference (FAA, 1995).

While the generics of human error or *genotypes* (Hollnagel, 1991) are essentially constant across work domains, the specifics or *phenotypes* (Hollnagel, 1991) are influenced by characteristics of the task and environmental context. This paper reviews general approaches to the study of human error and the characteristics of work in aviation maintenance as a foundation for describing the nature, incidence and consequences of human error in this domain. We review current efforts towards detecting, reporting, and managing human errors in aviation maintenance. Finally, we conclude by discussing future directions for reducing the incidence and mitigating the effects of human error in aviation maintenance and, thereby, improving aviation safety and efficiency of aviation operations.

## 2. Human error

Understanding the role of human error in an accident or incident is fundamentally different from simply attributing such an event to an inherently fallible human operator. Human error has been variously characterized as: any member of a set of human actions that exceeds some limit of acceptability (Swain and Guttman, 1983), any human action or inaction that exceeds the tolerances defined by the system with which the human interacts (Lorenzo, 1990), the failure to achieve an intended outcome beyond the influence of random occurrence (Reason, 1990), a necessary outcome to allow humans to explore and understand systems (Table 1) (Rasmussen, 1990; Reason, 1990), and derivative of operators' social experience of responsibility and values (Taylor, 1987). These definitions convey the multifaceted nature of human error. Principally, however, they suggest the two complementary proposals that: (1) human operators are organic mechanisms with failure rates and tolerances analogous to hardware/software elements of a system, (2) that human error is a pejorative term for normal human behavior in often unkind environments, where only the outcome determines if this behavior is deleterious. These two perspectives are also reflected in the two major approaches developed to address human error in accident and incident analyses: human reliability assessment (HRA) and human error classifications (Kirwan, 1992a). Summarized below, HRA methods and human error classifications are more fully reviewed and contrasted by Kirwan (1992a,b).

### 2.1. Human reliability analysis

The HRA approach is an extension of probabilistic risk assessment (PRA). Probabilistic risk

Table 1
Multifaceted human error taxonomy (adapted from Rasmussen, 1982)

| |
|---|
| Factors Affecting Performance |
| Subjective goals and intentions |
| Mental load, resources |
| Affective factors |
| Situation Factors |
| Task characteristics |
| Physical environment |
| Work time characteristics |
| Causes of Human Malfunction |
| External events (distraction, etc.) |
| Excessive task demand (force, time, knowledge, etc.) |
| Operator incapacitation (sickness, etc.) |
| Intrinsic human variability |
| Mechanisms of Human Malfunction |
| Discrimination |
| Input information processing |
| Recall |
| Inference |
| Physical coordination |
| Personnel Task |
| Equipment/procedure design, installation, inspection, etc. |
| Internal Human Malfunction |
| Detection |
| Identification |
| Decision |
| Action |
| External Mode of Malfunction |
| Specified task not performed |
| Commission of erroneous act |
| Commission of extraneous act |
| Accidentally coincidental events (sneak path) |

assessments identify all risks (including human error) that a system is exposed to, describe associations among these risks, quantify risk likelihood, and express this information in a fault tree or event tree representation. Human reliability analyses provide more detailed assessment of the human-related risks inherent in systems. Human reliability analyses identify human errors as the failure to perform an action, failure to perform an action within the safe operating limits (e.g., time, accuracy), or performance of an extraneous act which degrades system performance. Human error probabilities are then defined for each identified error as the ratio of the number of errors occurring in a certain interval, to the number of opportunities for occurrence. Human error probabilities may derive from either actual observation or simulation techniques. In addition to more traditional simulations (Seigel et al., 1975), simulation approaches have been developed which computationally represent a dynamic model of the human operator, tasks, and external situational factors (e.g., Woods et al., 1987; Cacciabue et al., 1993). Extensions of traditional HRA recognize the importance of considering the influence of environmental characteristics on the propensity for human errors and have included these "performance shaping factors" (PSFs) in calculations of HEPs (Kirwan, 1992a) and in rich simulations of the environment. One disadvantage of the HRA approach, is that it requires that the system exists in order to observe these error modes and collect data on error rates. As such, this method is of limited use in designing safe systems from inception. Simulation approaches provide the advantage of real-time generation of (simulated) human errors in response to (simulated) external conditions and events, and thereby avail predictive information by changing simulated conditions.

### 2.2. Human error classifications

The second major approach to investigating human error is more qualitative; that is to classify types of human errors. It is beyond the scope of this paper to review the spectrum of human error classification systems (see Reason, 1990; Woods et al., 1995) for a more detailed treatment of human error. Rather, this section describes three basic forms that these system may take, provides representative examples, and concludes by emphasizing the need for a holistic approach to classifying human error.

Human error classification schemes have been described as behavioral, contextual, or conceptual in nature (Reason, 1990). Behavioral classifications describe human errors in terms of easily observed surface features. Behavioral classifications partition human errors on such dimensions as their formal characteristics (omission, commission, extraneous) (e.g., Swain and Guttman, 1983), immediate consequences (nature and extent of injury or damage), observability of consequences (active/immediate vs. latent/delayed) (Reason and Maddox, 1995), degree of recoverability, and responsible party. These classifications provide no mapping of surface characteristics to causal mechanisms. Contextual classifications begin to address causality by associating human errors with characteristics of the environmental and task context. These classification systems are valuable because they emphasize the complex interactions among system components, including human operators, and generally result in richer data collection of circumstances surrounding incidents and accidents. However, contextual classifications are really correlational and not necessarily indicative of causal relationships. Further, these correlational classifications cannot, alone, explain why similar environmental circumstances do not deterministically produce repeatable errors (Reason, 1990).

Conceptual classification systems attempt to establish causality in terms of more fundamental, and likely predictable, characteristics of human behavior. Norman's (1981) distinctions between slips and mistakes is perhaps the simplest classification scheme in this category. Slips are failures in executing the correct intention. Mistakes result from mistaken intentions. More elaborate classifications typically begin with a model of human information processing and define error types based on the failure modes of information processing stages or mechanisms (e.g., Reason, 1990; Rouse and Rouse, 1983). Categories of systematic error mechanisms (effects of learning, interference among competing control structures, lack of resources, and stochastic variability) have been identified for each of three levels of cognitive control (skill, rule, knowledge) (Rasmussen and Vicente, 1989). Prabhu et al. (1992b) organize error shaping factors by these same levels of cognitive control. Although most useful for establishing causality and for predicting human error, conceptual classifications rely on theoretical inferences rather than observable data and are therefore more open to argument. These human error classifications address the error-proneness of information processing mechanisms of an individual operator.

A smaller contingent cautions that such efforts may drive human error research to be "individualistically myopic" (Quintanilla, 1987). That is, to stress the cognition of the individual to the exclusion of social and organizational factors (Quintanilla, 1987). Reason (1990) classifies human errors based on social values to distinguish between, strictly, errors and violations. Errors are, as described above, unwitting deviations. Violations are deviations from operating procedures, recommended practices, rules or standards that are deliberate. Reason (1990) also distinguishes between violations and sabotage. Violators intend the deviating acts, but not their potential for bad consequences. Saboteurs, however, intend both the deviating act and its bad consequences. Violations are shaped by three inter-related social factors: behavioral attitudes, subjective norms, and behavioral control (Reason and Maddox, 1995). Operators who commit attitudinal violations, do so simply because they know they can; and consciously weigh perceived advantages against possible penalties or risks. Operators who are concerned with the perceptions of subjective norms, may commit violations because they seek the approval of others. Finally, operators may not be able to exercise the behavioral control to not commit a violation. Other organizational factors which contribute to human error relate to the manner in which groups of individuals interact (e.g., Reason, 1987).

These classification schemes characterize various aspects of human errors. To fully address the causes and effects of human error, however, a more holistic approach is required. Rasmussen (1982) emphasizes this need to place errors in a rich context. His taxonomy (Table 1) considers not only mechanisms of human information processing malfunction, but also the task, situation factors (task, physical, and work time characteristics), operator affect and intentions, and ultimately, the external expression of the error.

### 2.3. *Responding to human error*

Perhaps the single most important contribution of human error investigation methods, both HRA and human error classifications, is to emphasize that the goal of such investigations is not to attribute blame. Rather, errors are traced beyond the operator who committed it to identify predisposing characteristics of the environment and task. Typically, accident investigations back track until *a* cause is identified (Rasmussen, 1985). Because it is usually possible to identify cases where an operator's failure to take compensatory actions allows a developing failure to become expressed, these failures are often attributed to human error. Such naive attributions of blame to the generic fallibility of human operators often halt accident investigations prematurely, obviating the opportunity to identify other causal or performance-shaping factors and develop interventions (Woods et al., 1995; Reason, 1990; Lorenzo, 1990). Reason (1990) suggests that in order to break out of this "blame cycle" we must recognize that: (1) human performance is shaped by situational and environmental contexts, (2) simply instructing someone to not take an action they did not intend to take in the first place is not very effective, (3) errors result from multiple contributing factors, and (4) the relevant characteristics of situations and environments are usually easier to alter than the relevant characteristics of operators (Allen and Rankin, 1995).

Of course the most obvious response to a human error is to identify the causal mechanisms and alter the system such that that error is not repeatable. Unfortunately this requires a sophisticated error-detection system, capable of identifying complex interactions, and the impractical assumption that human variability is minimal. Some would argue that even if eliminating all human error were possible, it may not be desirable. Rasmussen (1990) argues that what we call *errors* are unavoidable side effects of operators' exploration of the boundaries of acceptable performance. He contends that errors, or near errors, serve a valuable purpose in developing and maintaining operator expertise. Along similar lines, Senders and Moray (1991) suggest that eliminating the opportunity for error severely limits the range of possible behavior and thus inhibits trial and error learning, and reduces the flexibility of human operators. They argue that the key is to reduce the undesirable consequences of the error, and not necessarily the error itself. They therefore postulate the concept of an error-forgiving design, rather than an error-free design as a goal.

Hollnagel (1990) also argues that error tolerant system designs are necessary. He points out that knowledge about the limitations of human capacity (e.g., with regard to perception, attention, discrimination, memory) is used while making reasonable assumptions for system design. Such design decisions reduce the probability of system-induced human errors, those errors that can be traced back to particular configurations of the human–machine system (e.g., the interface design, the task design). However, Hollnagel (1990) suggests that system designers often overlook the fact that human capacity is variable and the actual variance could be larger than the expected variance in many situations. In other words, there is a category of errors that result from the inherent variability of human cognition. One approach to addressing this problem would be to reduce the requirements for performance until they were met by a preponderance of the situations. However, this could mean that the system would perform below capacity in the majority of the cases and the human operator might be underloaded. An alternate approach would be to design the system with error tolerance. Hollnagel (1990) proposes that an error tolerant system would:

- provide user with appropriate information at the appropriate time to minimize the opportunity for system induced erroneous actions,
- compensate for human perceptual dysfunction by providing information in redundant and simplified forms,
- compensate for human motor (and cognitive) dysfunction by maintaining the integrity of input data (through anticipation and context-dependent interpretation),
- contain provisions for detecting erroneous actions and for instigating corrective procedures,
- allow easy correction and recovery of erroneous actions by providing a forgiving environment.

Similarly, Rasmussen and Vicente (1989) provide guidelines for designing system interfaces that tolerate human error:

- Make limits of acceptable performance visible while still reversible.
- Provide feedback on the effects of actions to help cope with time delays.
- Make latent conditional constraints on actions visible.
- Make cues for actions, and represent necessary preconditions for their validity.

- Supply operators with tools to perform experiments and test hypotheses.
- Integrate cues for action.
- Support memory by externalizing effective mental models.
- Present information at the most appropriate level for decision making.
- Present information embedded in a structure that serves as an externalized mental model.
- Support memory of items, acts, and data that are not integrated into the task.

Reason (1990) suggests that systems could be designed to minimize violations by changing the organizational culture and social norms, and individual beliefs/values.

## 3. Aviation maintenance tasks and environments

Aviation maintenance and inspection tasks occur within the larger context of organizational and physical environmental factors. A system model of aviation maintenance and inspection (Latorella and Drury, 1992) defines four interacting components in this system (operators, equipment, documentation, and task) and suggests that these components interact over time as well as within both physical and social, or organizational, environments. In addition to considerations of the tasks performed, the system model emphasizes the interactions among operators, interactions of operators with equipment and documentation used, and the physical and job environment in which these tasks occur. *Operator* classifications include inspection and repair personnel at various organizational levels (line operators, lead operators, foreman level operators) as well as production foremen and engineers. The *equipment* used in inspection and maintenance tasks ranges from common tools (e.g., flashlights, mirrors, rulers) to more elaborate equipment requiring specialized training, such as that required for non-destructive testing/inspection (NDT/NDI) (e.g., eddy-current, magnetic resonance, dye-penetration techniques). The *documentation*, or more broadly, the *information environment*, used in inspection and maintenance includes not only those required and used to perform specific inspection and maintenance tasks (e.g., graphics and procedures in work cards, reference materials, defect reporting forms), but also those necessary to coordinate inspection and maintenance activities (e.g., shift turnover forms). The *physical environment* is defined by parameters such as temperature; noise level and type; lighting level, color, and distribution; and the presence of potential physical and chemical hazards to operators. For example, precautions must be exercised to ensure that personnel are not exposed to radiation during X-ray NDT inspections, or to excessive fumes when inspecting inside a fuel tank. The physical environment includes not only these ambient characteristics but also characteristics at the *workspace*, such as the adequacy of task-lighting provided by a flashlight (Reynolds et al., 1993). The *organizational environment* is equally important and is receiving increased attention in aviation maintenance. The following sections more fully characterize aviation maintenance and inspection tasks and the surrounding organizational setting.

### 3.1. Aviation maintenance and inspection tasks

The typical definition of human error in maintenance and inspection refers to the activities of the inspector or repair person. Drury (1996) describes the functions at this level of the system as (1) planning, (2) opening/cleaning, (3) inspection, (4) repair, and (5) buy-back. Initially, a team including the FAA, the aircraft manufacturer, and start-up operators, defines maintenance and inspection procedures for commercial aviation airlines.

Work items are defined by predictive models of equipment and material wear, and are informed by prior observations, as well as incidents and accident investigations. Airlines then define actual schedules in a process that must meet legal requirements (Shepherd et al., 1991). This process requires considering interference between inspection and repair tasks due to required access, equipment and/or personnel constraints, in an effort to minimize total aircraft out-of-service time. There are typically four types of inspection/maintenance checks. These range in the degree of inspection and maintenance work from the least detailed (flight line checks and A-checks) to the heaviest level (D-checks). The result of this *planning* function results in packaging maintenance and inspection items into a check, and generating work cards which specify these items and procedures for accomplishing their inspection/repair/replacement.

The *opening/cleaning* function prepares the inspection/repair area. Prior to inspection, the area must be cleaned and devoid of any oil, hydraulic fluid, or other visual interference. Typically, access panels are removed and internal cleaning must be performed. Cleaning and area preparation are usually performed by different personnel than inspection and repair operations. *Inspection* can be performed either visually (also using tactile and auditory cues) or using non-destructive testing methods, (e.g., eddy-current, ultrasonic, magnetic resonance, X-ray, and dye penetration) (Latia, 1993), which provide an abstracted or enhanced signal for visual interpretation. Regardless of the method, the inspection function includes the following sub-functions: (1) initiate, (2) access, (3) search, (4) decide, (5) respond (Drury, 1996,1994; Drury et al., 1990). Inspection begins with an inspector obtaining a work card and any equipment required for the job it specifies. After obtaining this equipment and understanding the requirements of the work card, the inspector locates the inspection site. Inspection requires searching the target area either visually or with the appropriate equipment until all items are addressed or the entire area is searched. As indications appear, inspectors must determine if they are faults or not. Faults identified during search are recorded for repair and buy-back inspection. Table 2 provides an example of these inspection functions for both visual and eddy-current inspection (Drury, 1996).

The *repair* function also begins with a work card. Repair work cards specify the repair job, procedure for repair, and note additional reference materials required. The repair function can be decomposed into sub-functions similar to the inspection subfunctions: (1) initiate, (2) site access, (3) part access, (4) diagnosis, (5) replace/repair, (6) reset systems, (7) close access (Drury, 1996). Repair begins with access of the appropriate work card, equipment, and parts for the repair. The repair person then locates the site of the repair and removes any additional parts to access the element requiring repair. Removed items are inspected and stored. Technicians perform diagnostic procedures specified by the work card and determine whether to repair or replace the target element. Once this determination is made, technicians may need to obtain additional parts before actually repairing or replacing the element. After the repair/replacement, the relevant systems are reset, fluid levels are restored, and the system adjusted to specification. The repair function concludes by closing the access to the target area and making final adjustments. Table 3 shows a decomposition of the repair function (Drury, 1996). Repairs may be performed on the aircraft itself, or as a sub-component process off-line.

Table 2
Examples of inspection functions: Visual and eddy-current (Drury, 1996)

| Function | Visual inspection | Eddy-current inspection |
|---|---|---|
| Initiate | Get work card<br>Read and understand requirements | Get work card and equipment<br>Read and understand requirements<br>Calibrate eddy-current equipment |
| Access | Locate area on aircraft<br>Assume correct position for viewing | Locate area on aircraft<br>Position equipment |
| Search | View area systematically<br>Stop if any indication detected | Move probe over rivet heads systematically<br>Stop if any indication detected |
| Decide | Compare indication against remembered standards (e.g., for corrosion) | Re-probe while closely watching signal on equipment monitor |
| Respond | If indication exceeds standards, mark defect and create repair sheet<br>Else, continue searching | If indication confirmed, mark defect and create repair sheet<br>Else, continue searching |

Table 3
Generic repair functions and tasks (Drury, 1996)

| Function | Tasks |
|---|---|
| Initiate | Read and understand work card<br>Prepare tools and equipment<br>Collect parts and supplies<br>Inspect parts and supplies |
| Site Access | Bring parts, supplies, tools and equipment to work site |
| Part Access | Remove items to access parts<br>Inspect/store removed items |
| Diagnosis | Follow diagnostic procedures<br>Determine parts to replace/repair<br>Collect and inspect more parts and supplies if required |
| Replace/Repair | Remove parts to be replaced/repaired<br>Repair parts if needed<br>Replace parts |
| Reset Systems | Add fluids/supplies<br>Adjust systems to specification<br>Inspect adjustments |
| Close Access | Refit items removed for access<br>Adjust items refitted<br>Remove tools, equipment, parts, and excess supplies |

A second maintenance person, usually an inspector, may re-inspect, or "buy-back", a repair before the item is closed (Drury, 1996). Prior to returning an aircraft to service, all scheduled items and additional items resulting from inspection must be either certified as complete or logged as deferred. Maintenance deferral is only possible in certain pre-defined situations, for items which are not safety-critical (Drury, 1996). These items are treated on the next scheduled, or event-driven maintenance cycle.

### *3.2. Organizational context*

The aviation maintenance and inspection system includes not only the individual technicians performing the functions above, but personnel in the organization level of the airline as well as at regulatory agencies, aircraft manufacturers, and component vendors. The organizational context in which aircraft maintenance and inspection occurs is equally important to an understanding of human error as the inspection and repair functions themselves.

At a higher level, the planning function translates organizational requirements (i.e., those imposed by regulatory agencies and manufacturers) into requirements for airline carriers, and consequently translates these requirements into a schedule of local activities for inspection or repair personnel. Another function of the organizational level is to provide quality control and assurance of the inspection and maintenance processes. Quality control in aircraft maintenance and inspection results from surveillance and auditing actions of regulatory agencies (e.g., Federal Aviation Administration (US FAA), Civil Aviation Authority (UK CAA)), as well as quality assurance functions in the airline companies (Drury, 1996). Quality assurance functions include: checking engineering change orders, auditing inspection and maintenance activities for errors, auditing components (and vendors) used for replacements, and examining record keeping (Drury, 1996). Failures of quality assurance as well as regulatory policies/practices allow maintenance and inspection human errors. These errors, and propagating effects of these errors, decrease aviation safety.

In addition to these specific functions, general organizational characteristics influence performance at the individual level. Organizational factors (e.g., definition of work groups/isolation of workers, reporting structures, payoff structures, and issues of trust and authority) demonstrably affect patterns of work in aviation maintenance operations (Taylor, 1990). More specifically, human error in a major airline carrier's maintenance facility is influenced by characteristics such as organizational structure, people management, provision of quality tools and equipment, training and selection, commercial and operational pressures, planning and scheduling, maintenance of building and equipment, and communications (Rogan, 1995a).

## 4. Human error in aviation maintenance

The previous section briefly outlines the functions involved at the individual and organizational levels of aviation maintenance and inspection. However, these simple descriptions do not convey the complexity of this system. Modern aircraft and the systems embedded in them are increasingly technologically complex. New methods for inspecting and diagnosing these systems are increasingly specialized. Further, inspecting and maintaining commercial aviation is organizationally complex; emerging from a socio-technic process in which hundreds, even thousands, of people are directly involved (Taylor, 1990).

These conditions combine to produce a work environment that predisposes the humans working in this system to err. For example, given that there are 14 different kinds of attachment lock mechanisms in a narrow body aircraft seat, the chances of overlooking a poorly locked seat are very high (Lutzinger, 1992). Attempts to simultaneously accomplish the competing goals of safety, timeliness, and profit result in implicit time pressures. Organizational/economic pressures may motivate operators to violate inspection/maintenance practices. Consequences of errors are not immediately obvious (Graeber and Marx, 1993). For example, in one accident a faulty maintenance action did not have an observable effect until 17 months after it occurred (NTSB, 1990). Delayed feedback dramatically reduces the ability of operators to learn from errors. Such delays also impede accident investigation because situational factors surrounding the offending "human" error are lost. In addition, because different types of maintenance problems present themselves randomly to individual operators, it is difficult for any one operator to identify what may be a systematic problem in an aircraft type or mechanism (cf. Inaba and Dey, 1991). Aircraft maintenance often spans multiple days and multiple shifts, making coordination of activities and information amongst different operators over different shifts very difficult. Quality control audits and inspections and error reporting systems obtain data on inspection and repair performance. However they do not typically provide consistent or timely feedback to operators on actual errors. Further, feedback during training for inspection tends to focus on procedural aspects of the task (e.g., setting up NDT equipment and troubleshooting rules) rather than providing feedback for other, more cognitive, aspects of the inspection task (e.g., making perceptual judgments) (Prabhu and Drury, 1992).

Given these complexities, it is not surprising that human operators in this system commit errors. Aviation maintenance and inspection errors can be described in terms of their most immediate, observable effect on aircraft equipment, ultimate effects on flight missions (incidents/accidents), and secondary effects on the airline carrier industry. Further, forms of errors in aviation maintenance and inspection are defined as failure modes of the tasks involved in their functions. The incidence and forms of aviation maintenance and inspection human errors are described in these terms below.

### 4.1. *Effects of maintenance errors on aircraft equipment*

Several studies have identified the most common, immediate effects of human error in aviation maintenance. A major airline shows the distribution of 122 maintenance errors over a period of three years to be: omissions (56%), incorrect installations (30%), wrong parts (8%), other (6%) (Graeber and Marx, 1993). A three year study by the Civilian Aviation Authority (CAA) found the eight most common maintenance errors to be: incorrect installation of components, the fitting of wrong parts, electrical wiring discrepancies (including cross connections), loose objects (tools, etc.) left in the aircraft, inadequate lubrication, cowlings, access panels and fairings not secured, fuel caps and refuel panels not secured, and landing gear ground lock pins not removed before departure (UK CAA, 1992, cited in Allen and Rankin, 1995). In-flight engine shut downs on Boeing 747's in 1991 were due to the following human errors, in order of occurence frequency, (Pratt and Whitney study cited in Graeber and Marx, 1993):

- missing or incorrect parts,
- incorrect installation of parts or use of worn/deteriorated parts,
- careless installation of O-rings,
- B-nuts not safety wired,
- nuts tightened but not torqued or over-torqued,
- seals over-torqued,

- not loosening both ends of connecting tube replacement,
- replacing tube assembly without first breaking connections between matching parts,
- not tightening or replacing oil-tank caps,
- not cleaning or tightening cannon plugs,
- dropping foreign objects into engines,
- allowing water in fuel, allowing Skydrol in oil system.

Data collected at a major US airline (Prabhu and Drury, 1992) revealed several major categories of human errors in maintenance and inspection tasks, these are:

- defective component (e.g. cracked pylon, worn cables, fluid leakage),
- missing component (e.g., bolt-nut not secured),
- wrong component (e.g., incorrect pitot static probes installed),
- incorrect configuration (e.g., valve inserted backwards),
- incorrect assembly sequence (e.g., incorrect sequence of inner cylinder spacer and lock ring assembly),
- functional defects (e.g., wrong tire pressure, over-tightening nuts),
- tactile defects (e.g., seat not locking in position),
- procedural defects (e.g., nose landing gear door not closed).

### *4.2. Accidents due to maintenance errors*

The types of maintenance errors contributing to accidents range from glaring omissions that are the direct cause, to more minor errors which combine with other off-normal occurrences to create these accidents (Graeber and Marx, 1993). Estimates of the contributions of maintenance factors to the incidence of aviation accidents and incidents vary. Sears (1986 cited in Graeber and Marx, 1993) states that maintenance was a contributing factor in 12% of the international accidents that occurred between the years 1959 and 1983 (Graeber and Marx, 1993), and flawed maintenance practices were the major factor in 3% of these cases (Boeing, 1993a). In a more recent survey, Boeing (1993b) found that changes in maintenance and inspection could have prevented approximately 16% of the hull losses and almost 20% of all accidents that occurred between 1982 and 1991. For this period, maintenance and inspection factors were implicated in 47 accidents in total, these accidents resulting in 1481 onboard fatalities (Graeber and Marx, 1993).

Several fairly recent accidents have been attributed, at least in part, to human error in maintenance and inspection operator tasks. Failure to install O-ring seals on an L-1011's engines allowed oil to leak out, eventually resulting in two of the three engines ceasing operation due to oil starvation (NTSB, 1984; Strauch and Sandler, 1984). The pilot had shut down the third engine earlier in the flight in response to a low oil indication, but was able to restart this engine and successfully reached the airport. Maintenance on a Continental Express EMB-120 was not adequately transferred to a second shift (NTSB, 1992). Forty-seven screws on the left horizontal stabilizer were not replaced, causing the leading edge to separate in flight and resulting in 14 fatalities (Shepherd and Johnson, 1995; NTSB, 1992). Failure to detect a pre-existing metallurgical defect resulted allowed a fatigue crack to form in a critical area of a DC-10's fan disk. Compounding the initial error, the resulting fatigue crack itself was unnoticed during inspection. In flight, this situation resulted in separation and discharge of the rotor assembly, catastrophic failure of the #2 engine, consequent severing of the flight-control hydraulic systems, and ultimately the loss of 111 lives and many other injuries (NTSB, 1990). In the Aloha Airlines accident (NTSB, 1989), failure to detect multiple site damage resulting from joining cracks resulted in hull failure and a crash landing. This error caused the catastrophic loss of the aircraft, and only exceptional pilot performance presented numerous fatalities in this accident.

In addition, accident investigators note the contributions of organizational factors to aviation accidents. Reason and Maddox (1995) describe the concept of an organizational accident/incident as one in which management decisions, emerging from the corporate culture, generate latent failures that are transmitted to the workplace where they create a local climate that promotes errors and violations. These latent failures occasionally break through engineered safety features (e.g., design, standards, procedures) to cause an accident/incident.

For example, while the Continental Express accident described above was primarily caused by a repair person's error (i.e., not replacing the horizontal stabilizer screws), the accident could not have occurred if both the air carrier's quality assurance functions and FAA's regulatory surveillance were attentive. Similarly, analysis of the Sioux City accident (NTSB, 1990) implicated inspection and quality control procedures during the engine overhaul process. Although correctly performed maintenance could have prevented the Aloha Airlines accident, this accident was attributed to both failure of inspectors to detect cracks, and failure of fatigue models to correctly anticipate crack growth and indicate required inspection (Drury, 1996). For every aircraft design, routine inspections, and occasionally replacement/repairs, are required at pre-defined intervals to prevent failures from developing (Hagemaier, 1989). Models of crack propagation, based on structural and material fracture mechanics, define these intervals (Goranson, 1989). Drury (1996) notes that this process invites misinterpretation of failures in model prediction as fundamentally human errors of inspection or repair. Accident investigation of the TWA Flight 843 that was destroyed following an aborted take-off found the precipitating event to be a malfunction in an angle-of-attack (AOA) sensor in the stall warning system. Although other factors were involved, the investigation report emphasizes that the precipitating cause was the failure of TWA's maintenance and quality assurance trend monitoring programs to detect the intermittent AOA malfunction.

While the self-auditing role of air carriers is undeniably important, the role of an independent and attentive regulatory agency is critical. Only one example is necessary to underscore this point. In 1990, Eastern Airlines and many of its top executives were indicted by a grand jury for falsifying maintenance records, disregarding FAA requirements that repairs be examined, and creating false records to indicate that required, scheduled maintenance had been performed (Nader and Smith, 1994). Without an independent regulatory agency's critical review of airline and manufacturer practices, the opportunity exists for the unscrupulous to optimize economy at the expense of safety.

### 4.3. Other effects of human errors in aviation maintenance

Accidents due to human error forcefully underscore the potentially dire consequences of maintenance errors on aviation safety. The relative rarity of these accidents, however, does not imply that maintenance errors are as rare. Accidents typically result from the combination of causal factors and must overcome several lines of defense. In addition to those that precipitated or facilitated the above accidents, maintenance errors with no direct consequences have been detected. For example, the accident investigation of the China Airlines, Flight 583 (which became unstable after leading edge slats were deployed at cruise altitude) detected that a rubber plug was left in the maintenance position for rigging the slat control system (NTSB, 1993a). Douglas Aircraft Company engineers stated that although the plug should be removed after maintenance, its presence did not affect the operation of the slat system. So maintenance errors may exist that, given other defense mechanisms built into the system are in place, are not consequential and therefore not usually detected. It is tempting to dismiss such seemingly inconsequential errors as unimportant. They are mentioned here for two reasons. First, errors which seem inconsequential may, in other circumstances, interact with other off-normal situations to result in a "sneak-path" accident. Second, even if a particular erroneous result is not damaging in effect, it may indicate a predisposing condition in the environment, task or operator's knowledge that may result in an error of greater consequence.

Although accidents are the most salient and poignant effects, human errors in maintenance activities have other important consequences. For example, maintenance errors have required air turn-backs, delays in aircraft availability, gate returns, in-flight shutdowns, diversions to alternate airports, maintenance rework, damage to maintenance equipment, and injury to maintenance personnel. Gregory (1993) finds that 50% of all engine-related flight delays and cancellations are due to improper maintenance. Thirty-three percent of all military aviation equipment malfunctions result from poor prior maintenance or improperly applied maintenance procedures (Ruffner, 1990). These consequences ultimately affect customer satisfaction and airline company productivity and profit. The negative effects of human error in aviation maintenance, as reflected in accidents, incidents, and other operational inefficiencies, are clear.

### *4.4. Predicting forms of inspection and maintenance human errors*

Extensions of human reliability and human error classification methods to the aviation maintenance and inspection area are rare. This section presents three approaches to studying aviation maintentance and inspection errors beyond simply cataloging their overt consequences to equipment. Most similar to the HRA approach, one study employs a fault tree analysis to investigate and quantify human error in aircraft inspection (Lock and Strutt, 1985). Lock and Strutt (1985) develop a flowchart to describe the inspection process (Fig. 1). Analysis of this flowchart yields six potential errors in the inspection process (Table 4), which may co-occur in more complex error forms. These errors are then represented in a fault tree (Fig. 2). Lock and Strutt (1985) identify five PSFs relevant to aircraft inspection (area accessibility, general area lighting, access and visual enhancement tools, motivation/attitude, and work method) and provide relative weights to indicate their importance for each inspection step. However, noting the difficulty of quantifying the probabilities needed to complete this fault tree, the authors do not actually perform an HRA analysis of human error probabilities.

Drury (1991) describes human error phenotypes based on the previously described model of maintenance and inspection functions. He defines these human errors by decomposing inspection functions into tasks, and identifying the failure modes of these tasks. These error categories were refined through observation of inspections, and discussions with inspectors, supervisors, and quality control personnel (Drury et al., 1990; Drury, 1991). Table 5 presents a sample of this error taxonomy. The taxonomy above only presents errors as observed, that is phenotypes of erroneous actions in aviation maintenance and inspection. Drury (1991) also provides a classification scheme for genotypes, the underlying mechanisms, of human error in aviation maintenance and inspection. He bases this classification scheme on Rouse and Rouse's (1983) error framework (Table 6).

In a different vein, Foyle and Dupont (1995) identify the twelve most common causes of maintenance personnel's "judgment interference." The motivation for this effort is a quote by Jerome Lederer, President Emeritus of the Flight Safety Foundation, "(Maintenance) error is not the cause of an accident. The cause is to be found in whatever it was that interfered with the (maintenance person's) judgment at a critical moment, the outcome of which was a maintenance error (Foyle and Dupont, 1995)." Table 7 explains this judgment interference in terms of a specific accident: on July 11, 1991, an aircraft maintenance technician (AMT) who was aware that at least two tires on a Nationair DC-8 had low pressure, boarded the aircraft and perished with 260 other persons.

## 5. Managing human error in aviation maintenance

Great strides have been made towards Secretary Peña's goal of zero accidents. On a national level, the 1995 National Safety conference (FAA, 1995) called for additional human factors research focused on error detection and prevention. Specifically, it suggested that the FAA flight standards should establish a national data base for aviation human factors research, develop a maintenance error analysis tool prototype, and develop a system for maintenance personnel based on the same principles as the Crew Resource Management (CRM) program for the cockpit. This section reviews recent efforts towards detecting and managing human error.

### *5.1. Detecting human errors in aviation maintenance and inspection*

Detecting systemic human errors, and associated performance shaping characteristics, is difficult due to low error rates, distributed occurrence over the system, and variability of error phenotypes for the same error genotype. There are two fundamental methods for detecting errors in aviation

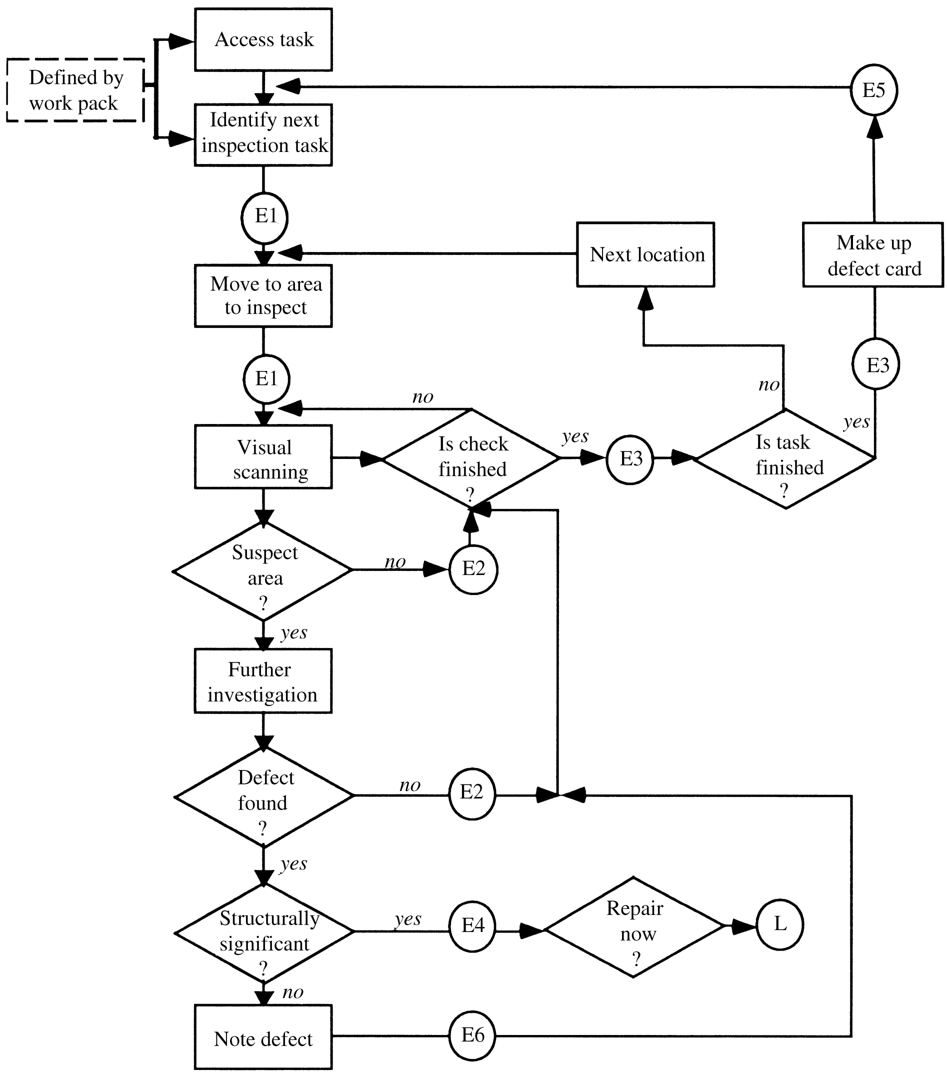


Fig. 1. Inspection Model Flowchart (adapted from Lock and Strutt, 1985).

Table 4
Potential errors in the inspection process (Lock and Strutt, 1985)

| Error Location in Flowchart | Definition |
|---|---|
| Scheduling (E1) | Wrong execution of either of the two tasks: "identify next inspection" or "move to location" |
| Inspection (E2) | Not seeing a defect when one exists |
| Inspection (E3) | If human induced, due to either forgetting to cover area, covering area "inadequately" or a scheduling error |
| Engineering Judgment (E4) | An error in deciding whether the area in which a defect is found is significant or not |
| Maintenance Card System (E5) | Arises because the work cards themselves may not be used to note defects on the hangar floor immediately as they are found |
| Noting Defect (E6) | The error is noted incorrectly or not noted at all |

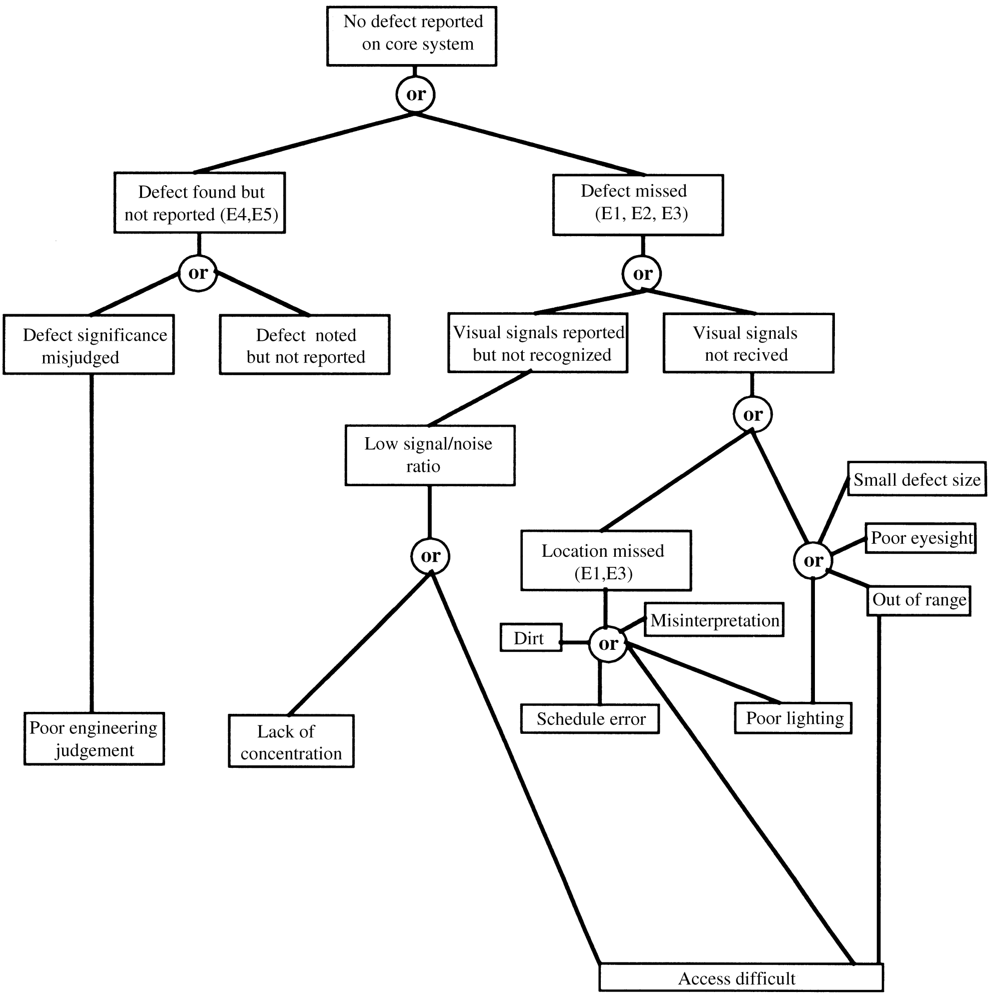


Fig. 2. Inspection Error Fault Tree (Lock and Strutt, 1985).

maintenance. The first detects human errors retroactively, and is based on error reporting responses to system-defined performance deviations. In contrast, there are other, more pro-active detection methods. This section reviews error reporting and pro-active error identification methods of detecting human error in aviation maintenance and inspection in the commercial aviation system.

### *5.2. Reporting errors in aviation maintenance and inspection*

Error reporting systems characterize, to varying degrees, perceived causes of a negative event. Error reporting systems, then, may identify human error contributions for a particular incident and may identify, as a result of this incident, systemic problems. These systems are therefore, reactive to errors inherent in the system. There are many different forms of error reporting systems. Most current error reporting systems show some common features (Drury, 1991; Latorella and Drury, 1992):

- They are event driven – the system captures data only if a difficulty arises or defect is found.
- Aircraft type and structure serve as the major classification type for reporting.

Table 5
Sample of aircraft maintenance and inspection errors by task step (Drury, 1991)

| Tasks for "Initiate" function | | Error(s) | |
|---|---|---|---|
| 1.1 | Correct instructions | 1.1.1 | Incorrect instructions |
| | | 1.1.2 | Incomplete instructions |
| | | 1.1.3 | No instructions available |
| 1.2 | Correct equipment procured | 1.2.1 | Incorrect equipment |
| | | 1.2.2 | Equipment not procured |
| 1.3 | Inspector gets instructions | 1.3.1 | Fails to get instructions |
| 1.4 | Inspector reads instructions | 1.4.1 | Fails to read instructions |
| | | 1.4.2 | Partially reads instructions |
| 1.5 | Inspector understands instructions | 1.5.1 | Fails to understand instructions |
| | | 1.5.2 | Misinterprets instructions |
| | | 1.5.3 | Does not act on instructions |
| 1.6 | Correct equipment available | 1.6.1 | Correct equipment not available |
| | | 1.6.2 | Equipment is incomplete |
| | | 1.6.3 | Equipment is not working |
| 1.7 | Inspector gets equipment | 1.7.1 | Gets wrong equipment |
| | | 1.7.2 | Gets incomplete equipment |
| | | 1.7.3 | Gets non-working equipment |
| 1.8 | Inspector checks/calibrates equipment | 1.8.1 | Fails to check/calibrate |
| | | 1.8.2 | Checks/calibrates incorrectly |

Table 6
Example of possible errors in calibrating NDI task step (Drury, 1991)

| Level of Processing | Possible Errors[a] |
|---|---|
| 1. Observation of system state | Fails to read display correctly |
| 2. Choice of hypothesis | Instrument will not calibrate. Inspector assumes battery is low |
| 3. Test of hypothesis | Fails to use knowledge of NiCads to test |
| 4. Choice of goal | Decides to search for new battery |
| 5. Choice of procedure | Calibrates for wrong frequency |
| 6. Execution of procedure | Omits range calibration step |

[a]This example is for task 1.8.2 shown in Table 5.

- Data is further classified, and its urgency determined, using expert assessment of error criticality.
- Feedback is not well-formatted to be useful to operators.
- Error reports can result in changes to maintenance and inspection procedures.

This section identifies two forms of error reporting. First, accident investigations and incident reports are considered as a form of error reporting. Second, we consider error reporting systems in the most conventional sense, those residing within airline companies and more formal regulatory reporting systems.

#### 5.2.1. *Accident investigations*

The National Transportation Safety Board (NTSB) conducts investigations of aviation accidents in which there is any loss of life or significant aircraft damage. These investigations routinely consider whether documentation reflects that

Table 7
Judgment interference in aviation maintenance personnel (Foyle and Dupont, 1995)

| Judgment Interference | Example |
|---|---|
| Lack of communication | The AMT did not inform the pilot that tire pressures were low, even after when the pilot stated "we got a flat tire, you figure?" on the final takeoff roll |
| Complacency | The tires had had low pressure for several days without attention |
| Lack of knowledge | Ignorance of the manufacturer's specifications for tire pressure |
| Distraction | (Any distraction to the AMT is unknown.) |
| Lack of teamwork | The AMT and the cockpit crew were flying together, yet did not appear to know maintenance status of the aircraft |
| Fatigue | AMTs did not go to sleep until at least 11 pm and were called up at 3 am. They had also been traveling with the aircraft and working on it during down time |
| Lack of resources | Nitrogen to inflate the tires was not readily available |
| Pressure | The AMT was apparently under much personal pressure to keep the aircraft flying for job security reasons |
| Lack of assertiveness | The base manager, who had no authority over the AMT, told him to "forget it" when it appeared they would be delayed 30 min if the AMT inflated the low tires |
| Stress | The AMT was counting on the success of this deployment to enable him to advance with the company and to be able to settle in Canada |
| Lack of awareness | The AMT was unaware that tire pressure was critical to the aircraftís safety |
| Norms | Company procedures allowed the AMT to make an error as an acceptable practice |

maintenance was performed as scheduled and was appropriate for the aircraft involved in the accident. Beyond this minimal investigation of maintenance performance, these investigations also consider whether inspection/maintenance personnel could have identified/repaired a problem that was not necessarily related to scheduled performance. Further, if an inspection/maintenance problem is implicated, the investigation extends to consider possible deficiencies in airline quality control and assurance programs, in the regulatory mechanism of the FAA, and in manufacturer's recommendations for scheduling inspection/maintenance tasks. These investigations result in recommendations to the airline companies (e.g., inspection/maintenance practices, environmental considerations, training, quality control and assurance practices), the FAA (e.g., ensure airlines adhere to maintenance schedules), and manufacturers (e.g., scheduling new or increasing the frequency of inspections/repairs/replacements). Investigation of the Continental accident (NTSB, 1992), described above, resulted in recommendations at the individual operator level (shift changeover), the airline level (quality assurance programs), and for the FAA (ensuring that airline quality assurance programs are sound).

Accident investigations can also result in the institution of specific inspections/repairs/replacement of components, or increase the frequency of inspecting/repairing/replacing certain components. For example, after identifying premature deterioration of seat cushion fire-blocking materials as a contributing factor in the China Eastern Airlines accident, the NTSB suggested that principle maintenance inspectors should inform operators of the need to "periodically inspect fire-blocking materials for wear and damage, and to replace defective materials (NTSB, 1993a)." Following the in-flight separation of an engine and engine pylon from a Boeing-747 due to a crack in the pylon forward firewall web, Boeing issued a service bulletin, calling for a detailed visual inspection of this area on Boeing-747 aircraft with similar engines (NTSB, 1993b). While NTSB reports thoroughly investigate the causal mechanisms of accidents and provide useful recommendations for addressing these failures in the system, relying on accident reports to identify these mechanisms is, aside from the obvious catastrophe of any loss of life, extremely inefficient. In addition, in order to perform the detailed analyses of accidents required, feedback at the operator level is diminished by its delay, and therefore contributing situational factors, are often missed.

*5.2.2. Anonymous incident reports*

The NTSB conducts formal investigations of accidents. Incidents are reported to the Aviation Safety Reporting System (ASRS), which is maintained by NASA though an independent contractor. The ASRS allows individuals to anonymously report incidents and problems to a centralized, non-regulatory repository. After clarifying details in the reports, ASRS personnel remove identifying information, allowing reporters to remain anonymous. Pilots are the primary users of this system and typically report incidents occurring during operation of the aircraft. Although mechanics also enter reports to the system, such contributions are much less frequent than the contributions of pilots. Maintenance/inspection issues, however, also arise from pilot-initiated reports. ASRS reports are searchable and are reviewed for salient or recurrent problems in a periodical, "Callback". Researchers can request key-word sorted compilations of ASRS reports. Thus, ASRS reports provide a means of identifying contributions of inspection and maintenance human error to aviation incidents.

One must exercise caution in using ASRS data. Several factors limit interpretation of this data: (1) reports are based on one person's perspective, and this perspective may be biased, (2) results of ASRS searches are not typically all-inclusive, rather they provide a sample of reports containing search terms, (3) the probability of reporting is ostensibly not equal over all types of incidents or potential reporters, therefore reports contained in the ASRS do not necessarily represent a statistically valid sample of actual occurrences. It is also important to note that, in exchange for reporting incidents, pilots receive limited immunity from FAA prosecution. Finally, although there is a mechanism for maintenance personnel to report incidents, ASRS reports are predominantly supplied by pilots. Despite these limiting considerations, ASRS reports provide useful information. They detail more examples of error phenotypes than NTSB reports, and provide a user's view of the factors involved, usually relatively soon after the incident. Allen and Rankin (1995) suggest that the aviation system would be well-served by an anonymous reporting system specifically for aviation inspection and maintenance technicians to report incidents during the maintenance process.

*5.2.3. Internal error reporting systems*

Airlines also maintain their own error reporting systems. Recent efforts have attempted to overcome three problems with prior generations of error reporting at the airline level: (1) error reporting systems have not been integrated within an airline, (2) performance shaping factors surrounding error occurrences are not well-documented in error reports, (3) error reporting systems have not been well integrated across airlines.

Most airlines monitor incidents and accidents in the system very stringently. Records are kept on such performance metrics as personnel injuries, aircraft or equipment damage, and delays. However, most of the error reporting systems are used separately by different departments and rarely used together to analyze the system as a whole (Wenner and Drury, 1996). Therefore, separate error reporting systems catalog different error phenotypes. This dissociation by error phenotype limits the ability to recognize what may be a common error genotype. Wenner and Drury describe a situation that highlights this problem: For example, if a mechanic drops a wrench on his foot, the incident would be recorded as an 'On the Job Injury'. If a mechanic drops a wrench on an aircraft, damaging it severely, the incident would be recorded as "Technical Operations Ground Damage." If the wrench was dropped on the aircraft, causing no damage, the incident would not be recorded at all. Finally, if a ground operations employee drops a wrench on an aircraft, the incident would be recorded as "Ground Operations Ground Damage." In each of these scenarios, the error (genotype) was exactly the same, only the final consequences (error phenotype) differed, differentiating the way in which each of these incidents is recorded. Clearly, the use of multiple reporting systems that are maintained by different departments, makes root error detection more difficult. Thus incident investigation and reporting tools must be developed so that they can be applied across airline systems. Wenner and Drury describe a prototype system, called the Unified Incident Reporting System (UIRS) that has a common reporting form and an outcome-specific form. The common reporting form gathers data for all incidents irrespective of whether the incident was a paperwork error, an injury, ground damage, or even had no adverse outcomes. This form then directs the user to one of the outcome specific forms based on the hazard patterns developed.

Airline error reporting schemes typically have been concerned with establishing accountability for an error and its consequences rather than understanding the causal factors and the situational context of the error. Analyzing data collected from an error reporting system that was designed to simply note consequences and assign accountability is usually fruitless. In these cases, accident/incident investigation usually terminates as soon as blame can be attributed to some human in the system. Similarly, error control methods derived from such an approach are usually in the form of reprimanding and further training the operator, and instituting an additional regulatory check for that specific occurrence. With such simplistic error reporting schemes, then, the situational context at the point of error is lost, and with it, the opportunity to more intelligently characterize and sensitively manage the true error mechanisms. A useful error reporting system must have a general theory of the task as well as situational factors which may affect task performance. The Maintenance Error Decision Aid (MEDA) developed by the Boeing Customer Services Division in cooperation with several airlines and the FAA, is an error reporting system that tries to capture the causality of an incident in terms of contributing factors. The objectives of MEDA are to (Allen and Rankin, 1995):

- Improve airline maintenance organizations' understanding of human performance issues.
- Provide line-level and organizational maintenance personnel a standard method for analyzing errors.
- Identify maintenance system deficiencies that increase exposure to error and decrease efficiency.
- Provide a means of error-trend analysis for commercial airline maintenance organizations.

MEDA has five-categories for reporting an error occurrence:

- General data (e.g., airline, aircraft type, tail/fleet #, date of incident, time of incident),
- Operational event data (e.g., flight delay, gate return, in-flight shut down, aircraft damage),
- Maintenance error classification (e.g., improper installation, improper servicing),
- Contributing factors analysis (e.g., factors related to information, equipment, airplane design, job, skills, environment, organization, supervision, communication. These include queries on correct information, inaccessible aircraft space, new task, inadequate task knowledge, time constraints, environment, poor planning),
- Corrective actions (i.e., intervention strategy in terms of: reviewing existing procedures and policies to prevent such incidents, and identifying new corrective actions for local level.).

In a recent field evaluation, MEDA appeared to meet its objectives (Allen and Rankin, 1995). Survey responses and evaluation of technicians' report forms indicated that MEDA provided a useful standardized investigation methodology to the maintenance organization. Technicians used response forms in a manner consistent with MEDA's standardized investigation methodology. The MEDA analysis identified some maintenance deficiencies. Finally, survey data indicated that maintenance personnel's understanding of human performance issues improved after using MEDA (Allen and Rankin, 1995). The field test also underscored the difficulty of instituting a new technology and process into an organization, and the need for human factors and process-specific training. Currently, MEDA is available to customer airlines as a means of improving their own maintenance operations and to improve communications with Boeing regarding design and manufacturing issues. MEDA promotes improvements in error reporting by more effectively capturing concomitant situational factors. In addition, by providing a common platform for error reporting, MEDA provides the opportunity for increased integration of error reporting among airlines and with manufacturers.

Results from internal error reporting systems reach the FAA via formal channels, such as Service Difficulty Reports and Voluntary Disclosures. The FAA, then, may disseminate information to manufacturers regarding specific maintenance problems by issuing Advisory Circulars and Airworthiness Directives. Advisory Circulars provide guidance for controlling the maintenance process and are non-mandatory. However, the FAA only issues Airworthiness Directives if it has conclusive proof of a problem. Adherence to Airworthiness Directives is mandatory. In addition to these reporting systems, manufacturers issue service newsletters and bulletins which contain some information on human error incidents.

### 5.3. Pro-active error detection methods

Error reporting systems are most useful for developing error management strategies to prevent the specific error addressed from reoccurring. In some cases, to the degree that situational factors and human error generating mechanisms are captured in these error reporting schemes, these systems may identify more generalizable systemic errors. However these methods are basically reactive; that is, an accident, incident, or other system-defined deviation must occur to precipitate these analyses. The safety of the aviation system would be much improved if we were able to identify systemic errors, and performance shaping factors of these errors, before incurring the costs associated with these precipitating events. The methods described below have recently been employed to pro-actively identify error-generating situations and characteristics of aviation maintenance and inspection operations.

#### 5.3.1. Audits

The Flight Standards service of the FAA performs periodic audits of airline inspection and maintenance programs. Most FAA audits are for regulatory purposes. These emphasize ensuring that airlines follow prescribed inspection and maintenance procedures, and have appropriate quality assurance programs. In addition to these formal, regulatory audits, errors may be detected by a human factors audit.

A human factors audit is a methodology for identifying lapses in work practices, inadequacies in the work environment, and human-task mismatches that can lead to human errors. Most audits are conducted using checklists and questionnaires. As part of a human factors audit, human factors experts with domain expertise may directly observe operators performing their jobs. These observers note the type, frequency, and cause of human errors. Observations are typically recorded according to a classification of failure modes guided by task analysis, and an understanding of relevant situational factors in the environment. As an example, Drury's aforementioned definitions of inspection and maintenance tasks were the foundation for identifying failure modes of these tasks. This classification scheme provided a structure for observing actual technicians' error patterns (Drury et al., 1990).

To conduct a human factors audit, one must first define: (1) how to sample (frequency and distribution of samples), (2) what factors to measure, (3) how to evaluate a sample (standards, good practices, and principles, for comparison), and (4) how to communicate results (Drury, 1997; Chervak and Drury, 1995). An audit must demonstrate validity, reliability, sensitivity, and usability. When properly used, audits can be an important means of pro-actively assessing error likelihood. However, audits can be somewhat difficult to conduct. They can be intrusive to the normal work environment. They must be performed by an individual with both human factors and domain expertise, usually a rare combination. It can be difficult to obtain a large enough sample size for a useful audit. Finally, the usual trade-offs exist between the breadth and depth of analysis, and time available to conduct the analysis. Drury (1997) describes implementation considerations, and factors affecting the success of audits. Galaxy Scientific Corporation has developed a computerized version of a human factors audit for aviation maintenance and inspection, ERNAP (Meghashyam, 1995).

#### 5.3.2. Subjective evaluations of system reliability

Some error detection systems use subjective rating scales to determine if the task environment is error-prone. This methodology assumes that a system's error-proneness can be deduced by having people who work in the environment subjectively assess a set of factors (similar to the concept of performance shaping factors or error shaping factors). While such assessments can be used effectively to complement reactive detection methods, implementing such systems requires caution. One must be careful to avoid biased questions, and to motivate assessors to provide factual, unprejudiced assessments. In addition, one must determine the sample size of the data, how the resulting data will be analyzed and interpreted, and how results will be implemented. It is also important to provide proper feedback to volunteer assessors. Without visible and effective feedback and actual resultant actions, such methods tend to lose credibility and can become ineffective.

James Reason developed MESH (Managing Engineering Safety Health) as a pro-active subjective assessment tool for British Airways (Rogan, 1995b). MESH assumes that the system's intrinsic resistance to accident-producing factors is due to the interplay of several factors at both the local workplace level and the organizational level. It affords regular measurement of the maintenance work force's and management's perception of the local and organizational factors. (Reason and Maddox, 1995). Randomly selected assessors periodically make simple subjective ratings on certain system factors through an anonymous computer-based survey. A given group of assessors operates for a limited period of time and is then replaced by a new group. The MESH program accumulates these inputs and summarizes the factors that could contribute to accidents or incidents. Quality control groups within the airline identify and prioritize issues in the MESH profiles. Technicians assess local factors and technical management personnel assess organizational factors. Technicians receive feedback in the form of newsletters and notice boards (Rogan, 1995b).

#### *5.3.3. Simulation approaches*

Direct observation, either by an expert or through subjective evaluation by individuals in a system, requires intrusion into the workplace. In addition, interpreting these observations for causal mechanisms is often difficult due to the number of situational and operator factors that vary, and interact, within a real system. Simulation methods offer an alternative approach for predicting human errors, allowing more careful control/isolation of situational and operator variables. Simulation implementations range from part-task simulators in which one observes operators performing simulated tasks, to virtual environments which include simulations of ambient conditions, to simulations of the system that include a simulated operator. In the aviation maintenance and inspection environment, part-task simulations provide the opportunity to observe operators perform visual and eddy-current rivet inspections (e.g., Latorella et al., 1992). More advanced simulations have not yet been developed for aviation maintenance and inspection, although they have been applied to other work domains. For example, a simulation exists of maintenance personnel in nuclear power plants (Gertman and Blackman, 1993).

### *5.4. Addressing human error control in aviation maintenance and inspection*

Once one determines that human error is a factor in an accident, incident, event, or error-likely situation, one must address how to control, or manage, this error. Most situations can be addressed through a variety of interventions. Further, interventions are most effectively implemented when used in combination. Interventions for error reduction include: selection, training, equipment design, job design, and aiding (Rouse, 1985). More detailed lists of interventions specifically intended for the aviation maintenance and inspection environment have been classified as short term and long-term interventions (Shepherd et al., 1991). This section reviews some of the techniques and approaches that have been proposed and applied to reducing the probability of human error in the aviation maintenance environment. This review considers the broad categories of: (1) training, (2) job design and organizational considerations, (3) workspace and ambient environment design, (4) task equipment and information design, and (5) automation. Finally we describe an approach to identifying, selecting among, and justifying intervention strategies for managing errors in aviation maintenance and inspection.

### 5.4.1. Training

Training at the individual operator level continues to improve and take advantage of new tools and methodologies. However there are still opportunities for improving individual training. For example, inspection training tends to focus on procedural aspects (e.g., setting up NDT equipment and troubleshooting rules) rather than providing feedback for other, more cognitive aspects (e.g., making perceptual judgments) (Prabhu and Drury, 1992). Transport Canada developed a workshop for training maintenance technicians to avoid the aforementioned "judgment interferences" (Foyle and Dupont, 1995). Based on the Transactional Analysis model, the Dupont Model distinguishes between rational ("adult") and emotional ("child") motivations. This workshop provides examples of how the rational/emotional interactions can affect a person's judgment during work, identifies technicians' behavioral types, and emphasizes the effects of stress, fatigue, and lack of communication on human performance (Foyle and Dupont, 1995). While this form of training has been provided to flightdeck crews for some time, it is only now being extended to the maintenance environment.

In addition, efforts have been directed toward providing aviation inspection and maintenance technicians with computer-based training (CBT). Three years ago, the Office of Aviation Medicine instituted a research and development plan to demonstrate and evaluate the use of CBT techniques for these technicians. The prototype system provided maintenance technicians with instruction for diagnosing the environmental control system (ECS) of a Boeing 767-300 (Johnson et al., 1992). In addition to providing diagnostic instruction and practice, the CBT system allows users access to all appropriate cockpit and maintenance bay controls for the ECS and access to interactive pages in the Boeing fault isolation manual (FIM). The prototype system was distributed to most of the world's airlines, via the Air Transport Association's (ATA) Maintenance Training Committee, and to most FAA certified aviation maintenance technical schools through the Aviation Technician Education Council (ATEC) (Johnson and Shepherd, 1993). Results from an evaluation study demonstrated that students trained with the CBT system showed the same level of post-training knowledge as those trained in the traditional instructor-led method. Subjective evaluations indicated that technicians preferred a combination of human and CBT instruction (Johnson and Shepherd, 1993).

A large portion of aircraft maintenance and inspection activities are accomplished by technicians working in teams. Thus, a technician has to learn to be a team member and coordinate and communicate effectively to accomplish the team objective. While teams can enhance performance, there are also many opportunities for human error in this work structure. Such functions as decision-making, knowledge-sharing, and communicating goals and objectives, play a crucial role in improving team performance. Recent efforts in training focus on enhancing teamwork in aviation maintenance and inspection. The success of Crew Resource Management (CRM) in improving team performance on the commercial flight deck, provides a model for improving collaborative work in the inspection/maintenance environment. The FAA has proposed extending the CRM approach to Maintenance Resource Management (MRM), or Technician Resource Management (TRM), to encourage teamwork and effective problem solving in maintenance crews (FAA, 1991,1995). Evaluations of the few MRM training programs attempted at airlines have showed success in these efforts (Taggert, 1990; Galaxy Scientific, 1993) in both objective performance measures and subjective measures of technician attitudes (Galaxy Scientific, 1993). Gramopadhye et al. (1996) describe a computer-based multimedia team training tool, the Aircraft Maintenance Team Training software (AMTT), which includes a team skills instructional module. This module addresses the key dimensions team skills: communication, decision-making, interpersonal relationships, and leadership. AMTT also has a task simulation module that allows users to apply learned team skills in a simulated aircraft maintenance situation.

Endsley and Robertson (1996) analyze situation awareness (SA) requirements for aircraft maintenance teams by asking operators to interpret elements in the environment and describe their spatial and temporal positions and trajectories (Endsley, 1988). Results suggested improvements for technician team training to reduce error and enhance performance (Endsley and Robertson, 1996). Teams should be trained to establish shared mental models. That is, the team should have a clear understanding of what other teams know and do not know. Teams should be trained to verbalize the decision-making process better. Technicians must be trained to conduct better shift meetings and perform as a team member. That is, there should be explicit training for team leads to convey to the team common goals, an understanding of who is doing what, and expectations regarding teamwork. Managers, leads, and technicians should be trained to provide better feedback (both positive and negative) on prior attempts. Additionally, training programs should address problems which cause a loss of situation awareness. One evaluation of the CRM approach in aviation maintenance found that such team training could also be improved by helping technicians transition new MRM skills to their actual working environment, to focus directly on training technicians how to voice disagreements, and to plan and publicize for recurrent MRM training (Galaxy Scientific, 1993).

#### 5.4.2. Job design and organizational considerations

Training has great appeal since it can rapidly reach a whole department or company. Drury (1996) states that training can easily be made airline-specific by using case studies of accidents or errors from that airline or from similar operations in other airlines. Drury describes an effort to bring about ergonomic/human factors changes via training in aviation maintenance. This effort required establishing and training a human factors task force, comprised of both management and hangar work force. A human factors expert coordinates the team and acts as the advisor for human factors issues. The training program utilized the SHEL (software, hardware, environment, and "liveware" (humans)) model (Edwards, 1972) to organize the human factors material. Results from this effort indicate several organizational factors that are critical to the success of these task forces; focusing on issues at the right level, having a champion in the organization for the whole effort, and maintaining trust that management actions would follow recommendations. Allen and Rankin (1995) also suggest organizational changes to improve aviation maintenance and inspection. Disciplinary actions should be uniform throughout an organization and should be structured to complement limited-immunity policies in conjunction with incident reporting (Allen and Rankin, 1995). At a higher-level of organization, the outputs of safety and information programs should be shared among airlines and manufacturers (Allen and Rankin, 1995).

#### 5.4.3. Workspace and ambient environment design

Several aspects of the ambient environment affect maintenance performance. Some maintenance tasks are performed in extremely cold conditions. At times this forces technicians to wear gloves during performance of their tasks, further complicating manipulation and tactile sensation. Volatile hydrocarbons in fuel tanks and cleaning agents at other access areas produce noxious fumes for inspectors and maintenance technicians. Recently new solvents have been identified that are less noxious to operators (Drury, 1996). Research has most fully addressed issues of lighting adequacy and postural/biomechanic hazards associated with aviation maintenance and inspection tasks.

Ninety percent of all inspection is visual inspection (Johnson and Shepherd, 1993). A general methodology, has been developed in cooperation with an airline partner, to recommend optimal illumination equipment for individual inspection tasks (Johnson and Shepherd, 1993). The resulting methodology uses task analysis data, lighting evaluations, subjective input from inspectors and evaluation of illumination sources to specify better portable area lighting, task lighting, and ambient illumination.

Maintenance tasks often require technicians to assume difficult postures and to work in restricted spaces. Reynolds et al. (1994) investigates the effects of performance in restricted spaces on effort and performance. Vertical restrictions on an inspection task demonstrably increase postural stress and respiration rate variability, a measure of decreased attentiveness (Reynolds et al., 1994). Sagittal restrictions, however, appear to improve operator performance over unrestricted control conditions, indicating that some physical restriction may improve task focus (Reynolds et al., 1994). This research has developed a program for identifying maintenance tasks where postural demands exceed human capability while ensuring safe and reliable performance, and for suggesting solutions to identified problematic tasks (Johnson and Shepherd, 1993).

Unfortunately, this reactive approach is the only real solution for improving postural problems for most of the aircraft being serviced today. However, future aircraft may inflict fewer such postural problems. Understanding that an aircraft design which forces awkward postures, restricted access to components, and requires frequent raising and lowering of equipment can lead to increased maintenance-related error frequency, Boeing has developed specific design criteria for the B-777 to facilitate access and maintenance (Marx, 1992). While this effort is promising, a more general effort towards developing standard guidelines for maintainability and inspectability would be most useful. MIL-STD-1472c provides some guidelines for maintainability. Mason (1990) describes the Bretby Maintainability Index that modifies the SAE maintainability index (SAE, 1976) to include such issues as weight of components, size and position of access apertures, restricted access for tools. This has been developed mainly for construction machinery, however it could be extended to focus on aviation maintainability.

#### 5.4.4. *Task equipment and information design*

Some "human errors" in aviation maintenance and inspection derive from poorly designed interfaces to equipment and information. Therefore, one method for controlling these errors is to redesign equipment and interfaces to information systems (including those implemented in paper). Interface issues are also important in the development of new equipment. Aviation maintenance and inspection tasks are increasingly computer based and include the use of new tools and techniques. As such, the human/machine interface to computer-based systems and new equipment is increasingly important. In general, designing these interfaces would benefit from usability assessment and engineering (e.g., Ravden and Johnson, 1989; Nielsen, 1993) (Table 8). Some specific human/machine interface improvements to aviation inspection and maintenance equipment include using templates for interpreting and calibrating NDI signals, and improving the interface to work cards. Technological improvements have also been applied to functions at higher organizational levels. For example, one computer-based system allows FAA inspectors to record information while auditing maintenance operations using a stylus input device (Layton and Johnson, 1993).

Work cards have been improved in three fundamental ways. First, the form of the work card has been redesigned to present information in a more readable, and organized manner. Second, work cards can be improved by providing the appropriate content, and in a usable form (e.g., graphically), and affording easy access to reference materials. Third, the physical interface to the work card is important and must be considered. Patel and

Table 8
Usability criteria for user interface evaluation (Ravden and Johnson, 1989)

| Factors | Guidelines |
|---|---|
| Visual Clarity | Information displayed on screen should be clear and well organized |
| Consistency | The way the system looks/works should be consistent at all times |
| Informative Feedback | Wherever appropriate and possible, the user should be given clear, informative feedback on where they are in the system, what actions they have taken, whether these actions have been successful, and what actions to be taken next |
| Explicitness | The system structure and working should be clear to the user |
| Appropriate Functionality | The system should meet the needs of the user when carrying out the task |
| Flexibility and Control | The interface should be flexible in the way the information is presented to the users |
| Error Prevention and Control | Design system to minimize the possibility of user error |
| User Guidance and Support | Informative, easy-to-use and relevant guidance and support should be provided to help users understand the system |

colleagues (Patel et al., 1994,1993; Drury, 2000) investigate these issues extensively. This research identifies human factors guidelines for formulating a more technician-centered work card. In a field evaluation, aviation inspectors preferred work cards redesigned according to these guidelines over original work cards (Patel et al., 1994). Drury (2000) extends this research to improve the physical interface of the work card. They implement aviation inspection work cards in a computer-based hypertext system on a portable computer. Field evaluations of this prototype system demonstrated a further improvement with this implementation. Technicians often must refer to reference manuals in the course of performing inspections and maintenance work. Providing this reference information in a more accessible and usable form facilitates performance (e.g., Inaba, 1991).

#### 5.4.5. *Automation*

Although some automation interventions appear useful, development of these has typically been technology driven, rather than human-centered and requirements driven. This approach has resulted in the development of automation systems that are not well integrated (Drury, 1996).

Table 9
Examples of automation in aviation maintenance and inspection (Drury, 1996)

| Function | Automation examples |
|---|---|
| Planning | • Automated stock control and parts ordering to ensure that lead times for obtaining parts does not extend with out-of-service time.<br>• Optimization heuristics for packaging required items into the length of a check visit. |
| Opening/Cleaning | • NDI devices eliminate need to open aircraft in some cases. |
| Inspection: initiate | • Automated information presentation (e.g., Marx, 1992)<br>• Hypertext workcards allow access to background documentation (Lofgren and Drury, 1994).<br>• IMIS system in military aircraft (Johnson, 1990). |
| Inspection: access | • Climbing robot performs eddy-current scanning of lap-splice joints (Albert et al., 1994). |
| Inspection: search & decision | • Effort towards automating signal processing and aiding final decision making (Johnson, 1989). |
| Inspection: response | • Hypertext workcards allow integration of inspection performance with documentation of response (Lofgren and Drury, 1994). |
| Repair: initiate | • Aircraft Visit Management System (AVMS) at United Airlines integrates inspection and repair activities (Goldsby, 1991). |
| Repair: diagnosis | • Variety of AI and expert system approaches to diagnosis aiding (e.g., Husni, 1992).<br>• Computer-based training with intelligent tutoring for diagnosis (Johnson et al., 1992).<br>• On-board diagnostic system improvements (e.g., Hessburg, 1992). |
| Repair: repair/replace | • Automation mostly limited to individual repair shop lines.<br>• CNC machining and robotic welding systems (Goldsby, 1991). |
| Repair: reset | (none) |
| Buyback/Return to Service | • Integration of inspection performance and response and maintenance actions makes buyback easier.<br>• Bar codes on badges and workcards to automate job control notation (Goldsby, 1991).<br>• Fully electronic logbook proposed. |

Table 9 presents automation approaches to aviation maintenance and inspection by function (Drury, 1996). In his review, Drury emphasizes the importance of considering the additional training requirements of automation interventions and sensitively incorporating automation into the organizational context and individuals' jobs.

### *5.4.6. Comprehensive and integrated approaches to error management*

In addition to managing human error in aviation maintenance, one must manage interventions. That is, how does one generate potential alternative intervention strategies, choose among these alternatives, and cost-justify these solutions to management? Drury et al. (1996) describe a prototype system for a more comprehensive approach to error reduction and management. This system begins with the assumption that pro-active error monitoring and reactive error reporting are both essential for effective error control. It is based on the premise that it is important to identify and organize error reporting information in a manner consistent with intervention strategies. The proposed system has five modules: (1) error reporting, (2) critical incident reporting (reports of situations where errors/incidents almost happened but were recovered without consequences), (3) error audit (auditing specific tasks to find human-system mismatches), (4) error assessment (anonymous assessment of the task environment by technicians and management), and (5) solutions database (of information from industry sources and human factors experts for design changes). This prototype system is called PERS (Pro-active Error Reduction System) and is being developed under an FAA research grant.

## 6. Conclusion

Aviation maintenance is a complex organization in which individuals perform varied tasks in an environment with time pressures, minimal feedback, and sometimes difficult ambient conditions. Aircraft, as well as inspection and maintenance equipment, are becoming more complex. As the commercial aviation fleet ages, and work force of maintenance personnel diminishes, maintenance workload is increasing. These pressures exacerbate the likelihood of human error in aviation maintenance and inspection processes. In fact, these errors have various effects on the aviation system; from inconsequential slips, to those which affect airline efficiency and passenger convenience, to those few which ultimately result in an accident. In recognition of this, the focus is now more toward understanding the nature of human error in aviation maintenance and inspection, and improving methods for detecting and managing these errors. We review both reactive and pro-active methods of error detection, and several intervention strategies for controlling human errors in aviation maintenance and inspection. Future directions in this area would be to develop: (1) a maintenance incident reporting system with limited immunity for reporting (Allen and Rankin, 1995), (2) a standardized, but rich, vocabulary/indexing scheme for characterizing situational and operator factors in error reporting, (3) technologies to facilitate recognition of hazardous patterns in situational and operator factors, (4) aviation maintenance system simulation (cf. MAPPS in Gertman and Blackman (1993) and CES in Woods et al., 1987), (5) virtual environmental simulations to support experimental investigations, (6) methodologies for identifying organizational structures and job design characteristics which dampen the likelihood and perseverance of human errors, (7) truly human-centered, integrated task aiding, automation, and training.

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