2.0 APPROACHES TO CONTROLLING MAINTENANCE ERROR

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INTRODUCTION

The rapid technological advances in aviation have not only meant the replacement of human control by computers, they have also brought about very substantial improvements in the reliability of equipment and components. This has been achieved by the use of better manufacturing processes and materials, as well as through the widespread availability of sophisticated diagnostic techniques. But the maintenance schedule for a modern aircraft still demands the repeated disassembly, inspection and replacement of millions of removable parts over its long working life. Thirty or even twenty years ago, these inspections would have resulted in the frequent detection and replacement of failed components. Then, the risks of in-flight failure due to intrinsic engineering defects probably outweighed the dangers associated with allowing legions of fallible people access to the vulnerable entrails of the aircraft.

But now the balance has tipped the other way. The greatest hazard facing a modern aircraft-aside from gravity-comes from people, and most particularly from the well-intentioned but often unnecessary physical contact demanded by the current maintenance schedules. Before this claim is dismissed as mere provocation, consider the following data from Boeing.1 Listed below are the top seven causes of 276 in-flight engine shutdowns.

- Incomplete installation (33%)
- Damaged on installation (14.5%)
- Improper installation (11%)
- Equipment not installed or missing (11%)
- Foreign object damage (6.5%)
- Improper fault isolation, inspection, test (6%)
- Equipment not activated or deactivated (4%)

These data show that various forms of faulty installation were the top four most frequent causal categories, together comprising over 70 per cent of all contributing factors. Comparable findings were obtained by Pratt and Whitney in their 1992 survey of 120 in-flight shutdowns occurring on Boeing 747s in 1991.2 Here, the top three contributing factors were missing parts, incorrect parts and incorrect installation. In a UK Civil Aviation Authority survey of maintenance deficiencies of all kinds, the most frequent problem was the incorrect installation of components, followed by the fitting of wrong parts, electrical wiring discrepancies and loose objects (tools, etc.) left in the aircraft.3

This paper takes as its starting point, the following facts relating to maintenance:

- Of the two main elements of maintenance - the disassembly of components and their subsequent re-assembly-the latter attracts by far the largest number of errors. As discussed elsewhere, re-assembly and installation afford considerably greater opportunity for going wrong, irrespective of who does the task.4 They are intrinsically error-prone activities.

- Of the various possible error types associated with the re-assembly, installation or restoration of components, omissions-the failure to carry out necessary steps in the task - comprise the largest single error type. In a recent survey, omissions counted for nearly 60 per cent of all recorded maintenance lapses in a major airline.4 Similar observations have been made in the nuclear power industry.5

ERROR MANAGEMENT

Error management has two components: (a) *error reduction* - measures designed to limit the occurrence of errors, and (b) *error containment* - measures aimed at limiting the adverse consequences of those errors that still occur. There is no one best way. Error management tools must be targeted at different levels: the person, the team, the task, the workplace and the organization. In this paper, we will focus on two recently developed error management techniques: ERK (the Error Reduction Kit) aimed at error-prone tasks; and MESH (Managing Engineering Safety Health) designed to identify proactively those factors within both the workplace and the organization that are likely to promote errors and impede their recovery.

ERK (The Error Reduction Kit)

The rationale

From an analytical point of view, there are at least two approaches towards a better understanding of maintenance omissions, one seeking to identify the underlying cognitive mechanisms, the other trying to determine what aspects of a task cause it to be especially omission-prone. The former route is made difficult by the fact that an omission can arise within a number of cognitive processes concerned with planning and executing an action. Even when the omission is one's own, the underlying mechanisms are not easy to establish, but when the omission is made by another person at some time in the past, the underlying reasons may be impossible to discover. The task analysis route, on the other hand, is more promising.

An everyday illustration of omission-prone task steps is provided by the job of duplicating a loose leaf document on a simple photocopying machine. There is strong evidence to show that the most likely omission is to leave the last page of the original under the lid when departing with the copy and the remainder of the original pages.

There are at least four distinct features of the task of photocopying that combine to make leaving the last page of the original behind highly likely.

- The step is functionally isolated from the preceding actions. Before, the step of removing the previously-copied page had been cued by the need to replace it with the next page. In this instance, there is no next page.
- The need to remove the last page of the original occurs after the main goal of the activity has been achieved-obtaining a complete copy of the document-but before the task itself is complete.
- The step occurs near to the end of the task. Natural history studies of absent-minded slips have shown that such 'premature exits' are a common form of omission. These errors can be prompted by preoccupation with the next task. However, in maintenance work organized around an eight or twelve hour shift pattern, there is no guarantee that the individual who starts upon a job will be the one to complete it. And even when the same person performs the whole task, there is always the possibility that he or she may be called away or distracted before the task is finished.
- The last page of the original is concealed under the lid of the photocopier-the out-of-sight out-of-mind phenomenon.

To this list can be added several other features which, if present within a given task step, can combine to increase the probability that the step will be omitted. Other omission-provoking features include the following:

- Steps involving actions or items not required in other very similar tasks.
- Steps involving recently introduced changes to previous practice.
- Steps involving recursions of previous actions, depending upon local conditions.
- Steps involving the installation of multiple items (e.g., fastenings, bushes, washes, spacers, etc.)

- Steps that are conditional upon some former action, condition or state.

- Steps that are not always required in the performance of this particular task.

Maintenance activities are highly proceduralized. It is therefore possible, in principle, to identify in advance those steps most vulnerable to omissions by establishing the number of omission-provoking features that each discrete step possesses. Having identified error-prone steps, remedial actions can then be taken to reduce the likelihood of these steps being left out.

The characteristics of a good reminder

Although there are a variety of cognitive processes that could contribute to an omission, and their precise nature is often hidden from both the actor and the outside observer, the means of limiting their future occurrence can be relatively straightforward and easy to apply, once the error-prone steps have been identified. The simplest counter-measure is an appropriate reminder. What characteristics should a good reminder possess? Some suggestions are listed below.

- A good reminder should be able to attract the actor's attention at the critical time *(conspicuous).*

- A good reminder should be located as close as possible in both time and distance to the to-be-remembered (TBR) task step *(contiguous).*

- A good reminder should provide sufficient information about when and where the TBR step should be carried out *(context).*

- A good reminder should inform the actor about what has to be done *(content).*

- A good reminder should allow the actor to check off the number of discrete actions or items that need to be included in the correct performance of the task *(check).*

The previous five characteristics are universal criteria for a good reminder. They are applicable in virtually all situations. There are, however, a number of secondary criteria that could also apply in many situations

- A good reminder should work effectively for a wide range of TBR steps *(comprehensive).*

- A good reminder should (when warranted or possible) block further progress until a necessary prior step has been completed *(compel).*

- A good reminder should help the actor to establish that the necessary steps have been completed. In other words, it should continue to exist and be visible after the time for the performance of the step has passed *(confirm).*

- A good reminder should be readily removable once the time for the action and its checking have passed-one does not, for example, want to send more than one Christmas card to the same person *(conclude).*

It should be noted that the reminders described above are not a permanent solution to the omission problem. They are at best 'first aid' measures to cope with the difficulties experienced in the present generation of aircraft-whose working lives will run for many years into the future. A more lasting solution would be to design components so that they can only be installed in the correct way. Another would be to make the system disable itself automatically when it detect the presence of missing parts. A third and more fundamental solution would be to design a reduction in the need for 'hands on' human contact during maintenance inspections.

ERK elements

ERK allows a non-human factors analyst (e.g., a quality specialist) to identify in advance those steps in a proceduralised maintenance task that are most likely to be omitted. There are features that make certain task steps especially vulnerable to omission, regardless of who is doing the job. ERK guides the analyst in assessing these features for both individual task steps and the work situation. It then describes how to provide effective reminders to reduce the chances of these omission-prone steps being overlooked.

ERK has six components, available on a single plasticised sheet.

- Instructions for use.
- Task Step Check list identifying 20 omission-prone features together with their scores (reflecting their individual importance in predicting omissions). This stage yields a score for each task step.
- Explanations of each of the omission-prone features.
- An Organizational and Situational Factors Checklist. These identify workplace features likely to affect the reliability of the workforce carrying out this task. These features include:-
  - Changes in organization, gradings or tools
  - Environmental factors (humidity, noise, illumination, etc.)
  - Manning levels
  - Shift patterns
  - Availability of parts, etc.
- Criteria for a good reminder
- Score sheet

MESH (Managing Engineering Safety Health)

The rationale

MESH is a PC-based diagnostic tool, created for British Airways Engineering in 1992 by a team from the University of Manchester, for assessing the local and organizational factors that lie at the heart of quality and safety. It is designed to make visible those latent conditions most likely to impair human performance. In effect, MESH provides regular 'check ups' of the system's 'safety health' as it exists within individual workplaces and at the wider organizational level. Its purpose is to identify (for any one assessment period) those 2-3 latent conditions that are most in need of attention and which, if left untreated, will contribute to quality lapses and maintenance errors in the future. By this means, the maintenance system is able to conduct a long-term quality and safety 'fitness' program in a principled and targeted fashion. Any organization has only limited resources. The continued use of MESH shows where these resources should be most effectively deployed and charts the progress of the remedial measures.

Local factors

Exactly what local factors are assessed varies from workplace to workplace. Below are 12 factors that have been used in line maintenance and casualty hangars:

- Knowledge skills and experience

- Morale
- Tools, equipment and parts
- Quality of support
- Fatigue
- Pressure
- Time of day/night
- Environment
- Computers
- Paperwork, manuals and procedures
- Inconvenience
- Personnel safety features

Assessments are made through simple ordinal ratings of the extent to which each one of the local factors had been a problem in relations to a small number of recent jobs (how these are specified depends on the work location - in line maintenance, they could be aircraft; in base maintenance they could be shifts). Ideally, the assessments are made by 20-30 per cent of the 'hands on' workforce in any given location. The assessors are selected at random and continue to make assessments for a limited period on a weekly basis, after which a new set is selected, and so on. MESH is a sampling tool: it does not try to measure everyone's opinion about everything.

The computer program automatically updates the average of the assessments made in the past and provides a bar diagram profile of the relative degree to which each of these local factors has constituted a problem in that particular place. The MESH program also includes a free text 'comments' facility that allows users to described specific problems. This has proved useful in guiding subsequent remedial actions. All assessments are carried out anonymously. When logging on, a respondent merely indicates his/her location, grade and trade.

Organizational factors

MESH also assesses the impact of common organizational factors on each workplace. Such a list might include the following factors:

- Organizational structure
- People management
- The provision and quality of tools and equipment
- Training and selection
- Commercial and operational pressures
- Planning and scheduling
- Maintenance of buildings and equipment
- Communication

As with local factors, assessments are made on the PC using simple ratings in relation to specific tasks or jobs. Organizational factors are assessed by the local technical management. These are the people on the interface between the organization at large and the particular workplace. Since organizational factors are likely to change more slowly than local factors, the assessments are made more infrequently, say monthly or even quarterly. The organizational factor data are summarized in the form of bar chart profiles, computed automatically by the computer program. The purpose of the profile is to identify the 2-3 organizational factors that are most in need of reform. Subsequent profiles will map the progress of these remedial efforts, as well as identifying fresh candidates for improvement.

A MORE FUNDAMENTAL PROBLEM

The fundamental problem with aircraft maintenance is that it requires people to come into direct contact with aircraft components on frequent occasions. The orthodox engineering approach presumes that maintenance activities are both essential and benign. From an engineering perspective, the optimal level of preventive maintenance is established by summing the costs of both corrective and preventive maintenance, and then identifying the level associated with the lowest overall maintenance cost.[6]

But suppose preventive maintenance did not always prevent failure and that corrective maintenance did not always correct it. Suppose that both of these activities actually had the potential for doing serious harm, rendering previously reliable components inoperable, or simply removing them altogether.

Figure 2.1 looks at the maintenance issue from a broader perspective-one that includes human as well as technical factors. Here are plotted (in a very speculative fashion) the risks to the system posed by (a) neglected maintenance, and (b) by the likelihood of errors being committed during either preventive or corrective maintenance. The latter plot is based on the assumption that the likelihood of error will increase as a direct linear function of the amount of maintenance activity. Since only a relatively small proportion of human actions are erroneous, the human failure risk will never rise above a fairly low value. But, as we shall see below, it is not the absolute value that matters, but the relative proportions of the maintenance neglect and maintenance error risks. It is also assumed that these error risks will not change in any systematic fashion over time. Technology may advance, but human fallibility stays the same.

In sharp contrast, however, the risks due to maintenance neglect are likely to diminish steadily as manufacturing techniques and the intrinsic reliability of materials improve with technological developments. This is indicated in Figure 2.1 by the family of diagonals advancing towards the lower left-hand corner of the graph. It is clear that if a given level of maintenance-determined by the economic and engineering considerations discussed above-remains relatively constant over time, then a point will soon be reached when the dangers to the system come to be dominated by even a relatively low error rate.

The data reported earlier on the causes of in-flight engine shutdowns show that all of the most common contributing factors are associated with human rather than 'unaided' technical failures. Of course, it could be argued that the advent of non-destructive testing and other advanced diagnostic techniques allow aircraft engineers to identify potential technical failures before they happen in flight, thus leaving human errors as the main residual category of failure. This may well be true, but it does not alter the fact that regular human contact with the 4-6 million removable parts on a modern aircraft poses an unacceptable level of risk.

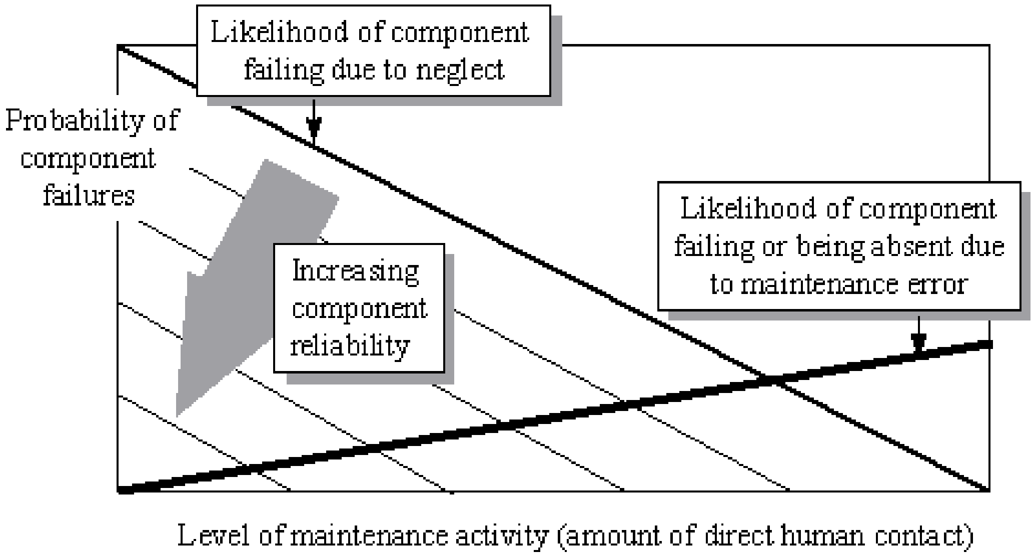

Figure 2.1 Comparing the risks to the system of component failure due to (a) neglected maintenance, and (b) errors committed during maintenance. The family of diagonal lines advancing to the lower left-hand corner reflect the increasing reliability of components over time.

Ironically, one of the pressures that sustains this high level of maintenance contact is the safety-criticality of the system. A catastrophic breakdown is unacceptable in commercial aviation. Everything must be done - and be seen to be done - to preserve the integrity and reliability of aircraft. But, as we have seen, the maintainer's touch can harm as well as heal. The point seems to be: the risks of the former may outweigh the benefits of the latter.

CONCLUSIONS

Aside from gravity itself, the greatest hazard facing modern aircraft comes from people, and most particularly from the well-intentioned but often unnecessary physical contact demanded by outdated maintenance schedules. We urgently need a greater awareness on the part of system designers and manufacturers of the varieties of human fallibility and the error-provoking nature of the maintenance task-especially during installation or re-assembly. Most of all, they must appreciate that maintenance can be a serious danger as well as a necessary defense. Until systems are designed and built with these issues in mind, good maintenance personnel will go on contributing to bad accidents and incidents, as well as to enormous financial losses.

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