QUANTIFICATION OF HUMAN ERROR IN MAINTENANCE FOR PROCESS PLANT PROBABILISTIC RISK ASSESSMENT

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At present, little is known about human error in maintenance other than post-incident reports. For reliable assessment and control of major hazards a technique for predicting the likelihood of human failure in maintenance is needed to reduce the uncertainty surrounding such events. Two established theoretical approaches, classical learning theory and probability theory, have been combined to develop a data-driven model of human performance. Over the period of a year, data have been collected from an Apprentice Training School and organisations engaged in industrial maintenance to characterise skill acquisition in panel wiring, electrical installation, welding, milling and design draughting tasks.

INTRODUCTION

Nowadays it has become almost impossible to write a paper on human factors in the assessment and control of major hazards without some mention being made of Three Mile Island, Brown's Ferry, Flixborough, or Bantry Bay.

Such journalistic devices usually work well, by seizing the attention of the reader, and alerting him to the reality of what can happen if errors are made in the course of construction, operation or maintenance of potentially high-risk systems.

Whilst it is not difficult to find other examples of human error contributing to the failure of major hazard systems, those mentioned above have not only captured the headlines, but share a feature which seems to have received relatively little attention in relation to their magnitude - they have all involved a substantial component of maintenance failure which has contributed to the initiation, course or consequence of a major accident.

Theoretical studies by authors such as Hall et al. (1981) show that if our estimates of human error are underestimates then the calculated effects on hazardous releases will be very great, whereas if our estimates are overestimates the effects will be comparatively small. Such studies also indicate that the likelihood of a severe accident is highly sensitive to human error and that maintenance error plays a sizeable role in the mathematics of major hazard assessment (Veseley et al. 1984).

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On an observational basis Taylor (1979) reports that 16% of the abnormal occurrence reports for components failures he studied were directly attributable to maintenance failure. Brune (1981) reported a similar result for maintenance, test and calibration activities, whilst Finnegan et al, (1979) report that 7% of the plant failure reports that they examined consisted of maintenance error. Sherwin (1982) showed that there is evidence that flaws arising from faulty maintenance procedures cause decreasing mean time to failure in the case of chemical pumps and valves. It is generally agreed that something between 60 and 80% of all major accidents are caused by human error (Joschek, (1980) and Rasmussen (1980)), and that about a quarter of these appear to involve a substantial maintenance failure component (Husseiny and Sabri, 1980).

Our experience tells us most forcibly that many of the really disastrous major hazard accidents have occurred precisely because insufficient attention was paid to consideration of the human factor in maintenance.

THE LITERATURE

If we are going to assess and control major hazards, therefore, it would seem appropriate to devise ways of understanding what sort of role such failure might play in determining the risk presented by large, potentially-hazardous systems (see for example, Potash (1981) and Bell (1984)), what the magnitude of such effects might be, and how one might set about controlling the potential hazard that the maintenance operator might unwittingly present.

Unfortunately, examination of the literature helps us little. Although we can find papers such as those by Irwin et al. (1964), Pontecorvo (1965), Siegel (1972), Akersten et al. (1981), Norros (1982), Norros and Wahlstrom (1983), Scott (1983), CSNI (1980) and Siegel (1981) with titles such as "Quantifying Human Error in Maintenance" and "Maintenance Reliability", most of them appear to offer little more than opinions or qualitative insights about what might cause error, and statements to the effect that, "Maintenance is a problem".

If we search the more general human reliability literature we tend to find papers such as those by Garrick (1967), Stewart (1981) and Hagen (1982) which give subjective judgements about the magnitude of error in maintenance based on rather slender evidence or the opinion of an eminent person.

With the exception of the analyses by Joos et al. (1979) which have been converted to a postulated error rate based on the likely number of operations per year for a given plant, the authors are not aware of any other published data relating to maintenance failure probabilities.

If maintenance failure is known to have strongly influenced the outcome of a number of very serious accidents, and if maintenance success is recognised as playing a major role in preserving system integrity we might justifiably ask ourselves why so little practical research has been expended on the "problem".

One reason for the apparent lack of interest is almost certainly the notion, shared by many PRA analysts, that equipment failure data already contain a substantial allowance for maintenance error, and that any analysis will already contain an indication of the threat to systems' integrity that maintenance failure could be expected to produce.

Other explanations for this apparent lack of concern may be the perception that new findings might make an already complex situation even more difficult to understand and model, or the justifiable view that every reasonable precaution is already taken to ensure that systems are not exposed to any significant maintenance failure.

These justifications for relative inactivity do not easily stand up to inspection. As the extent of the human contribution that might be made to equipment failure data is so far unquantified, it would be unwise to do anything other than recognise that there might be such a contribution. To assume, however, that equipment failure data completely cover all instances of system unavailability is, to say the least, a naive approach, especially as the probability of the sorts of major hazard accident referred to previously could not have been calculated with any certainty, using existing equipment unreliability data. If they had been that predictable then they probably would never have happened.

So here's our problem. We know that our modelling and assessment of major hazard operational failure is incomplete, and that the reliability technologists tell us not to worry - that it's all taken care of in the "bigger picture". We are likely to be uneasy about this because the evidence and our instincts tell us this isn't the full story, and we know that modelling without data isn't going to advance our understanding or reconcile competing views.

There are plenty of models (see, for example, Embrey, 1976, Meister, 1983, Bontoft, 1983 and Lees, 1983) for predicting human behaviour so why is it that thusfar the predictability of these major hazard accident scenarios has been so poor? The authors suggest that it is partly because the models are so poor, unvalidated (Williams, 1983) and specific to operational error, but principally because there are no real data associated with the reliability of routine maintenance-type tasks to give any practical insights into the potential vulnerability of plant to such interactions. To this extent it is clear that, despite the model development efforts of Siegel et al. (1984), nothing has happened in the last fifteen years to alter the conclusions of Smith et al. (1970) that developments in maintenance modelling are hampered by the absence of data.

THE MAINTENANCE FAILURE PROBLEM

Before deciding exactly what sort of data we are likely to wish to collect, some consideration of the sort of failures mentioned by Whitehouse (1984) or at the Public Inquiry into the Bantry Bay (1980) disaster could be of interest.

Amongst the many examples of human failure given by Whitehouse the following would seem to be particularly relevant in terms of the skills that we'd like to investigate:-

- a welded pipeline that failed at 50% of yield pressure
- a plug cock in the drain system at a refinery which an operator thought was shut when it was in fact open, because the handle had been reassembled at 90 degrees to its correct position.
- a maintenance man (with 20 years experience) who failed to locate and clip a cable correctly on a loom in a restricted space with the result that it was struck upon restart and the resulting short circuit ignited oily fly on the loom.

Examples of maintenance failure mentioned at the Inquiry into the fire and explosion at Bantry Bay showed for example, that one of the offshore foam tank operating valve levers was incorrectly installed because it worked in a different direction to the others, and it was also stated that there was evidence that the welding of the new sections of longitudinals in the oil tanker, "Betelgeuse", was in places defectively performed, "The longitudinal had not been properly set down close enough to the surface of the plate and probably a lack of fusion had occurred".

Apart from straightforward procedure-following, the sort of task that is likely to be of interest therefore might involve assembly, electrical installation and welding skills, amongst others.

Having recognised that major hazard plants are vulnerable to maintenance error, that we need to decide what the implications of such an interpretation might be, and knowing that current human reliability assessment techniques aren't going to help us to determine what the magnitude of such failures might be, what are we going to do?

Ideally, we need data that are derived from direct observation of failure on demand. Whilst such data can often be easily gathered for equipment failure by data logging, the collection of such data for maintenance failure is fraught with potential difficulties.

First the mere mention of an interest in monitoring the performance of maintenance personnel might be sufficient to precipitate industrial strife. Secondly, the logistic difficulties of reliably and accurately monitoring the occurrence of what would hopefully be extremely infrequent events at different parts of an industrial process or plant would appear, at first sight, to be insurmountable.

A POSSIBLE SOLUTION

Knowing that we want real data rather than estimates, that we need to gather such information in an industrial environment and that we're likely to have to expend inordinate resources obtaining it, we need a data collection method that posesses the vital characteristics of our subject area but which will reduce our resource and time needs to manageable proportions.

In 1982 it occurred to the principal author that what was really needed for such data collection would be something like a laboratory environment for the purposes of precise and controlled data recording and something like an industrial plant for the purposes of collecting task failure data that relate to the reality of performing industrial maintenance. By chance an opportunity arose to visit the Apprentice Training School (ATS) at Risley and it became apparent that the school possessed precisely the desired characteristics for data collection. Meanwhile visits to several organisations had shown also that in terms of equipment and environment the school was sufficiently like an industrial maintenance workshop that it was practically indistinguishable from the real thing. Not only that, but in terms of personnel the apprentices were, by definition, of a similar background and temperament to the maintenance staff that they would ultimately join.

Additionally, the work of the ATS was highly organised to ensure maximum use of resources and a steady throughput of students, all taught the same basic skills using standardised tasks.

Thus at any one time there was always a piece of training taking place that *could be monitored by one person. There were multiple workpieces of similar* configuration that could be salvaged for analysis, and the tasks were analogous to those of interest to our assessments.

The outstanding problem that had to be solved was the question of how information gathered from studying apprentices could be generalised to the real industrial context, and this is where another concept came into play.

Training is basically a period of error reduction and suppression during which individuals are encouraged to develop skills by monitoring their performance against some criterion and adjusting their behaviour to enhance the production of appropriate responses and minimise the likelihood of inappropriate responses.

If errors are made during this phase they will be clearly identifiable against criteria employed by training staff. Additional criteria can also be derived that would be representative of standards that must be achieved in industrial maintenance task performance. By comparing trainee-produced workpieces against these criteria it should then be possible to estimate the likelihood of an individual's work being in error.

Measuring the likelihood of error at this stage of skill development has obvious advantages. Error is much more likely than at the skilled level of performance and therefore the sample sizes of error are going to be correspondingly larger, thereby increasing the statistical reliability of resulting statements. It may also happen that error events affecting apprentices can be recorded, the frequency of which would be so low in practice that it would otherwise be infeasible to try to measure their likelihood in the field.

Thus the data collection environment of the ATS looked most promising. If monitored correctly, it could be expected to reveal the probabilities of task error as they occur at differing stages of skill acquisition. Therefore we had an opportunity to track the error probability reductions as they occurred with respect to accumulated time and experience.

This ability to track error probabilities is an essential feature of the modelling process, for it was assumed that if one or more tasks could be monitored not only during the initial stages of skill acquisition, but through into the highly-practised regime, we would be able to form the basis of a generalised learning model.

Fortunately learning theory is well-developed, so if the model could be validated it would no longer be necessary to speculate about error probability. Based simply on the evidence of the probability of error during early learning trials, it should be possible to extrapolate and predict the asymptotic likelihood of failure for any given task for highly-practised maintenance personnel - the group whose behaviour we are most anxious to be able to predict.

A similar methodology has been proposed by Williams (1982) for the assessment of cost-effectiveness in process plant design and has been shown to represent a valuable method for cutting down experimental programmes whilst achieving satisfactory design evaluations.

The advantages of such a technique are enormous. Often when new plant is designed it is not possible to do any more than speculate about the likelihood of error that might occur during maintenance, but with a predictive model, a simple experiment would be all that would be necessary to evaluate task performance on simulated or prototype hardware. The results of such an experiment could then be used to project likely operational performance from the model.

THE PROJECT

It was clear that what we needed was someone permanently available to monitor tasks as they were performed and assess error in such a way that neither the ATS staff nor the apprentices felt under pressure. We also wanted to collect as wide a range of data as posible in the hope that a means of evaluating its significance could be devised at a later date, even if no obvious means presented itself at the outset.

These requirements argued for the positioning within the ATS of someone of the same age group as the apprentices, who possesed the necessary social skills to integrate well with the running of the school, someone familiar with behavioural observation techniques and someone who had the time and ability to learn sufficient about the tasks to be able to know how to assess their performance. All these requirements converged on one source for choice of an investigator, a university department of ergonomics.

Fortunately the University of Technology, Loughborough operates a scheme whereby students in the Human Sciences Department are given supervised research and experience assignments of one-year duration leading to an additional qualification, the Diploma in Professional Studies. It was from this programme that the second author was recruited to implement the data collection exercise.

The ATS co-operated to the full and not only trained the investigator in the basic skills, but allowed him access to a full range of activities including welding, milling, design draughting, soldering, electrical installation and instrumentation, which facilitated the collection of a large amount of data from a wide variety of manual skills and a sizeable number of apprentices.

After initial familiarisation with the personnel, training activities and acquisition of the necessary manual skill, attention then turned to the task of finding comparable tasks performed by highly-practised maintenance personnel in field situations. Approaches were made to five enterprises which were known or thought to be engaged in equivalent work on a full-time basis. The criterion for contacting these organisations was that they should be maintaining large numbers of similar systems on a regular basis, and the assumption was made that occasionally there might be evidence of a maintenance task failure which could be detected.

The organisations were extremely helpful, recognising that occasionally, despite their best endeavours, a system could become unavailable because of such failure. Extensive inquiries led to the identification of tasks which were similar to those observed at the ATS and for which failure data could sometimes be assembled.

THE TASKS AND THE RESULTS

Milling

First year apprentices undertook a 7-week course in the machine milling of metals. The basic machining skills were taught via a series of exercises which progressed in difficulty. The exercises required apprentices to work to a set of drawings which specified dimensions and tolerances, surface finishes etc. The three tasks set were a G-clamp, a vice and lifting jack.

A suitable method of performance monitoring proved to be measurement of the closeness of a cut to its specified dimension. The whole sequence of cutting, from the initial cut on the first exercise, to the last on the final exercise was monitored using a micrometer and a pair of calipers.

In all a total of 263 measurements were taken and the likelihood of a cut's being out of tolerance was determined by reference to the proportion of observations that would have fallen outside the tolerance limits according to statistical properties of the normal curve.

Very high error was observed in this task with approximately 50% of the initial cuts being incorrect (p failure 5×10^{-1}) falling to 15% of the final cuts being out of tolerance (p failure 1.5×10^{-1}) after about six weeks experience.

Although an attempt was made to compare these results with those achieved by highly-practised staff it was not possible to complete this part of the data collection exercise.

Electrical Installation

Apprentices were required to design, install and test a light-industrial installation for lighting and power. The task was carried out in teams of two, and the investigator obtained data by observation of each pair, at different stages of completion of the installation.

A written record of errors committed was made by marking the location, and giving a brief description of each mistake made in construction on a diagram of the completed circuit.

Direct observation of each installation was supplemented by informal interviewing of apprentices in order to take some account of errors not apparent on the completed workpiece.

It was found that mechanical tasks such as deforming mechanical protection which occurred about 400 times produced error probabilities of about 10^{-1}, whereas cutting failure was about 3×10^{-2}. Failure to select the correct units was about 2×10^{-2}, failure to locate units in the correct position was about 6×10^{-3}, whilst failure to terminate physical protective systems at a unit was about 4×10^{-3}.

A concerted effort was made to find comparable evidence of inappropriate installation in an industrial context, and for a while it looked as though the requisite information would materialise from a study of vehicle fleet maintenance records. Although the problem was specified exactly, and the affected vehicles identified, the link was never established with any certainty, but there was strong circumstantial evidence that such failure did occur.

Draughting

A standard design/draughting task was given to all apprentices and assessed by other apprentices and tutors. For 30 drawings a total of 189 errors were found of which 103 were unique.

A method using the unique errors was devised for calculating the maximum number of errors that could possibly occur on a typical drawing produced in response to this standard specification, and this resulted in a value of about 300. As an average of just under 7 errors were made on each drawing it is postulated that the error probability is about 2×10^{-2}.

Obviously to determine the error probability for draughting tasks a method is required for estimating a plausible denominator. Although at the level of assessment of the apprentice drawings a method can be devised to estimate a denominator, it is much more difficult to estimate the denominator for ordinary industrial drawings.

However, an attempt was made to devise a method for calculating the likelihood of errors occurring on industrial plant drawings. By using three of the apprentices' standard drawings as referents, calibrating a perceptual regression equation using the probability of error on each standard drawing, and comparing the perception of the amount of error on the industrial drawings with that on the standard drawings, it was possible to estimate the likelihood of error in relation to the maximum number of errors which might have occurred. These estimates were derived from an experiment involving 5 assessors who were asked to make judgements about maximum error potential and perceived probabilities of error.

All nine industrial drawings so assessed had been thoroughly checked before issue. Application of the subjective assessment method indicated that the likelihood of errors on such drawings was about 4×10^{-3}.

Obviously such assessment methods do not take into account the severity of draughting and design errors, but give us some insights about the proficiency of draughting offices and the efficiency of the checking and change control systems. The majority of errors made by apprentices were errors of omission, followed closely by substitution errors.

The proportions were as follows:-

Omission	45%
Substitution	35%
Transposition	10%
Insertion	8%
Miscellaneous	2%

Panel Wiring and Multimeter Construction

An exercise requiring the construction of a simple electrical panel was completed by all apprentices. To monitor performance on this task, each completed panel was checked by the investigator for attainment of electrical continuity, correctness of wiring and appropriate component selection.

Similar checks were carried out on the performance of the multimeter construction task, which followed the panel wiring task.

2964 joints were soldered by 38 apprentices during the panel wiring task and 2652 during the multimeter task. The failure likelihood was found to be 2×10^{-3}, whereas the failure to terminate wires correctly or select the correct component was found to be 1.4×10^{-2}. (Comparable figures for the multimeter failures are shown in the "semi-skilled" column of Table 1).

A comparison was made between the performance of apprentices and skilled tradesmen by giving the same panel wiring task to 14 tradesmen in two maintenance organisations. Their error probability was found to be 9×10^{-4} for soldering and 4.8×10^{-2} for component selection.

Welding

The apprentices were trained in a variety of welding techniques by means of a range of tasks. The technique selected for study involved butt-welding using $^{1}/16$" mild steel plate, a neutral flame and a size 2 nozzle.

To assess the performance of apprentice welders, A1 certified and garage welders, samples of their work were destructively examined via tensile tests. Taking a design value for desired tensile strength of a hypothetical structure made from $^{1}/16$" welded plate it was possible to calculate the likelihood of an apprentice's weld failing, which was found to be about 5×10^{-2}, whereas A1 welds were predicted to have a failure likelihood of about 5×10^{-4} and a particular garage's welds a failure likelihood of about 5×10^{-2}. Apprentice welds were calculated to be about 30 times more likely to fail before the parent material than A1 welds.

OVERALL TASK RESULTS

Table 1

Nature of Task	Estimated Error Probability		
	Apprentice		Skilled
	Initial	Semi-skilled	Operative
ELECTRICAL INSTALLATION			
Deforming Mechanical Protection	10^{-1}	-	-
Cutting Mechanical Protection	3×10^{-2}	-	-
Component Selection	2×10^{-2}	-	-
Location	6×10^{-3}	-	-
Termination	4×10^{-3}	-	-
DRAUGHTING	2×10^{-2}	-	4×10^{-3}
PANEL WIRING			
Soldering	2×10^{-3}	1.1×10^{-2}	9×10^{-4}
Termination	1.4×10^{-2}	2.6×10^{-3}	-
Component Selection	1.4×10^{-2}	7.8×10^{-3}	4.8×10^{-3}
WELDING (Design Basis)	5×10^{-2}	-	5×10^{-4}

DISCUSSION

It is clear from the data gathered that skill can be quantified in terms of error probability. For every ten-fold increase in accumulated experience it looks as though we can expect the error probability to reduce by something like a factor of 3, although it must be supposed that beyond about 10,000 hours experience this effect will become asymptotic (see Table 1). It should also be noted that tasks involving high levels of manual dexterity are likely to *produce higher error probabilities than simple repetitious operations.*

This study might be regarded as the first step towards a quantitative model, for with a little more data and an opportunity to carry out a repeat study it should be possible to predict the nominal likelihood of highly-practised maintenance personnel error for any designated task, within the limits of accuracy required by reliability assessors.

It remains to be seen whether such a study, and its logical successor, a Testing Reliability Study, can be performed in the near future - both are urgently required for such assessment work.

CONCLUSIONS

A method for assessing the likelihood of maintenance error has been devised which seems to hold considerable promise for the assessment, and ultimately, the control of major hazards.

It has been shown quantitatively that highly practised maintenance staff are in the region of eight to twenty times less error-producing than apprentices learning their trade. The effects appear to be sufficiently predictable that it should be possible to formalise the findings of this study in a model, after the necessary validation has been accomplished.

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