A FRAMEWORK FOR HUMAN RELIABILITY IN AIRCRAFT INSPECTION

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1.0 INTRODUCTION

Maintaining civil aircraft air-worthiness requires the reliability of a complex, socio-technic system. This system's reliability is dependent on the reliability of its components (i.e, equipment, inspectors, the physical environment), and on how reliably these components interact. Error is the measurement counterpart of reliability, and most, if not all, errors can be classified at some stages as human errors. This paper uses the data collected from the task analyses of many inspection tasks (Shepherd, et al., 1991), and the human factors literature on human errors to derive an overall framework for error studies in inspection. This framework interprets the hangar-floor observations in terms of current theories of human error causation, and then uses this interpretation to list strategies for reducing or eliminating errors. The ultimate aim of this work is to ensure that data and theories of human error from other fields (e.g., nuclear power, chemical plants, transportation systems) can contribute to reducing the error potential of aviation maintenance and inspection.

The assessment of human error in complex systems is currently undergoing somewhat of a renaissance (Brown and Groeger, 1990). Classification schemes of errors have expanded from the early "omission/ commission" classification (Swain and Guttman, 1983 and Meister, 1971) to more behavioral- based classifications (e.g. Norman, 1981; Rasmussen, 1982; Rouse and Rouse, 1983, and Reason, 1990). While error classifications based on task characteristics may provide a convenient descriptive format for errors, error models based on human behavior can define causal mechanisms of errors. Identification of causal mechanisms and catalytic factors is necessary for predicting errors and thereby designing error tolerant systems for preventing errors. The approach taken here is to use a behavioral-based and system-based human error classification scheme to identify, predict, prevent or reduce, and report errors in aircraft inspection and maintenance. Operators may cause errors outright or, more likely, human frailties and characteristics may be "catalytic" factors (Rouse and Rouse, 1983); combining with other component characters to evolve "sneak paths" (Rasmussen, 1982) to error situations.

Whereas previous research in aircraft inspection and maintenance has utilized various empirical human factors techniques, this effort uses a behavioral-based human error modeling approach, housed in a conceptual aircraft inspection and maintenance system model (Figure 1). The system model provides a framework for error classification and therefore, a basis for improved error management. The following section describes the system model of aircraft inspection and maintenance. The final section details how the model can be useful for managing aircraft inspection and maintenance errors.

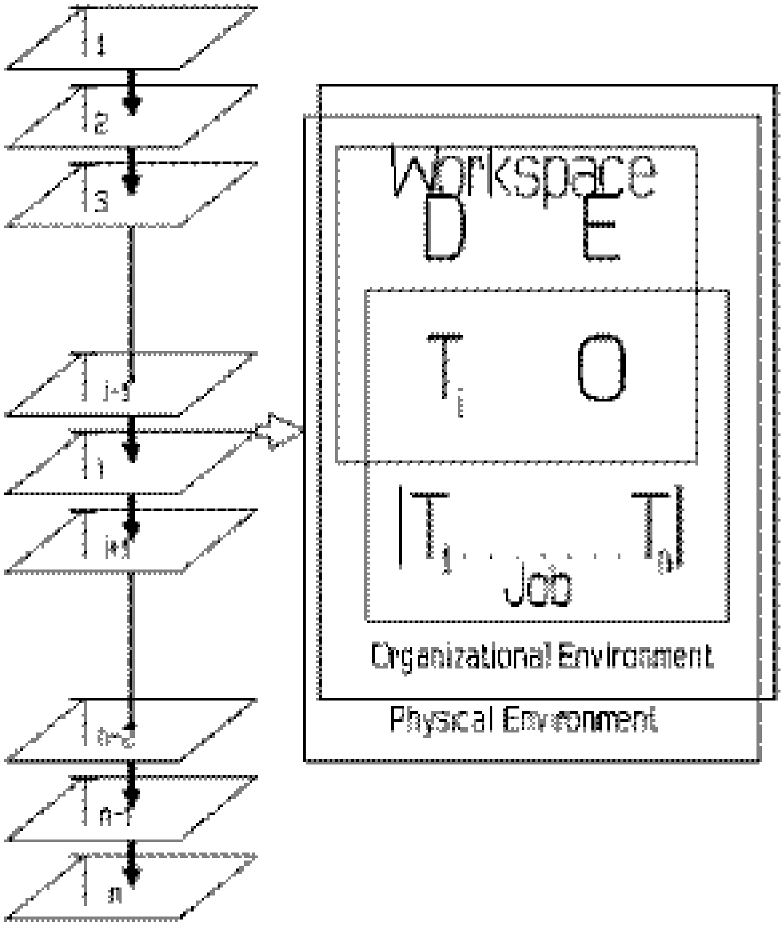

Figure 1 System Model

2.0 SYSTEM MODEL FOR HUMAN ERROR IN MAINTENANCE AND INSPECTION

The fact that errors emerge from, and are defined by, the interaction of system characteristics indicates the necessity of a system approach to the description and control of these errors. Such a system view of aircraft inspection and maintenance includes not only the traditional interaction of the operator and task requirements, but also includes operator interactions with equipment, documentation, and other personnel within the constraints imposed by the environment. The system model (Latorella and Drury, 1991) contains four components: operators (personnel), equipment, documentation, and task requirements. These components are subject to constraints of both the physical environment and the social environment. The job component can also be considered as a subset of the organizational environment in which tasks are defined. Similarly, the workspace component is a subset of the physical environment. This conceptual model is two-dimensional (**Figure 1**). The temporal sequence of the individual tasks

Operators. Aircraft maintenance and inspection **operators (O)** differ between organizations but belong to the same basic categories: inspectors (perhaps distinguished as either visual or NDT), maintenance, utility, lead inspectors, lead maintenance, inspection foremen, maintenance foremen, production foremen, and engineers. In addition to carrying out sequences of activities, personnel serve as informational resources to each other. Communication between personnel can be viewed as an information processing task similar to referencing a document. The organizational structure of the system imposes constraints on the amount of, format of, and the personnel likely to engage in, collaborative problem-solving communications.

Equipment. Both visual and NDT inspection use **equipment (E)**. There is specialized equipment for different types of NDT, including: eddy current, ultrasonic, magnetic resonance, X-Ray, and dye penetrant. Visual inspection requires flashlights, mirrors, and rulers. Use of this equipment requires specialized knowledge of its operating principles, and equally specialized knowledge for the interpretation of its output. Interpretation of visual stimuli or NDT output necessarily requires information processing by the operator, but may also require communication with other personnel.

Documents. A variety of **documents (D)** is required for inspection and maintenance. Workcards, which may include graphics and references to more comprehensive standards manuals, specify the task to be performed. Forms (shift turnovers, NRRs) are used to communicate between personnel and to document procedures, while additional documentation is used for training and retraining purposes. Physical characteristics of forms, documents and graphics affect the legibility of information and therefore, impact the ability to accurately perceive this information. Issues of comprehension are important for understanding the content of documents. Issues of representation are central to ensuring that graphics are appropriate and useful.

Task. A **task (Ti)** is defined as the actions and elements of one workcard or similar task order. Task characteristics which have been found to influence inspection include: defect probability, physical characteristics of the defect, the number of serial inspections, feedforward and feedback availability, and whether standards are used (Rodgers, 1983). These aspects of the task necessarily interact with personnel, organizational, job and environmental characteristics. Personal information processing biases may interact with the task structure and present problems such as searching in the wrong area.

Job. Jobs (J) are defined by the collection of tasks that an individual is expected to perform. However, there are many characteristics of the job which can not be described by the characteristics of its individual tasks. Job factors are derivative of the organizational environment and provide constraints for tasks (e.g., shift durations, work/rest cycles, day/night shifts, job rotation policies). These can further impact personnel physical (e.g., fatigue, eyestrain), affective (e.g., motivation, job satisfaction), and information processing (e.g., attention allocation) characteristics.

Workspace. The workspace, a subset of the physical environment, contains the task and the equipment, documentation and personnel required to perform the task. While illumination is an attribute of the physical environment in general, task lighting (such as a flashlight) is an attribute of the workspace. The degree of physical access afforded by the workspace is an important constraint on performance. Both these issues are currently being researched under continued funding on this contract (Drury, et al., 1992, and Gramopadhye, Reynolds and Drury, 1992).

Physical Environment. The physical environment is described by several parameters: temperature, noise level and type of noises, lighting level and light characteristics, and electrical and chemical sources. While some of these factors can either enhance or degrade performance, others indicate potentially hazardous conditions. The level and spectral characteristics of lighting affect the perception of fault indications. Impulse noises interrupt tasks and may result in skipped or unnecessarily repeated procedures. The level and frequency characteristics of noise affect the ability to communicate. Examples of hazardous conditions in the physical environment are exposure to X-rays emitted during X-ray NDT and fuel fumes encountered when inspecting the inside of a fuel tank.

Organizational Environment. The organizational environment, often ignored in the analyses of maintenance systems, has been shown to be influential in the patterns of work (Taylor, 1990) and therefore, possibly in the patterns of errors. Factors which have been identified as important include: the organization of work groups (or conversely, the isolation of workers), reporting structures, payoff structures associated with task performance, trust within one class of personnel, trust between classes of personnel and levels of personnel, selection/placement strategies, and human-machine function allocation of control and responsibility.

Using the System Model. The model in **Figure 1** is useful for depicting the goals of the system and therefore the functions that should be supported. The goals of the system are defined by the requirements of the personnel component in isolation and in conjunction with other system components. The personnel component is primarily described in terms of information processing characteristics and limitations. These characteristics influence the behavior of individuals' and their experience with other system components. The functions associated with the performance of tasks, use of equipment, and communication with co- workers are subject to error and are therefore of primary concern. These functions are then considered within the constraints of environmental factors which may affect error formation and/or propagation. Drury, Prabhu and Gramopadhye (1990) have compiled a generic function description of the maintenance inspection task requirements. The desired outcome for each of the task functions (Drury, 1991) which can be considered as the task's goal can be stated and, following Drury (1991), decomposed into the steps taken to accomplish the desired outcome. Note that the use of equipment has been included within these task descriptions and therefore would not be considered separately.

Errors must be described in the situational context in which they occur in order to identify contributing factors. **Table 1** shows some relevant characteristics of system components with which the individual may interact for the initiate task. Relevant characteristics of each system component can be identified for observed errors. The effect of these factors on performance has been suggested in many studies, however, the manner in which performance is affected, especially by combinations of factors, requires additional empirical investigation.

Table 1 System Component Influencing Factors

1.0 Personnel 1.1 Physiological 1.2 Psychological 1.3 Personality **2.0 Equipment** 2.1 Hand Tools 2.2 Displays 2.3 Control **3.0 Documentation** 3.1 Type of Information Included 3.2 Style (Intelligibility) 3.3 Formatting (Visual Clarity) 3.4 Content (Usefulness, Appropriateness, Veridical) 3.5 Legibility (Physical) **4.0 Task** 4.1 Physical Requirements 4.2 Informational Requirements 4.3 Characteristics	**5.0 Job** 5.1 Physical Factors 5.2 Social and Organizational Factors **6.0 Organizational/Social** 6.1 Structure 6.2 Goals 6.3 Trust 6.4 Motivational Climate/Incentives 6.5 Function Allocation/Job Design 6.6 Training/Selection Methods **7.0 Physical Environment** 7.1 Lighting 7.2 Noise 7.3 Temperature/Ventilation 7.4 Chemical Hazards 7.5 Vibration 7.6 Electrical Shock Hazards **8.0 Workspace** 8.1 Proximity 8.2 Anthropometrical Constraints

3.0 AIRCRAFT INSPECTION AND MAINTENANCE ERROR MANAGEMENT

Error management may be considered as a three part objective. Errors which are evident in an operational system (error phenotypes) must be identified and controlled. Secondly, in order to reduce the likelihood of unanticipated error situations, errors must be predicted and systems must be designed to be error tolerant. Thirdly, error reporting systems must provide error and contextual information in a form which is appropriate as feedback to personnel. Operators may then use this information to adjust their error control and prevention strategies or alter environmental characteristics. This section presents strategies for error control, prevention through error-tolerant systems, and finally the need for a context-sensitive error reporting scheme.

Error phenotypes (Hollnagel, 1989), the specific, observable errors in a system, provide the foundation for error control. Error prevention and the development of design principles for error avoidance rely on genotype identification (Hollnagel, 1989), associated behavioral mechanisms and their interaction with system characteristics (Rasmussen and Vicente, 1989). Here, error phenotypes are obtained empirically and from a failure-mode-and-effects analysis of task and communication models. These phenotypes are considered in light of their ability to be self-correcting and the type of error which they represent. They are further characterized by the relevant aspects of the system components with which they interact. The resulting list of phenotypes, their error correctability and type, and the pertinent situational factors allow designers to recognize these errors and design control mechanisms to mitigate their effects. Rasmussen and Vicente's (1989) methodology is used to identify genotypes associated with each phenotype. This yields mechanisms of error formation within the task context.

3.1 ERROR CONTROL AND PREVENTION

Error control strategies can be derived by classifying error phenotypes according to components of the system model (Figure 1) and Rasmussen and Vicente's (1989) systemic error mechanisms. This classification framework aids in suggesting intervention strategies appropriate to the error and the system components involved. The system model provides a useful means of classifying observed errors for this purpose and relating them to specific human factors interventions. There are a number of personnel factors of general importance to controlling errors. Personnel interactions are extremely important aspects of the performance of the inspection and maintenance tasks. Equipment should be designed to support task requirements and accommodate human information processing characteristics. The physical and organizational environments should be designed to enhance task performance and ensure the safety and motivation of personnel.

Various intervention strategies have been suggested for the control and prevention of errors. Rouse (1985) identifies five general interventions and proposes a mathematical model for describing optimal resource allocation among the strategies. These five general categories are also reflected in the more detailed listing of intervention strategies proffered by Drury, et al., (1990). These interventions have been tailored to the aircraft inspection context and were classified as either short-term or long-term strategies. The intervention strategies from these two sources are described below in detail in Table 2 and Table 3. Table 2 presents a compilation of the intervention strategies and design guidelines proposed by Rasmussen and Vicente (1989), Drury, et al., (1990), and Rouse (1985).

Table 2 Error Management Strategies

SHORT-TERM INTERVENTIONS Shepherd, et al, 1991)

1. Worksheet design
2. NDI equipment calibration procedures
3. NDI equipment interface
4. NDI equipment labelling of standards
5. Support stands
6. Area localization aids
7. Stands/areas for NDI equipment
8. Improved lighting
9. Optical enhancement
10. Improved NDI templates
11. Standards available at the workplace
12. Pattern recognition, job aids
13. Improved defect recording
14. Hands-free defect recording
15. Prevention of serial responding (inadvertent signoff)
16. Integrated inspection/repair/buy-back - improve written communication
17. Integrated inspection/repair/buy-back - improve verbal communication

LONG-TERM INTERVENTIONS (Shepherd, et al, 1991 and Rouse, 1985)

18. Identification of errors - error reporting
19. Integrated information systems (feedback, feedforward, directive)
20. Training
21. Selection/placement

ERROR REDUCTION RESOURCES (Rouse, 1985)
(also notes training and selection)

22. Equipment design
23. Job design
24. Aiding

RASMUSSEN'S "COPING" GUIDELINES
(Rasmussen and Vicente, 1989)

25. Make limits of acceptable performance visible while still reversible.
26. Provide feedback on the effects of actions to cope with time delay.
27. Make latent conditional constraints on actions visible.
28. Make cues for action, put only convenient signs, but also represent the necessary preconditions for their validity (symbolic).
29. Supply operators with tools to make experiments and test hypotheses.
30. Allow monitoring of activities by overview displays.
31. Cues for action should be integrated patterns based on determining attributes (symbolic representations).
32. Support memory with externalization of effective mental models.
33. Present information at level most appropriate for decision making.
34. Present information embedded in a structure that can serve as an externalized mental model.
35. Support memory of items, acts and data which are not integrated into the task.

Table 3 Error Management Strategies

		SYSTEM ELEMENTS							
Systemic Errors	Levels of Cognitive Control	Task	Personnel	Job	Workspace	Equipment	Documentation	Physical Environ.	Organize Environ.
LEARNING	Skill	6,11,12	20		6	6,22,24,25	6,24	25	
	Rule	11,26	20			11,22,24,26	1,2,24,26		
	Knowledge	13,19, 28	16,17,18,20	16,17, 26,29		13,19,22, 24,26,27,29	1,16,19,24		17,18,29
INTERFERENCE	Skill	12,14		23,30		14,24,30	24		
	Rule	11	20	23		3,11,22,24, 31	24		
	Knowledge	19,32	16,17,20	15,16, 17,23, 32		3,19	1,16,19,21,32		15,17,32
LACK OF RESOURCES	Skill					33			
	Rule					33	33,34		
	Knowledge	13,19, 34	16,17,20,21	16,17, 23,34		3,4,10,13, 22,24,33,34	1,16,19,24,33,34		17
STOCHASTIC VARIANCE	Skill	6,12,14	16,17,20, 21,35	23	5,6,7,8	3,5,6,7,9, 10,14,22, 24,35	6,24	8	
	Rule	11	16,17,20, 21,35			11,22,24,35	2,24,35		
	Knowledge		16,17,20, 21,35	16,17		4,22,35	16,35		17

Error genotypes, rather than the aforementioned phenotypes, are classified according to the system model, using Rasmussen and Vicente's (1989) systemic error categories and Rasmussen's levels of cognitive control (Skill, Rule, Knowledge). This characterization of error genotypes allows prediction of possible, but so far unanticipated, error phenotypes. Unanticipated errors can be predicted by considering tasks at each level of cognitive control and each error mechanisms' possible perturbation of performance within the context of the specific system components involved. Given an error genotype cell, intervention strategies (which also have been classified by system component, systemic error mechanism, and cognitive control level (Table 3) can be identified for its control.

3.2 ERROR REPORTING IN AIRCRAFT INSPECTION AND MAINTENANCE

Currently, error reports are primarily used for documenting error situations for administrative purposes; internal or external regulatory agencies. There are many different regulatory mechanisms for reporting errors to the FAA. In addition, the Air Transport Association (ATA) has proposed modifications to those. All of these reporting systems have the following common features:

1. They are event driven. The system only captures data when a difficulty arises or a defect is found.
2. Aircraft type and structure serve as the classification parameters for reporting.
3. Expert judgements of error criticality are used to further classify data and determine its urgency.

4. To some extent in all systems, the feedback of digested data to users is not well-engineered. Thus, for the end-user level, the data collection effort is largely for naught.

Error reports in maintenance and inspection produced for administrative purposes are typically concerned with establishing accountability for an error and its consequences rather than understanding the causal factors and situational context of the error. This type of information is not appropriate for use as performance feedback to inspectors or maintenance personnel, nor is it helpful information for error tolerant system design. Error reporting schemes are developed from within an organization and therefore vary greatly among organizations. The framework of these error reporting schemes is event driven and developed iteratively, thus additions are made only with the occurrence of a new error situation.

To alleviate the difficulties of inconsistency, and provide an appropriate and useful structure for error data collection, an error reporting scheme should be developed from a general theory of the task and the factors which shape how the task is performed; principally, the behavioral characteristics of the operator, but ideally also organizational environment, job definition, workspace design, and the operators' physical, intellectual and effective characteristics. Effective error categorization systems are not only descriptive but are prescriptive, providing information for specific intervention strategies (i.e. Langan-Fox and Empson, 1985 and Kinney, et al., 1977).

4.0 SUMMARY

In the preceding sections a framework has been provided for the classification and control of human error in aircraft inspection. The proposed system model of aircraft inspection and maintenance recognizes the fact that the interaction of the task with the human and the environment is the basis of most human errors. Thus an attempt is made to shift the attention from the task to these interactions. Based on the system model, the S-R-K framework of Rasmussen (1983) and the systemic error categories of Rasmussen and Vicente (1989), a methodology for identifying intervention strategies has been proposed.

As Rasmussen, Duncan, and Leplat (1987) note, it is necessary to shift the focus of analysis from the task to the interaction of the task and the operator for classifying errors. Furthermore, taxonomies of human error must encompass the analysis of not only the task characteristics but also the information processing mechanisms associated with the subtasks. It is apparent that other situational characteristics (i.e., environmental conditions) are also useful for the sensitive classification of errors (Stager and Hameluck, 1990).

Both the taxonomic approach of Drury and Prabhu (1991) and the taxonomy for error management strategies developed here can be used as a basis for formulating error reporting schemes. Upon occurrence, errors can be classified by level of cognitive control, type of systemic error, and by causal or catalytic elements of the system. As previously mentioned, the categories of system elements can be refined as illustrated in Table 3 to provide a more descriptive error characterization. Identification of these parameters will likely involve detailed investigation of the error situation including extensive operator interviewing. This data store can be analyzed for trends in error sequences, effects of different intervention strategies on error-type frequency, and for the efficacy of intervention strategies over all types of errors.

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