WHERE EXACTLY DOES IT HURT, MR. FEED PUMP?

BY

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And now I see with eye serene,
The very pulse of the machine;

WILLIAM WORDSWORTH

Summary

This article reviews, with a submarine bias, the historical and technical perspectives of machinery health condition monitoring and concludes that the time is ripe, and that the technology is available, for a fundamental change to the Royal Navy's approach to maintenance.

Introduction

Confusingly, a number of different phrases are used to describe the basic techniques considered in this article. On-condition maintenance, condition monitoring, machinery health monitoring, *in-situ* maintenance assessment, non-dismantling maintenance evaluation, non-destructive inspection—all mean the same thing: a way of determining what maintenance (if any) a system or equipment needs without opening it up to see.

The title of this article is not wholly frivolous—non-dismantling interrogation is one area where the medical profession is ahead of other engineers. Surgeons simply do not split their patients open 'to see if they are all right' or 'to see why they are still working' without some evidence of need to repair or maintain; nor do they conduct such maintenance on an 'hours run' basis despite the similarity in design of all units and the considerable size of the sample. It is arguable whether a wear-out phase is readily discernible and, like so much of our machinery, Mean Time Between Failures and Failure Mode are determined more by the ambient conditions and the usage profile that the subject experiences than by innate design characteristics. In essence, the physician relies on getting answers to certain questions either by dialogue or by the use of sensors (temperature, pulse, X-rays, etc.) before making the bold incision. Such questions and their engineering classification are shown in TABLE I. It is finding ways to carry out this sort of conversation with our machinery that constitutes condition monitoring.

Throughout this article, some mechanical bias is evident. Condition monitoring is naturally biassed towards mechanical maintenance for two reasons. Firstly, the need to determine whether to dismantle implies some penalty (in terms of time, labour, resources) in dismantling. This penalty is readily apparent in almost all mechanical equipments where massive enclosures and fastenings are necessary to contain an internal pressure or provide the necessary strength to the assembly. In many cases in electrical engineering those constraints do not apply and a simple cover can be easily removed. Secondly, electrical engineering enjoys the self-evident benefit of electricity (eminently measurable) as its working fluid. Thus the dialogue with the system is already available—a good computer now tells you how it's feeling!

A submarine bias has already been mentioned, and, although this is in part due to the author's own experience, a case can be made that the submarine flotilla is where condition monitoring is most pressingly required. Submarine maintenance engineering is, of course, little different from that in any other vessel, but the capital and running expenditure, intrinsically confined conditions (with limited access and difficult shipping routes), relatively lower availability, and military importance of these 'new capital ships' all add up to suggest that it is here that maintenance optimization should be prosecuted most vigorously.

TABLE I

Medical Questions	*Classification*
'Do you feel well?'	Condition monitoring
'Describe your symptom'	Condition monitoring
'Where does it hurt?'	Failure mode identification
'Does this hurt?'	Failure mode identification
'Cough'	Condition monitoring
'When did you last see a doctor?'	Maintenance history
'Jump up and down on this bench'	Performance testing

History

Condition monitoring is as old as engineering. Indeed, the old type of maintenance engineer had two particular strengths—knowing when to overhaul his machinery, and knowing how. His knowing *when* was attributed to 'knowing his machinery' or 'having a feel for it'. In today's terms, that meant using his data bank of experience to establish a datum of acceptability against which he could compare the signals provided by his sensors: sight, sound, touch, smell, taste, and the 'sixth sense'—an indefinable feeling that all is not well.(1) The trouble was that this was subjective, unquantified, and difficult to communicate to others. In fact, 'experience'.

So, with the advance of technology, engineering design progressed and machinery became more complex, more highly rated, denser. Add to this the Second World War, in which regular service engineers were augmented by engineers of experience, but not of the relevant experience, add also a demand for more availability from our dwindling fleet, and things had to change.

That change was to planned maintenance. It was probably the only way that the technology of the day could have sustained the fleet and it was, broadly, a great success. It allowed, at least on paper, for the designer to specify the maintenance that he thought necessary for the machine; for Class Authorities (later the Ship Maintenance Authority) and Headquarters to chip in and add their views; and for the ship's engineer officer eventually to accept, reject, or modify this weight of paper opinion on how and when to maintain his machinery. It also gave an opportunity for dockyards to plan refit work. There were, however, and are still, problems. Firstly, the designer is unlikely to be the best person to determine the optimum maintenance for an equipment. He will not be experienced in its usage, its ship-borne environment, nor the standards of its operation and maintenance. He is also subject to opposing pressures: specify too much maintenance, and he is failing to meet a Statement of Requirements and will diminish his company's chance of continued orders; specify too little and his product will gain a reputation for breakdown. And what machine is he specifying *for*?—the as-designed model or the equivalent of the Friday-afternoon car with all its tolerances at the limit.

The Maintenance Authority and Headquarters may find themselves at odds too. The Maintenance Authority's answer to persistent defects in an equipment may be to shorten the maintenance interval (regrettably the converse is seldom true). (2) The Headquarters approach is to design out problem areas; the ship stands some danger of ending up with a heavily modified equipment which needs very little maintenance and, to go with it, an elaborate maintenance package most appropriate to its original (un-modified) condition.

A final difficulty: the existence of a comprehensive maintenance schedule and the carrying out of the work it calls up may confer an undesirable complacency on ships' officers and their administrative authority. But does the completion of a fairly arbitrary package of maintenance actually improve short-term availability or say anything meaningful about the ship's material state? And is it not possible that the secure feeling of having recently completed all scheduled maintenance may discourage that critical and inquiring approach which engineers should cultivate?

The Need for Change

In these days where fashion reigns over enduring virtue, and ephemera oust solid principles, the prudent engineer looks hard, and looks again, at proposals for change. The importance of distinguishing between technology push (what you *could* do) and market pull (what you *should* do) is considerable.

What is it, then, that the present maintenance policy is not giving us that alternatives could provide?

It is certainly not giving us *cheapness*. The through-life maintenance bill for a SSN is approximately equal to the capital cost of one of these extremely expensive vessels.

It is not giving us *availability*. Usage/upkeep ratios for H.M. ships can only finally be considered satisfactory when they are limited by the availability of the crew rather than the machinery.

It is not giving us *freedom from defects*. The average submarine arrives in refit with probably one or two significant defects. The last third of its long, expensive refit is spent almost exclusively in testing, tuning, and remedying defects in wake of maintenance to achieve operational status on departure. But, because we have never run a submarine for two successive commissions without this intervening maintenance, we do not know from what defects in the second commission that maintenance is saving us. Further, the improvement to reliability conferred upon an equipment by maintenance must be dependent on the *quality* of maintenance. For instance, if (simplistically) a machine has deteriorated to a condition 10 per cent. inferior to the design condition but the maintainer can only be relied upon to refit to 20 per cent. below design condition, then its final condition will be worse than its initial. In practice, we know this is true—much of that long testing period referred to above is devoted to identifying and rectifying maintenance-created defects. Maintenance statistics reflect runs of failures on individual equipments—cases where the maintainer 'didn't get it right' first time. Where we deem it sufficiently important, we invoke saturation control and surveillance—quality control—to improve the 'maintenance efficiency' to an acceptable figure—and a most expensive enterprise it is too. (A nuclear refuelling team effectively does the job twice over: once to practice, once the real thing. Whilst this is inevitable in this case, it indicates the lengths to which quality control may have to be taken to achieve the desired efficiency.)

Some Disquieting Trends

The need for change is reinforced by some significant trends in the technological sense. The procurement/maintenance/usage environment that existed when planned maintenance was introduced is now changing to such a degree that it raises questions about what were then tacit, reasonable assumptions, both within the Royal Navy and nationally.

Defence Contractors

Not many years ago, defence contracts were prized as being interesting '*Grand Prix*' work which yielded a highly desirable quantity of development work, a good degree of motivation, and advanced a company's capabilities in the commercial market. No more—at least not in the marine engineering field. Defence contracts now are highly complex, yield a low profit rate on a very small number of orders, and are commercially irrelevant. Increasingly we are forced to put all our eggs in one rather reluctant basket as firms drop out of the defence game. Thus the system designer is progressively denied the opportunity to specify the components he wants (and with them a consistent maintenance policy); he must now take what is available commercially and navalize it externally—by building it into a shock-proof, noise-proof, watertight box for instance. The maintenance characteristics of such an equipment will have been determined by commercial rather than naval requirements.

Ship Design

Economic and military pressures have demanded successively more compact and dense machinery system layouts. Such arrangements cut two ways into maintenance effectiveness or maintainability—by limiting space round a machine for *in-situ* maintenance and by making shipping routes more difficult for upkeep by exchange. Of course maintainability appears as an objective in Staff Targets but, because of the difficulty of quantifying it compared to other military characteristics, it never achieves a high essentiality marking and becomes a soft target for economies. As a result, despite elaborate exercises at the design stage, a ship design is often accepted which ensures that some maintenance activities extend their timescale many times over by the influence of 'wooding'.

Training and Capability of Maintenance Personnel

The complexity of present-day machinery coupled with a vigorous policy of upkeep by exchange have had a pronounced effect on the maintenance capability of naval and dockyard personnel. Skill of hand has to some extent been displaced by diagnostic ability: the capability to build up a machine from a kit of parts has replaced that of refurbishing worn components. Even where the traditional skills of fitting and turning are adequately taught during initial training, there is little opportunity to keep in training thereafter. (In the author's recent experience, the best fitter and machinist in a nuclear submarine was an ex-UW ordnance mechanician—who enjoyed making model locomotives. His superiority in this field over the marine engineering artificers seemed to cause them no embarrassment.) It has also become clear, in the nuclear fleet at least, that the necessary pre-occupation with watch-keeping excellence to achieve submarine and reactor safety has further reduced ship's staff maintenance competence.

Within the dockyards, the effects have been the same, although some of the causes have been different. Upkeep by exchange, line overhaul, the use of specialist civilian contractors, and the need to create new skills (electronics, test-and-tune teams, dockside test organizations, and others), rationalization of yard facilities—all these factors have reduced a dockyard's pool of relevant experience for 'jobbing maintenance'.

Condition Monitoring: The State of the Art

Much of this article so far has been devoted to examining the historical and technical background to planned maintenance; it has been shown that this has its shortcomings and that present trends suggest that things are likely to get worse.

Classically it is necessary to match resources to objectives. If the resources are fixed, or it is desired to reduce them, then the objective must be modified. The proportion of the Navy's budget spent on maintenance cannot be viewed with equanimity. It is the author's view that the amount of maintenance carried out in the Fleet is excessive, and that the adoption of a policy of condition monitoring can reduce this, not only without a reduction in availability but actually with an increase. So, a double gain: the reduction of the resources committed to maintenance and an increase in ship up-time.

There is nothing new about condition monitoring. It was the basis of the old 'experience' maintenance policy. As a trendy new term, it is often assumed to incorporate flashy electronic units, yards of computer tape, shiny gadgets. It must be emphasized that the engineer with the Mk 1 screwdriver is as much a part of the condition monitoring scene as these advanced fruits of current technology. The tools are in the main available, having been developed for the investigation of defects and potential problem areas. What is needed is an organizational change, not a technical one.

The difficulties with condition monitoring consist of deciding what should be measured (what parameters describe an equipment's condition), what are the limits of acceptability, and how to carry out those measurements. The literature describes a vast number of methods, many already in use within the R.N.

Measurement techniques may be grouped by the characteristic they are concerned with as follows:

Performance: All aspects from valve leakage rates to pump handling rates, heat-exchanger balances.

Wear: Bumping clearances, impeller erosion, sealing-ring wear, pipe thickness testing, proximity sensors, crankshaft deflections.

Vibration: Broadband 'general severity' measurements, discrete frequency/amplitude plots for source identification.

Introspection: Use of inspection ports, introscopes, boroscopes,

Spectrometry: Analysis of corrosion, erosion products for quantity and constituents, e.g. SOAP, water chemistry.

Materials testing: Thickness testing, crack growth determination, stress wave emission techniques.

Nothing much new here—the techniques have all, as has been mentioned, been developed already. It is the co-ordination of these techniques into an approach to maintenance that is still missing.

Progress in Other Fields

It is salutory to observe what has been going on in industry and the Merchant Navy in this area. In attending several gatherings, mostly convened under the heading of terotechnology, in the past two years, it has become clear to the author that, whilst we in the the Royal Navy have been pondering, discussing, and analysing, others have been quietly getting on with expediting condition monitoring. A large British tanker fleet has converted from a 100 per cent. planned maintenance policy to a 60/40 mix of condition monitoring to planned maintenance. Not only do they report significant improvements in availability and reduction in maintenance costs, but also seagoing engineering staffs have welcomed the change—since it returns to them the involvement and participation in maintenance optimization that slavish adherence to an impersonal maintenance schedule had removed. The British Steel Corporation has widely adopted condition monitoring—and found it necessary in the process to make significant changes in its management structure to accommodate this change. In this respect, they represent a substantial move by most of the process industries in this direction. The USN and CAF have not been idle in this field either. It is understood that the latter has been considering the adoption of a change to a 'defects only' policy for gas turbines.

What could be Achieved

It is difficult to quantify what could be achieved without trying it. Subjectively, it is believed that it might be possible to reduce a nuclear submarine refit by as much as a third—in work content if not time. Against this saving it might be necessary to expend some extra time before the refit started in a greatly expanded version of the present pre-refit tests; eventually, of course, condition monitoring would become such an integral part of the ship's maintenance package that no additional time would be necessary since a continuous record of machinery condition would be available.

Clearly, as with all innovation, the greatest gains will come for those ships designed with a policy of 'on-condition maintenance' already established. Thus the full impact of such a change will not be seen for many years even if we start today.

Some Difficulties

There seem to be a number of main difficulties associated with the change proposed here. None however is seen as being of such importance as to discredit the proposal, but their effect may be to alter the preferred ratio of condition maintenance to planned maintenance.

Firstly, a change of the magnitude suggested will profoundly affect the way the Royal Dockyards plan and carry out their work. It is, of course, agreeable for a dockyard to work to a 'standard work package', predicted years in advance. The introduction of condition monitoring will reduce the predictability of refits and will introduce uncertainties not only of content but also of total quantity of work to be done which will not be resolved until the refit start date. However, it is considered that the dockyards must, however painfully, adapt to the needs of the Fleet.

Secondly, some increase in unplanned unavailability is likely, particularly in the initial stages. The question that will have to be answered for each ship and each class of ship is 'What is the ratio of importance of unplanned unavailability to planned unavailability?' Or, put another way, would we accept an increase in planned availability of say 10 per cent. in exchange for an increase of say 5 per cent. in machinery breakdowns at sea. It is a difficult comparison of unlike parameters, but it is one that ought to be made. Due weight will also have to be given to the difficulty of extracting defective components 'out of routine'.

Thirdly, there is the concept of 'maintenance fat'. If we are maintaining our fleet for readiness for war, we want a large proportion of our ships to be available on a split yarn to go to war and stay at war without further maintenance. Does not the principle of not maintaining until strictly necessary reduce this fat? It is argued that, although it may do, we do end up with a much better idea of our ships' capabilities than we have now—an improvement on the current situation where assumptions that recently refitted ships are the most reliable are often proved to be wrong.

We may also find ourselves sailing into uncharted waters once we lose the concept of 'group working'—that is, of maintaining geographically adjacent machinery at the same time over a reasonably extended period. It is fair to say, however, that this is a problem not addressed by the present maintenance schedule which treats all equipments individually. The task of scheduling mutually compatible maintenance across systems is left to the discretion of the ships' officers. It underlines the truism we have come to understand—that the Ship is the System.

Lastly, there is the technical difficulty of foreseeing from the present information what 'life' there is left in an equipment or system. With long intervals between refits, can we ever afford not to do a full dismantling maintenance on an equipment and then leave it for some years before its next natural opportunity? This brings us to the difficulties quoted already of deciding what to measure and how to determine acceptable limits. There is no easy answer to this; it is a matter for painstaking detailed work on a case by case basis, calling for careful professional judgement and an effective feedback system to update the data base. But such work, however painful and time consuming, must surely lead to a better answer than the present *ad hoc* arrangements.

Where Next?

It is concluded from the foregoing that there can be no real argument about whether to adopt a different policy for maintenance—the questions remaining are 'When?' and 'How?'. Various equipment sponsors will claim that for their equipments the change has already started; certainly, in the gas turbine world, increasing use is being made of performance comparison and trend monitoring techniques. However, allowing a policy to synthesize from such specialized areas does not make for speed or consistency and, by never facing some of the overall problems that have been mentioned, may lead to greater difficulties later. So now seems a good time to start.

The question of 'how' involves almost the whole spectrum of naval technical administration:

(*a*) The Naval Staff, led by the Directorate of Fleet Maintenance, must start the ball rolling. What would be most valuable here would be a re-affirmation of the optimization of through-life costs (cf. unit production or series costs) as the financial basis for ship design and procurement. The Naval Staff will also need to set up a Working Party to provide an arena for contributions from the many concerned parties.

(*b*) The material departments (DGS and DGW) will have a major part to play both in contributing to the policy discussion, pointing design contractors in the right direction, and correlating the many authorities concerned in applying condition monitoring techniques. Single points of contact with good communications throughout their departments will be needed. In particular, the identification of salient parameters and the quantification of their acceptable limits will demand much from these departments.

(*c*) The Ship and Submarine Maintenance Authorities will be major factors in the execution of the policy, once established. The re-casting of maintenance schedules to reflect the 'see if' rather than the 'do' policy will be a lengthy and difficult task.

(*d*) CED will be faced with the difficulties described earlier with respect to Dockyard work. Considerable introspection and re-arrangement of working practices will doubtless be necessary to accommodate the new policy.

(*e*) Finally, as ever, Fleet, Squadron, and Ships' staffs will be responsible for absorbing and carrying out the policy, which will have its share of ambiguity, contradiction, and plain impossibility. They will be vitally important too in the feedback link of saying what is actually happening to the machinery during the transitional period. When one looks at the difficulties experienced in even the comparatively modest feedback exercises conducted in recent years, it may not be an exaggeration to say that the establishment of really effective feedback paths is likely to be the most crucial and the most troublesome area of activity.

Conclusion

A change in maintenance policy is proposed which is as fundamental in its way as the recommendations of the Engineering Branch Study (3). Although the gains are still unquantifiable, the technical aspects are feasible and the policy will place naval maintenance in a position appropriate to civil and merchant practice and to current technology. We will at last be able to ask 'Where exactly does it hurt, Mr. Feed Pump?' and get an answer.

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1. Discounting, with regret, the likelihood of telepathic links between engineer and machine (how simple that would make life) it seems possible that this is more an intuitive summing of abnormal signals received by the other senses, none of which is abnormal enough individually to trigger a conscious alarm state. This is subconsciously added to background knowledge of past usage and maintenance in the particular ship and in the Fleet in general. (If current claims to telepathy are to be believed, it is even conceivable that such a summing could be made locally and unknowingly by an operator, and transmitted to a remote engineer with a lower 'alarm-setting'. But the *Journal* is not the place for such speculation.)
2. In practice, it can be shown that if an equipment exhibits a burn-in phase, such action may actually increase the Hazard Rate.
3. See DCI(RN) S166/75.