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The Use of Condition Monitoring Information for Maintenance Planning and Decision-Making

Kari Laakso and Tony Rosqvist
VTT Industrial Systems, Finland

Jette L. Paulsen
Risø National Laboratory, Denmark

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Abstract

A survey is presented outlining the use of condition monitoring information in three Nordic nuclear power plants. The questions of the survey relate to the role of condition monitoring in strategic, as well as operative, maintenance planning and decision-making. The survey indicates that condition monitoring is increasingly implemented at nuclear power plants, but very selectively and in a rather slow pace for predictive maintenance. A combined strategy of condition based maintenance and predetermined preventive maintenance is applied for important equipment such as main circulation pumps and steam turbines. A realistic aim is to reduce the number of costly or error prone maintenance and disassembling inspection activities by condition monitoring given that the approach enables a good diagnosis and prediction. Systematic follow-up and analysis of such condition monitoring information followed by a case-specific planning and decision making of timely and rightly directed maintenance actions can justify an extension of the intervals of a number of predetermined inspection, maintenance or periodic testing tasks.

Key words

Condition monitoring, maintenance planning, decision making

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NKS Secretariat
P.O. Box 30
DK – 4000 Roskilde, Denmark

Phone +45 4677 4045
Fax +45 4677 4046
www.nks.org
e-mail nks@catscience.dk

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Customer: NKS/SOS-2.2 project

Kari Laakso & Tony Rosqvist
VTT Industrial Systems
Jette L. Paulsen, Risø National Laboratory

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Kari Laakso, Tony Rosqvist
VTT Industrial Systems, Finland
Jette L. Paulsen,
Risø National Laboratory, Denmark

Abstract

In a modern operating and maintenance organisation for nuclear and advanced power plants, condition monitoring plays an important role in managing the maintenance and operability activities. Basically, condition monitoring helps to control the safety and economy of the plant operations. In order to establish a framework for understanding problems and solutions related to the use of condition monitoring information in strategic and operational maintenance decision-making, the respective decision contexts are modelled as process models.

The report includes a survey of the utilisation of condition monitoring information for predictive maintenance in three Nordic nuclear power plants. Based on the survey the following general observations can be stated;

- A combined strategy of condition based maintenance and predetermined preventive maintenance is applied for very important equipment such as main circulation pumps, steam turbines and turbine condensers;

- For less important equipment, the maintenance management at a nuclear power plant tends to wait for experiences of condition based maintenance in other type of power plants;

- The reluctance to change manners of proceedings in nuclear power plants is relatively high and risk is not taken in implementing new condition monitoring for predictive maintenance unless a high fault coverage of the monitored equipment and cost benefits are demonstrated (in many cases, existing condition monitoring systems at plants are used for condition monitoring but at a rather slow pace for condition based maintenance);

- A realistic aim of condition monitoring is to reduce the number of costly or error prone predetermined maintenance and disassembling inspection activities. Condition monitoring, together with an increase of proper tailoring of maintenance actions (timing, localisation, work), based on the analysis of condition monitoring information, can justify an extension of the intervals of comparable predetermined inspections and preventive maintenance.

- Display systems for online condition monitoring of equipment by using existing process monitoring and control data have also a great potential in increasing the condition based maintenance.

The current report is a working report that will be completed at the HRP MTO research period 2003 – 2005. The feedback from the plants is very crucial in developing process and decision models for condition monitoring that meet the generic and specific needs at the plants.

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1. Introduction

In a modern operating and maintenance organisation for nuclear and advanced power plants, condition monitoring plays an important role in optimising the maintenance activities. Basically, condition monitoring helps to control the safety and economy of the plant operations.

The objective of condition based maintenance is twofold: Firstly, to avoid extraneous outages or damages due to unexpected failures in equipment, secondly, to decrease costs related to maintenance (e.g. periodic replacements, repairs or fault finding tasks). Thus, condition-based maintenance is a means to achieve a better control of risks but also a better return on investments on maintenance.

The development of condition monitoring approaches and techniques, and information technology, together with nowadays more stringent economic and safety requirements of power plants has led to the development of systematic maintenance planning towards condition based maintenance.

Condition based maintenance means preventive maintenance consisting of parameter and performance monitoring and the subsequent actions. Predictive maintenance is condition based maintenance carried out following a forecast derived from analysis and evaluation of significant parameters of degradation of the item [CEN – prEN 13306, 1999]. Fig. 1 illustrates the change of cost effectiveness with respect to added value due to improved dependability for specific maintenance strategies.

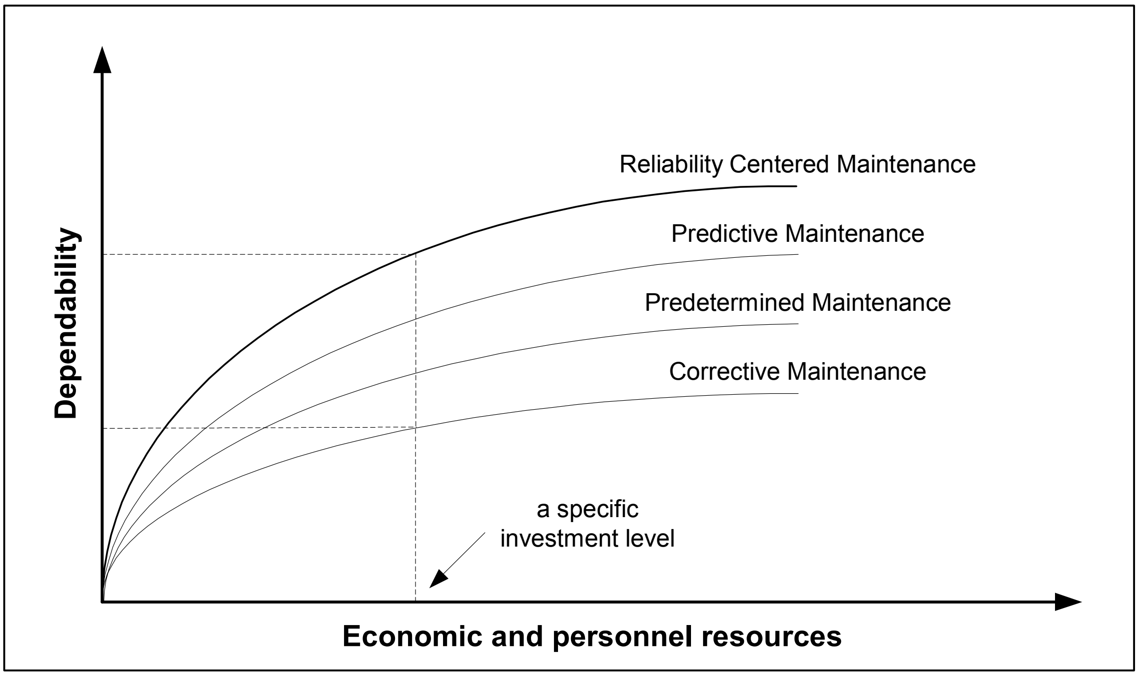


Figure 1. Cost effectiveness with respect to Dependability Added Value (value that is seized due to improved dependability) for distinct maintenance strategies.

The fundamental question in Maintenance Management is which maintenance strategies should be adopted [Laakso, Simola, Skogberg and Dorrepaal, 1999]. A change from the current maintenance strategy to a more systematic and developed strategy is usually conducted in a stepwise fashion. The more advanced is the maintenance strategy, the better management and more demanding manners of proceedings utilising expertise, information, more advanced data analysis and smarter technology, are required.

Expectedly, present research in the Maintenance Management field is focused on the exploration of manners of proceedings in condition based maintenance planning and decision making, and the use of modern information technology. The objective of the research is to describe the predictive maintenance process and develop flexible decision models and decision support systems (DSS) to aid strategic, as well as, operational maintenance decision-making.

The Machinery Information Management Open Systems Alliance (MIMOSA) [Tom Bond, 1997] proposes and facilitates conventions, guidelines and recommendations that promote cost-effective unification of machine information, condition assessment and control technology. Especially, MIMOSA has developed a data flow model that links various data sources with analysis models to support strategic maintenance planning and steering of operational maintenance activities.

The current report focuses on process and decision models related to:

1. Strategic maintenance planning with the focus on the utilisation of condition monitoring information,
2. Operative maintenance steering, given that an indication of an incipient or hidden fault has been observed from condition monitoring.

The above decision context are modelled as process models, in order to establish a framework for understanding the problems and solutions related to the use of condition monitoring information in maintenance decision-making.

The report also includes a state-of-art study of the level of the utilisation of condition monitoring information for predictive maintenance in three Nordic NPPs.

The current work will continue at the HRP MTO research program 2003 – 2005.

2. The diagnostic and prognostic capability of condition monitoring approaches

The technical challenge of condition-based maintenance is to acquire right information for identification and localisation of faults and about the state of the degradation in equipment.

First, the process of degradation is depicted by the causal chain:

Failure (and wear) mechanism(s) -> Degraded equipment -> Functional breakdown.

The main purpose of condition monitoring is to detect a fault, or a degradation process, that has reached a certain symptomatic level and to provide an indication of the abnormality in time before the functional breakdown occurs.

Condition monitoring in power plants may be based on several condition monitoring - approaches, for instance [Hytönen & Savikoski, 1998; Kokko 2000, Luukkanen 2002]. In the following figure 2 different condition monitoring methods and an ideal information flow from the monitoring into condition based maintenance is given.

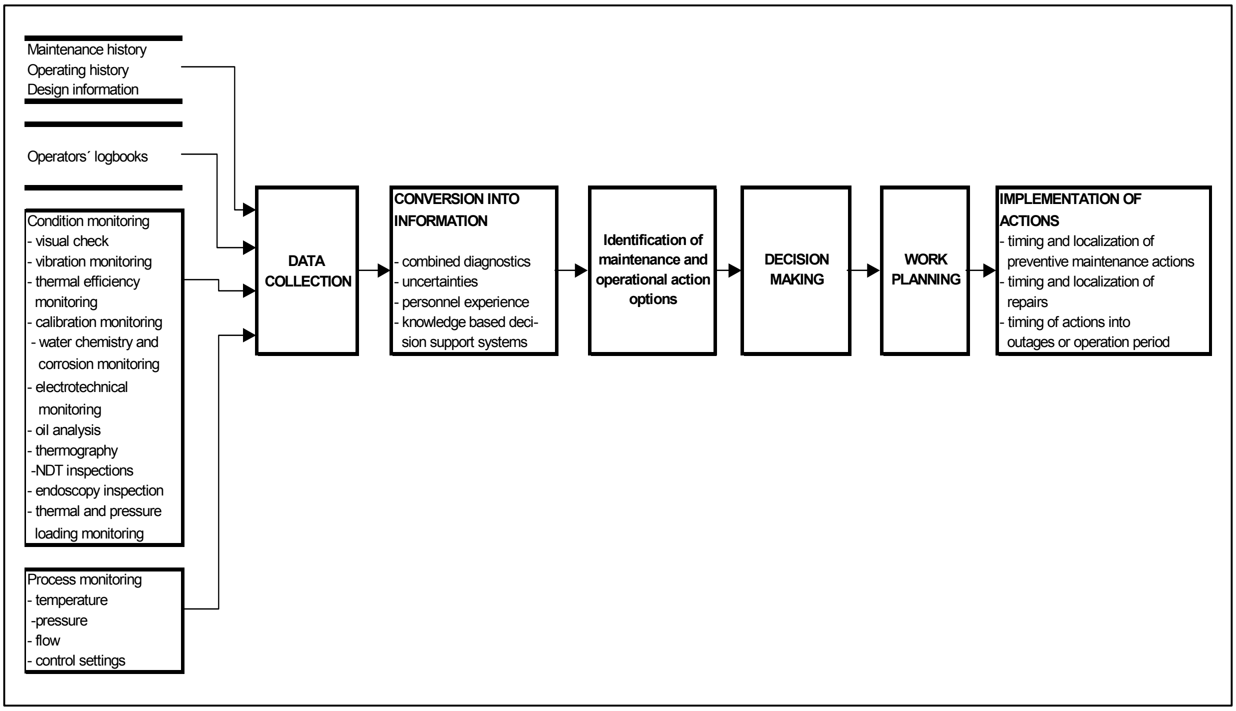


Figure 2. Information flow from condition monitoring into condition based maintenance, [adapted from Luukkanen, 2002].

The above figure on information and activity flow shows how condition based maintenance consists of parameter and performance monitoring and subsequent actions.

In the words of Hunt of condition monitoring techniques are given [Hunt, 2000]: 'Machine faults produce certain signals which certain monitors can monitor', i.e. there has to be the aligning of Fault – Signal (symptom) – Monitor. This is also reflected in the causal chain of degradation as indicated above. It is important to realise that the 'Signal' can be related both to equipment condition and state of the process [Paulsen, 2000].

With an example related to advanced condition monitoring of process instrumentation for nuclear power plants, the benefits of condition monitoring, given that the process and condition monitoring signals are reliable, can be grouped according to [Fantoni, 1999]:

- Technical Specifications compliance
- Efficiency optimisation
- Incipient fault detection

In the first case generally, periodic testing and condition monitoring are used in verifying the operability of safety related equipment, whereas in the second case, process monitoring data is used to verify that the operating system or equipment is functioning at the specified or optimal operating point [Sunde et al., 2001]. In the third case, the condition of the equipment is monitored to ensure economic and safe operation of the equipment. Generally in this case, prediction of time to failure is crucial for operative maintenance decision-making. In the following we will not distinguish condition monitoring - signals from process monitoring - signals unless otherwise noted.

For strategic maintenance planning, the diagnostic and prognostic capability of a condition monitoring approach has to be known, before any decision regarding the potential usefulness of the approach can be evaluated.

For instance, periodic walk-around checks are useful for identification of a large range of fault signals and symptoms and, combined with good personnel experience and expertise, they can provide a pertinent diagnosis and forecast of the degradation of e.g. some rotating equipment and valves. But visual and walk around checks alone cannot reveal hidden faults or generally the underlying failure mechanism and location (the degraded item) or facilitate a good prediction of the time to functional breakdown of different important equipment.

The condition monitoring - approaches thus vary with respect to capabilities for diagnosis and capabilities for prognosis.

The diagnostic and prognostic capability is here defined as the capability of condition monitoring approaches to produce an early indication (diagnosis) and to yield an accurate and precise prediction [Pulkkinen 1991] of a functional breakdown, given that a degradation process is under way..

Accuracy, precision and detection sensitivity, are defined in Fig. 3. Both condition monitoring approaches in Fig. 3 have the same accuracy (both are unbiased in the sense that on average they produce right predictions) and precision (both have the same spread depicted by the 'arrow').

Approach 'A' has, however, a lower detection threshold and gives more time to steer operative maintenance activities in the case of on-line condition monitoring. In the case of diagnostic testing for a hidden fault at a predetermined time point in the interval $[t_A, t_B]$, method A would yield an indication and a prediction, whereas method B would leave the fault undetected. The reason for a lower detection level may be a better sensitivity of the condition monitoring - equipment for the detection of a symptom, or the measurement of another symptom that is more apt for fault detection, that is, fault resolution and fault coverage, respectively. Concepts related to diagnostic testing are found in IEC / 706-5 (1994).

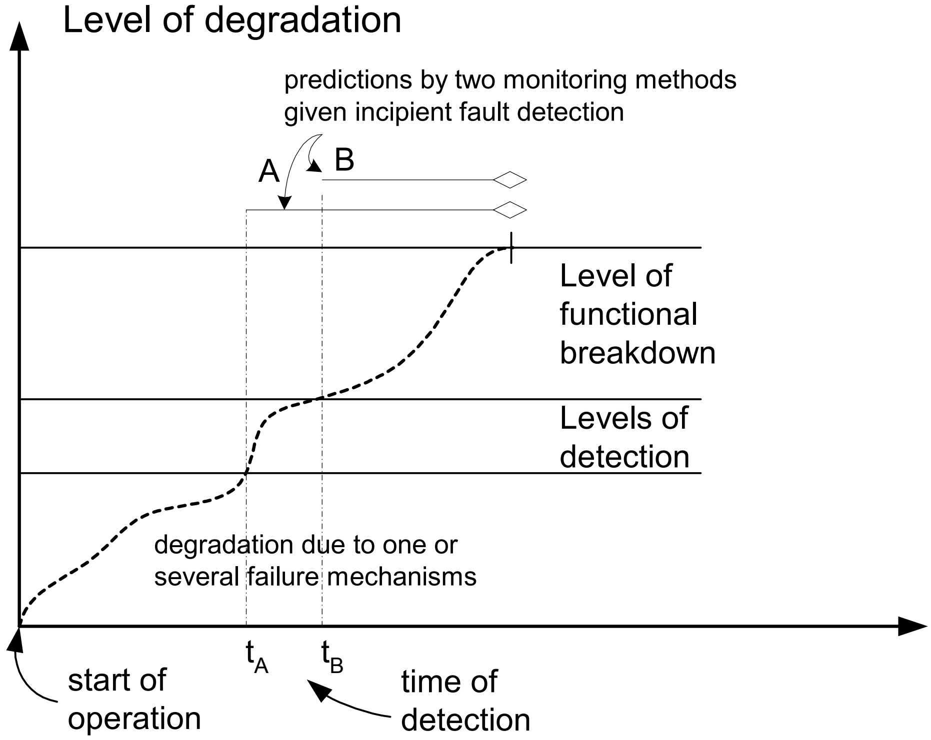


Figure 3 . Accuracy, precision and detection times of two condition monitoring approaches.

3. Condition monitoring in maintenance decision-making

3.1 Objectives for strategic and operative maintenance decision-making

We define two objectives of the strategic and operative decision contexts related to condition monitoring. In the rest of section, these definitions will guide us in detailing the role of condition monitoring information in the respective decision contexts, and put decision models used to evaluate and select the best course of action into a broader perspective.

<u>Def.1</u>: 'Strategic condition monitoring objective'
The objective of strategic maintenance decision-making, related to the use of condition monitoring information, is to improve the cost effectiveness and safety of operating the plant by the use of condition monitoring information.

<u>Def.2</u>: 'Operative condition monitoring objective'
The objective of operational maintenance decision-making based on condition monitoring information is to minimise costs and safety hazards due to a possible functional breakdown given the indication of an incipient or hidden fault from condition monitoring.

The role of condition monitoring in strategic and operative maintenance planning differs with respect to the available information and the time frame of decision making. In strategic maintenance planning we basically use unconditional probabilities or average properties (over time) of the equipment and systems for the planning of the maintenance resource allocation. In operative maintenance planning we condition our decision on an observation of an incipient failure indication provided by the condition monitoring system, e.g. on-line condition monitoring instrumentation. The objectives are, however, fundamentally the same, as in both decision contexts the decision should optimise the plant's performance in the long run as well as in the short run coherently.

The decision options in the above decision contexts are different. In the former situation the decision options relate to long-term maintenance planning, whereas in the latter case they relate to short-term maintenance steering.

3.2 Strategic maintenance planning utilising condition monitoring

The developments of condition monitoring methods and information technology, as well as renewals of automation and information systems, provide new opportunities to implement better condition monitoring solutions at operating plants. The decision rationale for adopting new condition monitoring options is depicted by the diagram in Fig. 3, where the decision context of strategic maintenance planning is modelled using the IDEF0-notation[1].

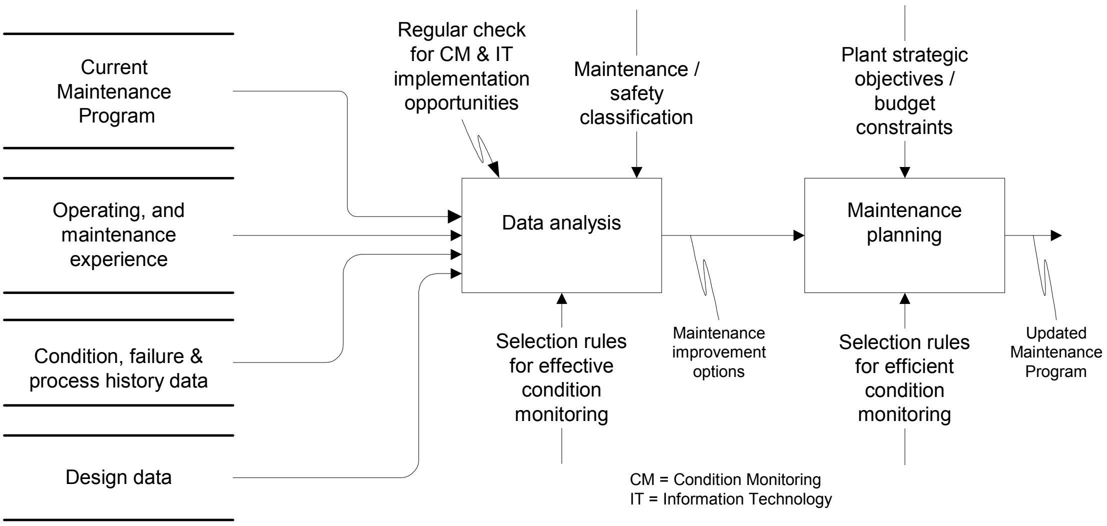


Figure 4. IDEF0-model of the decision and activity context related to strategic maintenance decision-making.

Effective condition monitoring options are first identified meaning that the diagnostic effectiveness of the option has to be sufficient enough to be considered as a useful maintenance task option. The search for new condition monitoring opportunities is a more or less scheduled plant life and maintenance management activity and is depicted by the first 'control' arrow in the first box in Fig. 4.

To support the identification of effective, preventive as well as predictive, maintenance actions, a logic tree, shown in Fig. 5, has been developed [MSG-3, 1988]. The questions in the first column are of strategic relevance and the answers should be based on the maintenance

[1] The basic IDEF0-building block is a box with arrows coming in and going out from the activity box. Arrows from the left denote materia and/or data which are transformed to new materia and/or data which then emerge at the right. The transformation is supervised by controls and rules coming from the top, according to certain mechanisms and procedures coming from below.

classification of equipment, or in particular, the safety classification, as depicted by the second 'control' arrow in the first box in Fig. 4. The linking of answers and subsequent questions reflect the logic or mechanism of identifying effective condition monitoring options, as depicted by the 'mechanism' arrow in the first box in Fig. 4.

Logic tree (LTA)- for the identification of effective maintenance actions

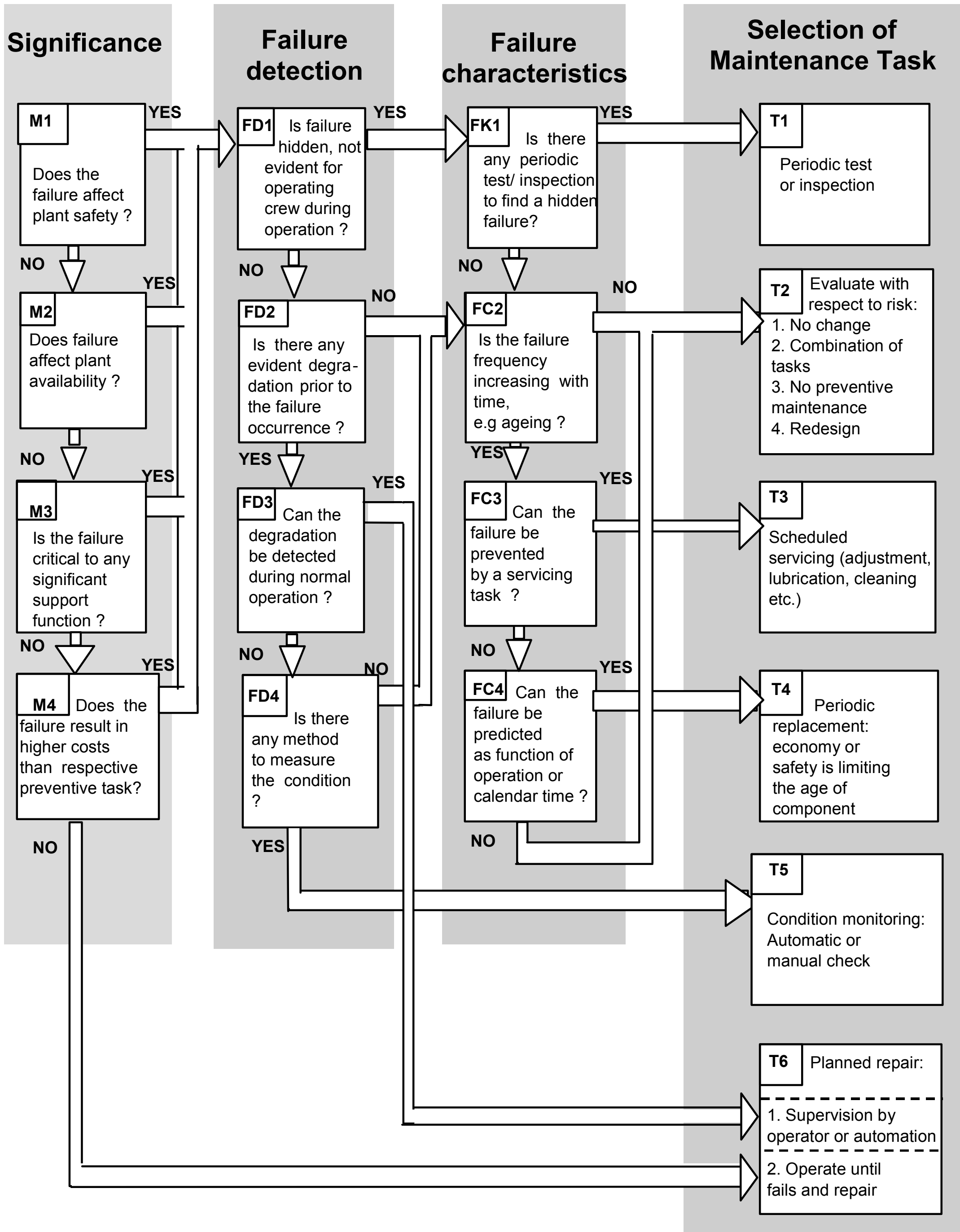


Figure 5. A Logic Tree for the identification of effective maintenance actions [MSG-3 1988].

It is important to note that the use of the logic tree is a qualitative assessment method screening out those maintenance action options that do not qualify for a more detailed analysis involving quantitative performance assessments. The developed logic tree is tentative with respect to identifying effective condition monitoring approaches. More research and feedback from the plants are needed for developing logic trees better suited to direct modern condition monitoring on right equipment locations in power plants.

When an effective condition monitoring option has been identified, its efficiency will be evaluated before implementation. This requires an efficiency comparison of the condition monitoring option, possibly bundled with other maintenance options, with the current maintenance program, with respect to selected criteria. The criteria are objectives and constraints reflecting the plant's maintenance strategy, as depicted by the 'control' arrow in the second box in Fig. 4.

In practise, the expected sums of maintenance (preventive, predictive and corrective maintenance) costs and production loss, associated with alternative maintenance options, are compared with each other to find the cost minimising option [Laakso and Strömberg, 2001]. Some monitoring options may, however, not be feasible due to budget constraints or unacceptable technology. Figure 6 illustrates the efficiency evaluation problem as an investment evaluation problem, where a balance between investments in maintenance and cost savings, incurred by controlling production loss and repair costs, is searched. In the case of the simple cost model (a 'mechanism'), the optimum maintenance program would be such that the total cost is minimised.

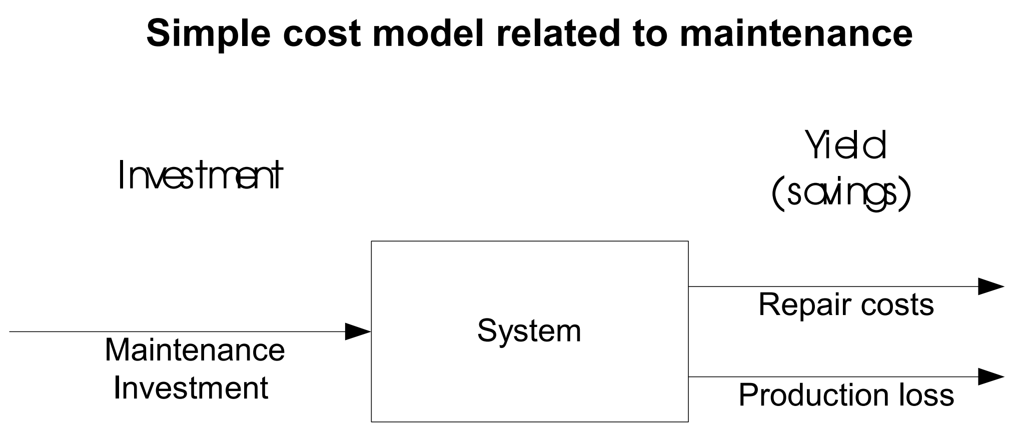


Figure 6. A simple cost model for maintenance strategy efficiency evaluation.

In a more general efficiency evaluation setting, intangible objectives, such as safety, may also be included. Typical end objectives and attributes (measures) are listed in Table 1. A fundamental objectives hierarchy [Keeney, 1996] is shown in Fig. 7, where the fundamental objective 'Maximise safe and economic production' is specified by the end objectives.

With each attribute is associated a measure that is used to further specify the actual value measurement of the maintenance options. Some attributes have natural measurement units, with money being a natural unit for production loss and repair cost. The influence of a maintenance option is shown in the means-ends objectives network [Keeney, 1996] in Fig. 8.

Predictions of the performance of optional maintenance actions, in terms of the measures coupled with the attributes, are usually uncertain estimates. If data is not available, expert judgements are needed. A mechanism for obtaining an overall score of an option is obtained by using an additive value function Eq. (1), as defined in multi-attribute value theory [Keeney and Raiffa, 1993].

$$V(a_k) = w_1 * v_1(a_k) + \ldots + w_n * v_n(a_k) \quad \text{for all options } a_k,\ k = 1,\ldots,K \tag{1}$$

where V(.) denotes the overall value or score, w_k are weights reflecting the relative importance of the end objectives, and $v_i(.)$ the attribute-specific value functions.

Table 1. End objectives and corresponding example attributes and measures.

Objectives	Attribute (examples)	Measure
• safety	- number of faults	# (count)
	- hazards of faults	mSv (dose)
• production	- availability	€
	- efficiency	€
	- quality	€
• repair costs	- man-hour cost	€
	- spare part cost	€
	- damage cost	€
• predetermined maintenance costs	- man-hour cost	€
	- replacement cost	€

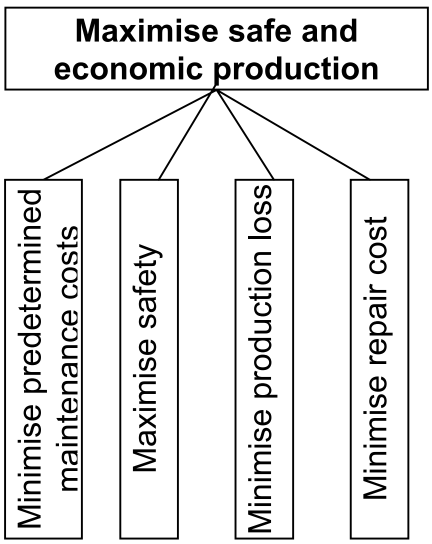


Figure 7. A fundamental objectives hierarchy related to the evaluation of maintenance options.

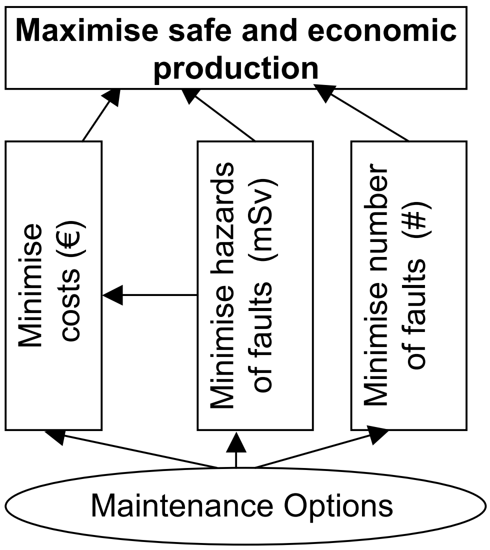


Figure 8. A means-ends objectives network related to the evaluation of maintenance options.

The performance of an option with respect to some attributes may be functionally dependent. For instance, if some option decreases the number of faults it is logical that the costs related to repair will decrease also. These consequences are, however, considered as preferentially independent in an additive value function, depicting the fact that the options can be valued with respect to each objective separately. It should be noted, that the attributes (measures) related to production; availability, efficiency and quality, are the factors defining the Overall Equipment Effectiveness (OEE) [Hansen, 2001]

Finally, an updated maintenance program, including possible implementation of efficient condition monitoring options, is obtained as a result of the planning and decision-making process, as depicted in Fig. 4.

From the point of view of company finance, a better performance with respect to an objective usually requires additional investments in maintenance. The investments are deterministic whereas the better performance is usually not exactly known. In cases where the uncertainty is significant, an investment may be unworthy, i.e. risky. Based on the utility theory, the above additive value function can be generalised to situations where the evaluation takes into account uncertainties and the risk attitude of the decision-maker. The additive value function is then replaced by an additive utility function. In strategic maintenance decision-making the uncertainties with respect to the outcome of the options' performances are usually considered as practically negligible.

Maintenance investment costs related to condition monitoring include not only the sensors, the information technology, and the training of personnel, but also the necessary monitoring, data storage and the analysis work. Furthermore, the condition monitoring equipment has to be maintained by expert maintenance personnel, incurring running costs.

Reliability centred maintenance analysis has helped to select between maintenance strategies and plan maintenance programs for important equipment at major nuclear power utilities [Chevalier et al., 2002]. The selection between predetermined preventive maintenance or combined preventive maintenance strategy (with increased condition based and longer intervals of periodic disassembling inspections and maintenance) for different equipment, can be supported by Logic Tree methods and Value Functions to evaluate the value impact (Dependability Added Value) of each strategy.

Basically, the combined preventive maintenance strategy includes a periodic follow-up analysis of condition, failure and process history data in order to reveal indications of possible faults within the equipment, not covered by the adopted on-line condition monitoring. The results of the "condition review" are used to assess the need for an extra disassembling inspection and other case-specific maintenance actions in the next annual maintenance outage to avoid surprise failures due to longer inspection intervals.

3.3 Operative maintenance steering based on condition monitoring

The basic problem in operative maintenance decision-making based on the information from condition monitoring is 'What should be done when an indication of an incipient or hidden fault has been detected? Continuing operation may lead to costs related to a degraded performance of the system and possible shutdown and damage if the functional breakdown occurs. The decision context is shown in Fig. 9.

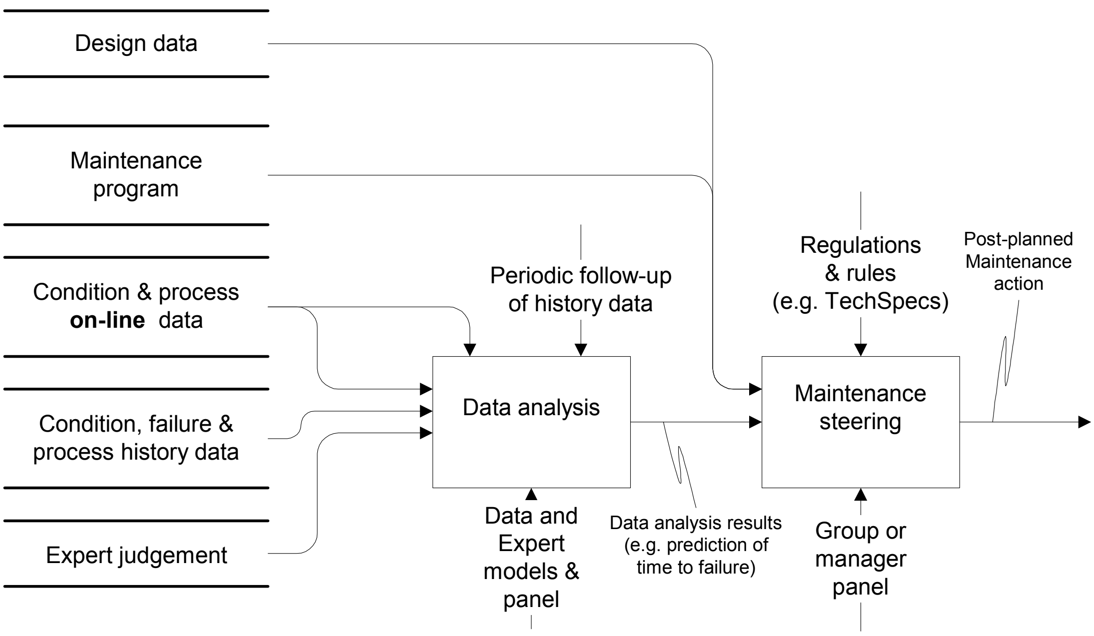


Figure 9. IDEF0-diagram of the decision context related to operative maintenance decision-making.

The decision-making process reflected by the diagram in Fig. 9 is as follows: Firstly, given an on-line indication of an incipient failure, data analysis is conducted based on on-line and condition and process history data, and experts' judgements related to the diagnosis of the observation. Typically, the nature of the fault is determined and an estimate of the time to failure (functional breakdown) is produced. Secondly, the maintenance action to be performed during operation or outage is planned, taking into account applicable regulations and rules.

In practice, in meetings or expert panels several questions pertaining to the data analysis are addressed in the first phase of the process. The relevant questions are:

1) Are the signals obtained reliable?
2) What other evidence supports the observation?
3) What type of a degradation or failure mechanism is it and in which item is it located?
4) How long does the equipment fulfil its function before the functional breakdown?
5) What has been done before in the same situation?
6) What are the consequences of an early shutdown for maintenance actions?
7) What are the consequences of the shutdown for operation and safety?
8) What are the consequences of a functional breakdown?

The answers to these questions support decision-making whether to a) stop for an inspection and related maintenance action as soon as possible, b) run to a post-planned shutdown, or c) run to the pre-scheduled shutdown. The decisions can be made at different levels organisation such as managerial, shift supervisor or by support of maintenance supervisors and operators principally depending on the nature of the expected consequences of the decision on safety, availability or economy. These, decision options should be evaluated against the objectives that are defined in the strategic decision context.

A generic cost table, related to the question 8) above, is shown in Table 2, indicating the cost consequences of different maintenance steering decisions in fault situations relevant to production.

Table 2. Operational maintenance decision outcomes related to prime costs given incipient fault indication.

Short-term operational maintenance decisions	Failure develops into functional breakdown	Failure does not develop into functional breakdown
"Immediate shut-down"	-	High cost (prompt production loss and high extra maintenance cost)
"Run to post-planned shut-down"	Very high cost (production loss and repair cost)	Moderate cost (planned production loss and extra maintenance cost)
"Run to next scheduled shut-down"	Very high cost (production loss and repair cost)	No extra cost

Here, we have assumed that 'Immediate shut-down' is prompt action that may exclude necessary time for acquiring maintenance resources and action planning. 'Post-planned shutdown' is a more realistic option as it takes into consideration the planning and preparation time of resources and actions, and for instance, production revenues. The option 'run to scheduled shut-down' involves no extra cost [Laakso et al., 1999]. Fig. 10 illustrates the prediction problem when an incipient fault has been detected at time s_0. The functional breakdown can occur at the time points t_1, t_2 or later.

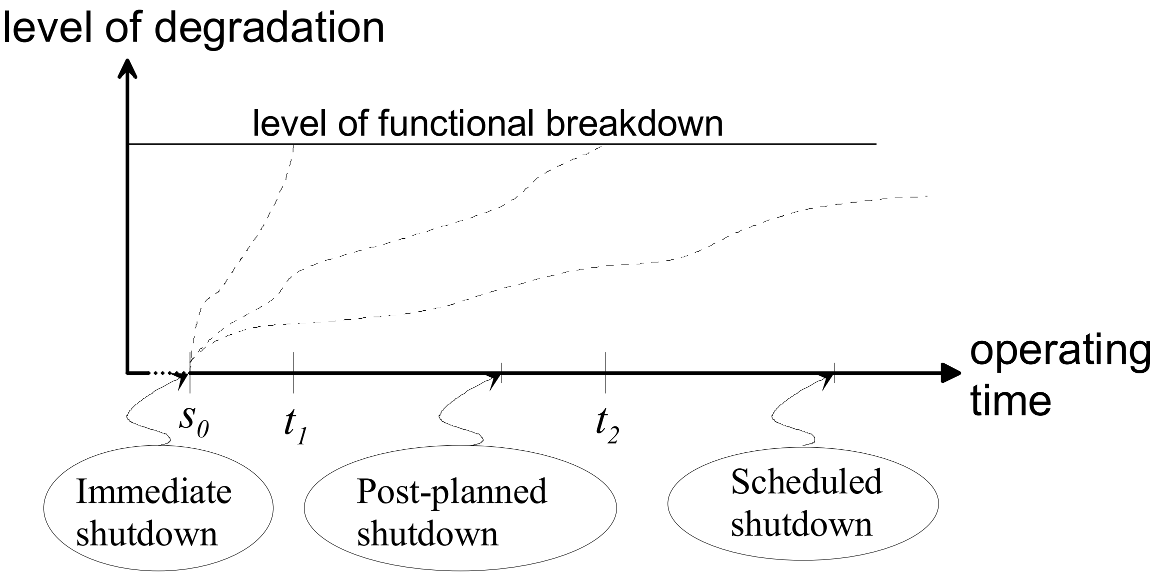


Figure 10. Time points related to the operational maintenance decision options and realisations of the failure time (t_1, t_2*) measured from the time of observation of an incipient failure (*s_0*).*

Different methods ('mechanism' in the first box in Fig. 9) for combining the evidence in the data analysis in the first phase of the decision-making process have been developed. In the case where the prediction of the time to functional breakdown is coupled with uncertainties additional measurements and data-analysis may have to be performed [Roverso, 2000]. In the case where data is scarce or not representative, the use of experts' judgements may be the only way of obtaining any estimates of the time to failure [Rosqvist, 2002]. In the case where lot of empirical condition and failure data is available, fitted models can be used, for instance, the proportional hazard model [Jardine, 2002].

Current praxis of decision-making can be described as informal manager and group meetings ('mechanism' in the second box in Fig. 9), where a decision is established. In the case of (e.g. standby) safety equipment, the Technical Specifications give clear limits for action. For instance, the current limiting conditions for operation for the latest Nordic BWRs state that with one out of four subsystems inoperable, power operation may continue 30 days without restrictions. Further, with two out of four subsystems inoperable, 3 days of repair time is allowed without restrictions for operation [NKS/RAS - 450, 1990].

An interesting approach to using plant expertise in controlling abnormal events is the TOP-concept by Fortum [Ruokonen, 2002]. A Centralised Performance Centre is established, with the aim at providing organisation-wide remote support related to condition monitoring data interpretation, analysis and fault detection including operating point optimisation.

4. Survey of the use of condition monitoring in three Nordic NPPs

4.1 The questionnaire

Visits to three nuclear power plants (Barsebäck, Loviisa and Olkiluoto) were performed and reported during May- August 2001. The expertise available during the interviews is shown in Table 3.

Table 3. The expertise available during the interviews.

Plant	Expertise (area of responsibility)
Barsebäck	Condition monitoring, maintenance planning, reliability centred maintenance analysis, mechanical maintenance
Loviisa	Condition and performance monitoring R&D, maintenance planning and steering, plant life management, maintenance history systems, mechanical maintenance
Olkiluoto	Production, maintenance and outage planning, maintenance information systems, Turbine, reactor, mechanical maintenance

The interviews were performed as open, informal and interactive group meetings at each plant. The interviews and addresses were structured according to the questions in Table 4.

Table 4. Questions presented to the maintenance personnel at the three NPPs.

Long-term maintenance planning	Short-term maintenance steering
1. How is condition monitoring data linked to the maintenance information system? Is it analysed off-line together with other failure data? 2. How can periodic testing or inspection be reduced by implementation of condition monitoring? Do you have examples or ideas from your plant? 3. How is the implementation of condition-based maintenance linked to the strategic maintenance decision making? What decision criteria or decision support methods are used?	4. How is the existing process and control data for process operability monitoring utilised for on-line condition monitoring of equipment? What good examples do you have at your plant? 5. Do you utilise display systems for on-line condition monitoring of equipment by using existing process and control data (without installation of extra measurements)? How can the displays and diagnosis be improved? 6. Are decision models utilised for determining timing of operational maintenance action when an incipient failure indication is observed? How reliable are such indications taken for? What kind of decision rules on operative actions do you have at your plant? Examples?

Additions were introduced based on the experience from the first plant visit to Barsebäck to the above questions 1 and 5:

1. What databases do you have on condition monitoring data?
5. Do you have some plans or ideas on "maintenance control room"?

The grouping of the question to long-term and short-term maintenance decision making is motivated by the differences in the information available for the decision-makers at the time of decision-making [Rosqvist et al. 2001].

4.2 Answers obtained from the maintenance managers and personnel

Each question makes an own section with a conclusion reflecting the general concerns, trends, good examples and possibilities related to the question.

4.2.1 How is condition monitoring - data linked to the maintenance information system? Is it analysed off-line together with other failure data?

Conclusions:

The current disparate condition monitoring systems, process computer and maintenance information databases do not allow or utilise data-warehouse operations, except to a limited extent at one plant. The expectations of the usability of data-mining vary, but a linking of the condition monitoring databases, and process monitoring database with the maintenance information system data was found to open possibilities for better monitoring and analysis of equipment condition, and improvement of maintenance steering. The linking of data from different databases by e.g. data-warehouse functions could help to produce better information for maintenance planning.

The approach adopted to develop condition monitoring seems to be bottom – up, except the integrated condition and performance monitoring of turbines and generators. Plant management may feel that there is a risk of excessive consumption of expensive engineering resources for analysis of indications from different condition monitoring systems which produce only minor benefits for the equipment maintenance and operability. Therefore, buyers and users of condition monitoring systems want to have clear evidence of the usability of the system for diagnosis, maintenance planning and decision-making before a commitment to the development and implementation of it is achieved.

4.2.2 How can periodic testing or inspection be reduced by implementation of condition monitoring? Do you have examples or ideas from your plant?

Conclusions:

A realistic view related to an increased implementation of condition monitoring is the possibility of prolonging of existing preventive maintenance action intervals and the steering of these by analysis of condition monitoring information. Especially, this is the case for costly and error-prone preventive maintenance activities. Condition monitoring has prolonged the interval of inspections and steered timing of preventive maintenance actions such as disassembly inspections of turbines and main circulation pumps or tightness testing of isolation valves.

The maintenance data warehouse function had at one plant helped to trace and update the preventive maintenance planning data and complete it with notes from condition monitoring. This function had facilitated for the user an easy way to plan case-specific maintenance actions, i.e. adding or deferring of a planned preventive maintenance action justified by results from condition monitoring. At another plant the large amount of all the planned preventive maintenance, periodic testing, condition monitoring and NDT actions, which are performed according to different programs, had been collected and directed to the right equipment places to specify their proactive maintenance programs. This information had been made visible for the plant personnel in the maintenance information system on the actual individual equipment places. This information helps to integrate both the planning and the monitoring of the preventive actions, including repair strategies at the correct maintenance level.

At one plant, the correct detection coverage of the failure modes' in testing was found to be a more important development task than the relaxation of the test interval. A constraint of periodic testing interval changes are the regulations as applied to safety related equipment, and these decisions cannot thus be made by the plant only.

4.2.3 How is the implementation of condition-based maintenance linked to the strategic maintenance decision-making? What decision criteria or decision support methods are used?

Conclusions:

The maintenance classification, taking into account safety classification refinements, is under progress in the three plants. The maintenance classification is a strategic basis for maintenance planning and later on maintenance changes. The role of condition monitoring is dependent on the decision criteria in the selection process of corrective, preventive and predictive maintenance tasks.

Strategies and decision criteria for implementation of condition monitoring and predictive maintenance are not sufficiently developed yet. No plant is directly examining the dependence between the importance of the equipment and the price of the resources used for its maintenance. A combined strategy of condition monitoring and disassembling inspections was mentioned at one plant to be the strategy for the most important equipment to reduce the risks of detecting surprising faults leading to unplanned outage extensions.

A present vision of the plants is 'From maintenance to operability control' which aims at preventive maintenance in time.

4.2.4 How is the existing process and control data for process operability monitoring utilised for on-line condition monitoring of equipment? What good examples do you have at your plant?

Conclusions:

An advanced vibration and condition monitoring system of the turbine generator set, utilising also process parameters, has been installed at all plants in the control room area for operational supervision with support from technical experts.

Process monitoring data in the plants is abundant, but the integration and the interpretation of it to indicate equipment condition are still mostly lacking. The data storage capacity of the process computers appears also to be a limitation for the long-term trend follow-up of the process parameters for condition monitoring at some plants.

Operators are unwilling to invoke possibly unnecessary actions, and condition monitoring of equipment through the control room would require extra activity from the maintenance personnel. A modification of the manner of proceedings between the operators and the maintenance personnel requires training and motivation. A crucial challenge is also the secure linking of the process data network to the more general plant and maintenance information network in the plant.

4.2.5 Do you utilise display systems for on-line condition monitoring of equipment by using existing process and control data (without installation of extra measurements)? How can the displays and diagnosis be improved?

Conclusions:

Process and control data based displays have been used in a very limited extent for equipment condition monitoring. Condition monitoring displays have, however, a great potential, and serve as a most natural step in increasing the role of condition-based maintenance. The displays should show trends and equipment operating points rather than instant states of the process. The condition monitoring displays would utilise parameters from several sensors without installation of any expensive new measuring points or cabling [Paulsen, 2001]. Such condition monitoring displays are possible to implement in the control room area in connection to the installation of new or modified process computer or automation systems, or in the design of new plants.

In the control room of one plant, some advanced condition display solutions were integrated into an expert system for the function and condition monitoring of selected turbine plant equipment. In other plants, the thermal efficiency and leakage monitoring of turbine plants is based on fixed process measurements supervised by the operational planning section.

The displays for condition monitoring should be available for the equipment responsible maintenance personnel. One plant had an advanced load and transient follow-up system of the primary piping connected to the plant network and the maintenance office. The process measurements of the system were hardwired and not linked through the process computer system.

Data security and organisational questions are crucial challenges that have to be solved at first, if the principle of computerised "maintenance control rooms" is seriously targeted, as noted in the previous section.

R & D notes on 4.2.5:

A technical report on "Advanced display systems on for condition monitoring" [Paulsen,2001] is enclosed as Appendix 1 to this report. The appendix summarises the R& D performed by Risø National Laboratory in connection to the NKS/SOS-2.2 subproject on how existing process and control data for process monitoring can be utilised for on-line condition monitoring of equipment and systems. The purpose is also to present a vision on the condition monitoring of components and systems in "computerised control rooms" and how to make such condition information visible for maintenance and operability staff. Advanced displays could visualise the component operating points and characteristics to indicate the equipment condition. This kind of condition monitoring has not been possible in traditional control rooms, which have single sensor single indication systems. We get so possibilities to present the monitoring results in a more proper way for condition monitoring and identification of case-specific maintenance needs for operative maintenance steering. The conventional type of indications does not give information directly on the condition of the equipment and systems, but more on the function of the equipment, systems and the plant.

4.2.6 Are decision models utilised for determining timing of operational maintenance action when an incipient failure indication is observed? How reliable are such indications taken for? What kind of decision principles on operative actions do you have at your plant, please give examples?

Conclusions:

Neither generic action procedures nor decision models exist at any plant on how inspections, repairs and operative actions should be planned when an incipient fault indication appears. The current decision-making praxis can be viewed as a form of an <u>expert panel</u> where at least the following questions are answered:

1) Are the signals obtained reliable?
2) What other evidence supports the observation?
3) What type of a degradation or failure mechanism is it and where is it located?
4) How long does the equipment fulfil its function?

5) What has been done before in the same situation?
6) What are the consequences of letting the equipment fail ?
7) What are the consequences of an early shutdown for maintenance actions?
8) What are the consequences of the shutdown for operation and safety?

The answers to these or related questions support the decision-making whether to a) stop as soon as possible, b) run to a post-planned shutdown, or c) run to the pre-scheduled shutdown.

A methodological paper addressing the above decision problem utilising experts' quantitative judgements on time to failure given an incipient fault indication is in Rosqvist (2002).

5. Conclusions

In a modern operating and maintenance organisation for nuclear and advanced power plants, condition monitoring plays an important role in managing the maintenance and operability activities. Basically, condition monitoring helps to control the safety and economy of the plant operations. The development of condition monitoring methods and information technology, together with nowadays more stringent economic and safety requirements of power plants, is increasingly shifting the emphasis from predetermined preventive maintenance towards predictive condition based maintenance.

A survey has been presented outlining the use of condition monitoring information in three Nordic nuclear power plants. The questions of the survey related to the role of condition monitoring in strategic, as well as operative, maintenance planning and decision-making. The results of a survey on the experience from condition monitoring at three Nordic nuclear power plants are presented. The survey indicates that condition monitoring is increasingly implemented at nuclear power plants, but very selectively and in a rather slow pace for predictive condition based maintenance. The aim of a predictive maintenance strategy is right timing and direction of maintenance actions taking also into account production and resources. Based on the survey the following general observations can be stated;

1) A combined strategy of condition based maintenance and predetermined preventive maintenance is applied for very important equipment such as main circulation pumps, steam turbines and turbine condensers;
2) For less important equipment, the maintenance management at a nuclear power plant tends to wait for experiences of condition based maintenance in other type of power plants;
3) The reluctance to change manners of proceedings in nuclear power plants is relatively high. Risk is not taken in implementing new condition monitoring for predictive maintenance unless a high diagnostic effectiveness to identify the fault modes and deviations in the monitored equipment and the cost benefits are demonstrated (in many cases, existing condition monitoring at plants is not utilised for condition based maintenance);

4) A realistic aim of condition monitoring is to extend the intervals of costly and error prone maintenance and disassembling inspection activities. By introducing case-specific maintenance actions based on the analysis of good condition monitoring information, the predetermined inspections and maintenance can be deferred and their intervals prolonged given that the approach enables a good diagnostic capability and prognosis. A systematic follow-up and periodic analysis of such condition monitoring information, followed by a case-specific planning, decision making and implementation of timely and rightly directed

maintenance actions, can justify an extension of the intervals of a number of predetermined inspection, maintenance or periodic testing tasks.

In the case of strategic maintenance decision-making this shift has raised the need to develop decision-making support for the planning of the maintenance program taking into account the opportunities provided by condition monitoring. In the case of operational decision-making this shift has raised the need to develop process models and decision support for maintenance steering given an indication of an incipient fault in the monitored equipment and to develop displays visualising better the equipment condition. These decision and activity contexts have been graphically modelled using the IDEF0-notation. Existing decision and activity models are linked to the decision contexts of both strategic and operational maintenance decision-making. The objective of this linking is to provide the developers of decision models, a comprehensive perspective of the decision-making and activity processes related to the use of condition monitoring information.

The current report is a working report that will be completed at the HRP MTO research period 2003 – 2005. Development of process and decision models for condition monitoring, and logic trees for selection of right actions, is needed to support the operative as well as strategic maintenance and operability planning and decision-making, and the manners of proceedings, in a direction of condition-based and predictive maintenance. Display systems for online condition monitoring of equipment by using existing process monitoring and control data have also a great potential in increasing the condition-based maintenance. The feedback from the plants utilising condition monitoring information is very crucial in developing decision models, and manners of proceedings, that meet the generic and specific needs at the plants.

The best opportunities to introduce condition monitoring techniques and approaches in the plant are during the modernisation and modification projects at existing plants and in the new plants. Existing process and control data aimed for process monitoring could also be utilised better for condition monitoring of equipment. Data displays supporting condition monitoring, extension of condition and process data storage capacity, integration of information networks, installation of condition monitoring equipment or equipment with integrated condition monitoring capabilities, etc., are all possibilities that can be utilised.

References

Bond, T. 1997. Data to information with MIMOSA, Machine, Plant and Systems monitor, Nr.1, Coxmoor Publishing Company, UK.

CEN-prEN 13306. 1999. Maintenance terminology. European Committee for Standardisation, Brussels.

Chevalier, R., Despujols, A., Ricard, B. 2002. Issues and prospects concerning the monitoring and condition based maintenance of EDF´s power plants. In The Proceedings of Euromaintenance 2002. 3-5th June 2002. Pg 407-419.

Hunt, T. 2000. Condition monitoring techniques today. What is available ? Proceedings of Maintenance, Condition Monitoring, and Diagnostics- International Seminar. Held October 2-3, 2000 in Oulu, Finland by POHTO in co-operation with the University of Oulu. POHTO Publications. p. 69- 78.

Hansen, R. 2001.Overall Equipment Effectiveness, Industrial Press, New York.

International Electrotechnical Commission. 1994. IEC 706-5: Guide on Maintainability of Equipment – Part 5: Section 4: Diagnostic Testing. IEC, Geneva.

Fantoni, P.F. 1999. On-Line Calibration monitoring of process instrumentation in power plants. EPRI Plant Maintenance Conference, June 21, 1999, Atlanta.

Hytönen Y,. Savikoski, A. 1998. Plant life management at Loviisa. IAEA Specialists' meeting on "Policies and Strategies for Nuclear Power Plant Life Management". Vienna, Austria, 28th to 30th September, 11p.

Jardine, A. 2002. Optimization of condition based maintenance - Smartly interpreting condition monitoring data. VTT Industrial Systems seminar. 10 september 2002. 12 p. OHs.

Keeney, R, Raiffa, H. 1993. Decisions with Multiple Objectives, Cambridge University Press.

Keeney, R. 1996. Value-Focused Thinking, Harvard University Press.

Kokko, V. 2000. Current situation and prospects of condition monitoring of electrical equipment during operation. Proceedings of Maintenance, Condition Monitoring, and Diagnostics- International Seminar. Held October 2-3, 2000 in Oulu, Finland by POHTO in co-operation with the University of Oulu. POHTO Publications. p. 159-173.

Laakso, K., Sirola, M., Holmberg, J. 1999. Decision Modelling for Maintenance and Safety. International Journal of Comadem (Condition Monitoring & Diagnostic Engineering Management 1999) 2 (3):13-17.

Laakso, K., Simola,K., Dorrepaal, J., Skogberg, P.. 1999. Systematisk underhållsanalys med beslutsstöd. Metodik och verktyg för effektivisering av underhållsprogram, January 1999, NKS-7, ISBN 87-7893-055-3.

Laakso, K., Strömberg, A. 2001. Systematic Analysis of Maintenance Strategies of Technical Systems. Presented at BALTICA V International Conference on Condition and Life Management for Power Plants. Porvoo, Finland, June 6-8, 2001. Documented in VTT Symposium 211. Vol. 2. Pp. 535-545.

Luukkanen, P. 2002. Discussion and development material. Fortum Power & Heat. Loviisa Nuclear Power Plant.

MSG-3. 1988. Airline/manufacture Maintenance Program Development Document. Maintenance Steering Group-3 Task Force. Air Transport Association of America. Rev. 31.3.1988 No 1.

NKA/RAS-450 1990. Optimization of Technical Specifications by Use of Probabilistic Methods. A Nordic Perspective. Final Report of the NKA project RAS-450. Laakso, K (editor). Prepared by Laakso, K., Knochenhauer, M., Mankamo, T. Pörn, K. NORD Series 1990:33. Copenhagen. 156 p.

Paulsen, J. 2000. Design of Simple Display Systems for Condition Monitoring, Using Invariants and Physical Laws. Paper presented at CSEPC2000, Korea.

Paulsen, J. 2001. Advanced Display Systems for Condition Monitoring. Summarized R& D contribution from Risø National Laboratory to the NKS/SOS-2.2 research subproject 8 p.

Pulkkinen, U. 1991. A Stochastic Model for Wear Prediction through Condition Monitoring. In Operational Reliability and Systematic Maintenance (Eds. Holmberg, K. and Folkeson, A.), Elsevier Applied Science, pp 223-243.

Rosqvist, T., Laakso, K., Pyy, P. 2001. Maintenance Decision Support Based on Decision Models and Condition Monitoring Ínformation. Paper number 12 presented in session C4 in the Enlarged HPG Meeting 2001, Lillehammar, Norway.

Rosqvist, T. 2002. Stopping Time Optimisation in Condition Monitoring. Reliability Engineering and System Safety, Vol. 76 , Nr. 3, pp. 319 – 325.

Roverso, D. 2000. Soft Computing Tools for Transient Classification. Information Sciences, Vol. 127, preprint.

Ruokonen, T. 2002. Optimised plant life cycle profits through the top solutions.In The Proceedings of Euromaintenance 2002. 3-5th June 2002. Pg 275-282.

Sunde, S., Bodal, T., Porsmyr, J. TEMPO - A computer system for monitoring and optimisatian of thermal performance, Technical Report HWR-638, OECD Halden Reactor Project, Halden, Norway.

Appendix 1 to the NKS/SOS-2.2 report on the Use of Condition Monitoring Information for Maintenance Planning and Decision Making

Advanced display systems for condition monitoring

Introduction

The purpose of this section is to describe how to apply on-line process data for condition monitoring of equipment and systems in computerised control rooms and make this information visible for maintenance staff and operability personnel. The use of computers for data acquisition, and at some companies also for control of the plants, gives possibilities for supervision of the condition of the equipment of the plant and its subsystems in a way which was not possible in traditional control rooms with the single sensor single indication system. Advanced displays could use the component operating points and characteristics to indicate the condition. Thus the monitoring is presented in a proper way to support the operative maintenance steering. The conventional type of indications does not give information directly on the condition of the plant equipment but more on the function of the plant and systems.

Background

The background for the present report is coming from the studies done during a couple of years in the NKS/RAK-1.4 and NKS/SOS-2.2 subprojects about maintenance optimisation. In these studies ageing and degradation of components has been a part of the study. Ageing can be long term phenomena, where a decision on when to change the component requires some indicators, which could be seen from a safety point of view or from an economic point of view. From a safety point of view the indicators could be high or increase in the failure rate of the component. From an economic point of view the repair hours per year for the component could be one of the maintenance indicators. Expected degradation of components is one of the inputs on when to perform case-specific preventive maintenance. Preventive maintenance can be done periodically or on the basis of condition monitoring. Condition monitoring can be used for monitoring of both ageing, expected degradation and faults on the component and system. Condition monitoring has mostly been based on special monitoring of special phenomena with special equipment. Examples of traditional condition monitoring are:

- vibration measurements and analysis,
- measurements of metallic particles in oil,
- monitoring of pressure drop across filters,
- monitoring of closing times for valves, and
- monitoring of power consumption of electric motors.

These measurements are both on-line as they are e.g. for turbine vibration monitoring at power plants, but they are also periodic off-line measurements during predetermined tests. For some equipment measurements are done during the predetermined functional and operability testing, which is the only possibility to perform a kind of condition monitoring. This kind of equipment is e.g. in the standby systems and the safety systems, which are not in duty during normal operation.

The study done together with the Halden Reactor Project in Norway about display systems is another contribution to the present work. In the Halden project the presentation of information is in the focus. In this project both operation, degradations and failures are treated with the purpose to give the operators better information for improving their supervision, but also to give them a better knowledge about the condition of the plant. This should increase the operator's situational awareness and his ability to detect incipient failures before the faults propagate into plant disturbances affecting the safety or the production. In the case of a sudden failure, a proper information system should also give the operators an increased ability to diagnose the failure.

Several methods can be used to elicit important information to the operators in case of known failures or degradations. Unknown failures are more problematic, but one general method has been developed to cope with this problem, too.

What is condition monitoring?

Some words need some further explanation in this work domain.

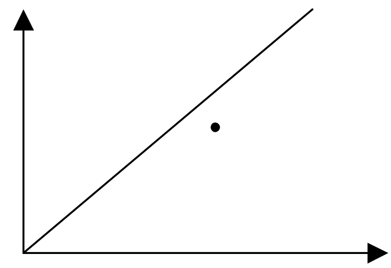
Condition	=	the state in which anything is.
Performance	=	the level of a success of a machine.
Function	=	use or duty.

Condition monitoring of a component is, in this report, a measure of the state of the component. The state means here a measure of the difference between designed performance and actual performance in the actual environment, circumstances etc. Condition of a component is <u>not</u> the same as the function of the component. The function of a component can be correct, even if the condition of the component is poor. In automated systems the control system will compensate for the poor condition of the component. E.g. the control system will speed up the pump, if the pump is not able to give the expected flow due to degradation of the propeller. (He works OK even if he has a cold)

In order to know the designed performance (initial state) is it necessary to know the initial characteristics of the component.

In the case that the initial characteristics are not available some other methods can be used. The present characteristics of the component in question can be logged during operation in a period and changes from this state can then be observed.

<u>Example</u>



The figure shows the characteristics for a component in a coordinate system. In this case the component has a linear characteristics which could be the flow as a function of the speed at a positive displacement pump. The black dot is the actual operating (working) point for the pump. If the working point deviates from the characteristics, it indicates some degradation in the pump. The degradation could be a back-flow through the suction valves, due to not tight valves. The failure could also be a system failure where gas is mixed in the feed water and thereby decreases the resulting flow of the liquid. The characteristics is for pumping the liquid and not a liquid-gas mixture.

Methods

Implementing displays for condition monitoring requires an analysis of the components and systems. The analysis must elicit how the components age, degrade or fail. Failures in the corresponding system influencing the performance of the component must be taken in account too.

Risk and reliability analysis methods are strategic methods, which can be used in the process of assessment of system failures and their consequences. Hazard identification and consequence analysis method are known methods and useful in this context. Even if risk analysis methods are developed for major hazards the same strategies are useful also for treating minor problems.

The use of functional modelling, FMEA (Failure Mode and Effects Analysis) and HAZOP (Hazard and Operability Study) are valuable methods in the decision of the content of the information system. For larger systems Fault Tree Analysis could be valuable, too.

In the analysis for design of condition monitoring displays the following questions should be answered:

- What is the purpose of the system and the display?
- What are the problems of the system?
- How do the problems occur?
- How are the problems observed?
- How to present the problems for the user?

The purpose of the component or system is defined in the design of the plant and should be known of the designers of the condition monitoring systems.

The question about which problems that could occur in the system in question, is the question where the risk analysis methods could be used to elicit the hazards if they are not obvious.

How the problems occur can be obvious for small systems, but it can be necessary to use a fault tree analysis for analysis of larger systems.

How the problems are observed or could be observed, if the necessary measures are taken, is another analysis on how a root cause is observed or how it propagates to an observable situation.

How to present the information to the user in a proper and easily way is not described in any method, but requires some ideas that will be presented in this paper. Most important is that the presentation has the right content.

In this report a number of examples from different components will be given to give ideas of how to design displays for condition monitoring for other types of components, too.

The components that will be described are pumps and heat exchangers.

Pumps

The types of pumps that will be treated in this chapter are centrifugal pumps and positive displacement pumps.

Centrifugal pumps

A frequent degradation mode of a centrifugal pump is wear of the propeller. This degradation mode will often be observed by vibration in the pump. Another way to observe the degradation is through observation of a too low flow at the actual speed of the pump and thereby also by observing a too low pressure increase across the pump. In the case of an existence of a flow control this will be seen as an increase in the speed of the pump to satisfy the flow demand and/or pressure demand.

Table 5. The strategy used on a centrifugal pump for condition monitoring display design.

What is the purpose?	Keep a certain flow or pressure.
What are the problems?	Flow problems
How do they occur?	Wear of the propeller
How are they observed?	Flow too low or speed too high
How to present the problem for the user?	Actual working point (wp) and the characteristics for the pump at speed n. Trend curves for the measured variables

A proposal for a condition monitoring display for a centrifugal pump is shown below.

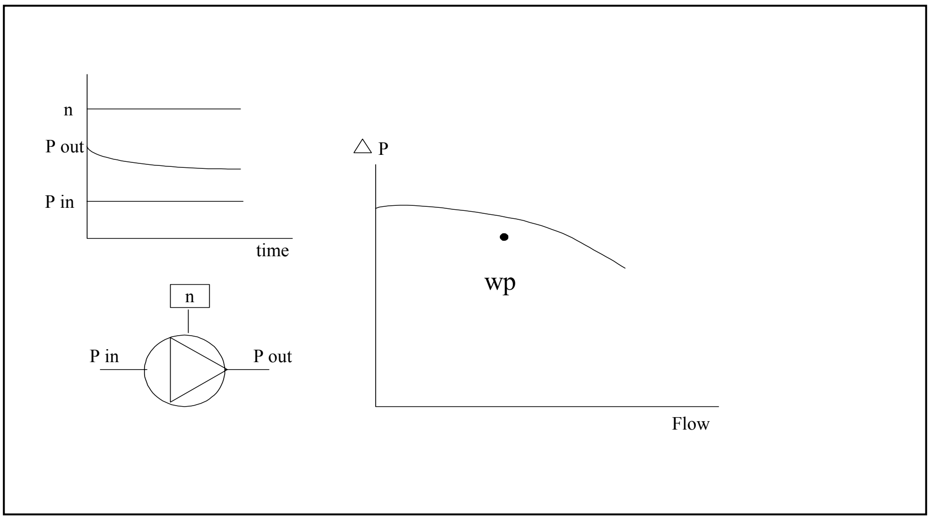


Figure 11. A condition monitoring display for a centrifugal pump.

In the above display, the characteristics of the pump and the actual working point (wp, operating point) are shown. Furthermore there are shown the variables as a function of time. Low and high-limits for the present component can be implemented in the display, too.

Positive displacement pumps

In this category several types of pumps exists. Among them are:

- Piston pumps, and
- Diaphragm pumps.

Positive displacement pumps are often used in systems requiring a high pressure and a low flow. These pumps have a linear characteristics. The strategy used in design of condition monitoring on this type of a pump looks as the following.

Table 6. The strategy used for design of a condition monitoring display for a positive displacement pump.

What is the purpose?	Keep a certain flow and pressure
What are the problems?	Flow problems
How do they occur?	Wear in suction valves ………..
How are they observed?	Flow and pressure too low or speed too high
How to present the problem for the user ?	Actual working point (wp) and the characteristics for the pump. Trend curves for the measured variables

A proposal for a condition monitoring display of a displacement pump looks like the following.

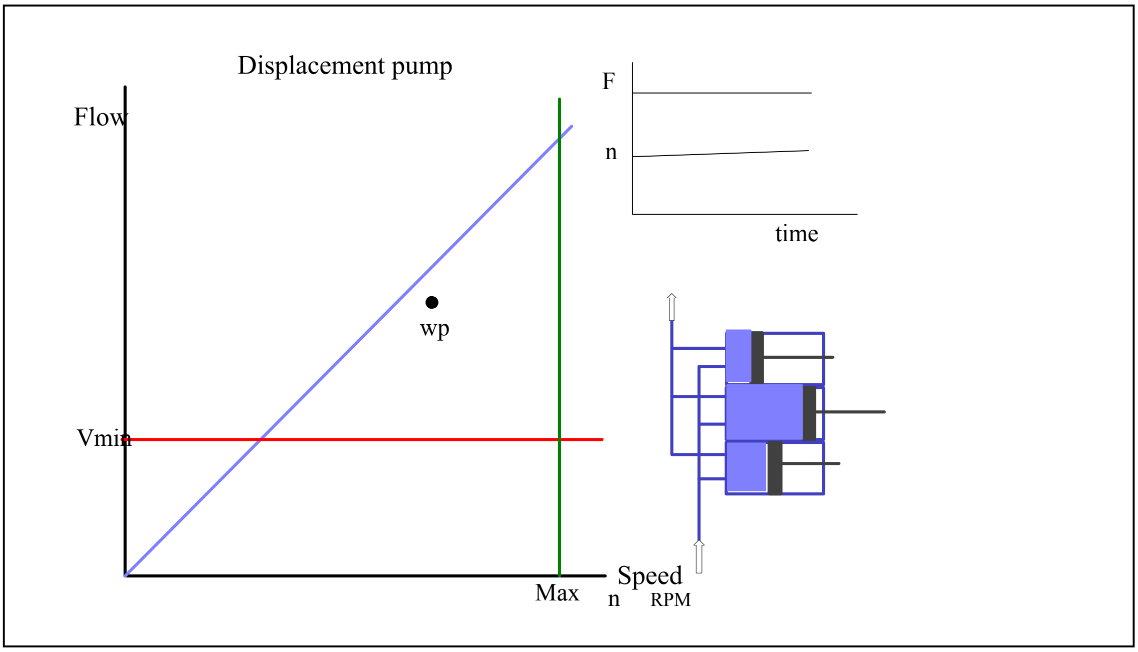


Figure 12. A condition monitoring display for a displacement pump.

On this type of displays it is rather easy to see, if the operating (working) point deviates from the characteristics. In this display is also implemented a lower limit for the speed and also the highest speed possible. This gives a triangle as an 'allowed' working area and also an indication when a maintenance action is necessary.

Heat exchangers

Heat exchangers can be divided into several types and for different purposes. The most common heat exchangers are used for:

- Heating
- Cooling, and
- Condensation.

<u>Heat exchangers</u>

The mostly used types of heat exchangers are:

- Tube heat exchangers,
- Plate heat exchangers, and
- Duple tube heat exchangers with concentric tubes.

The tube heat exchangers are used for many kinds of purposes. The plate heat exchangers are used for heating and cooling. The duple tube heat exchangers are used for many kinds of purposes and are very suitable for slurries. The degradation and failure modes are to a certain degree the same for all types of heat exchangers, but the consequences in the first phase can be different. The most common degradations and faults in heat exchangers are:

- Fouling on the heat transmission surfaces
- Leakage between the primary and secondary sides, and,
- For plate heat exchangers also leaks to the environment are common.

The consequence of fouling on heat transmission surfaces is decrease in the heat transmission coefficient (k) and an increase in the pressure drop across the heat exchanger (dP).

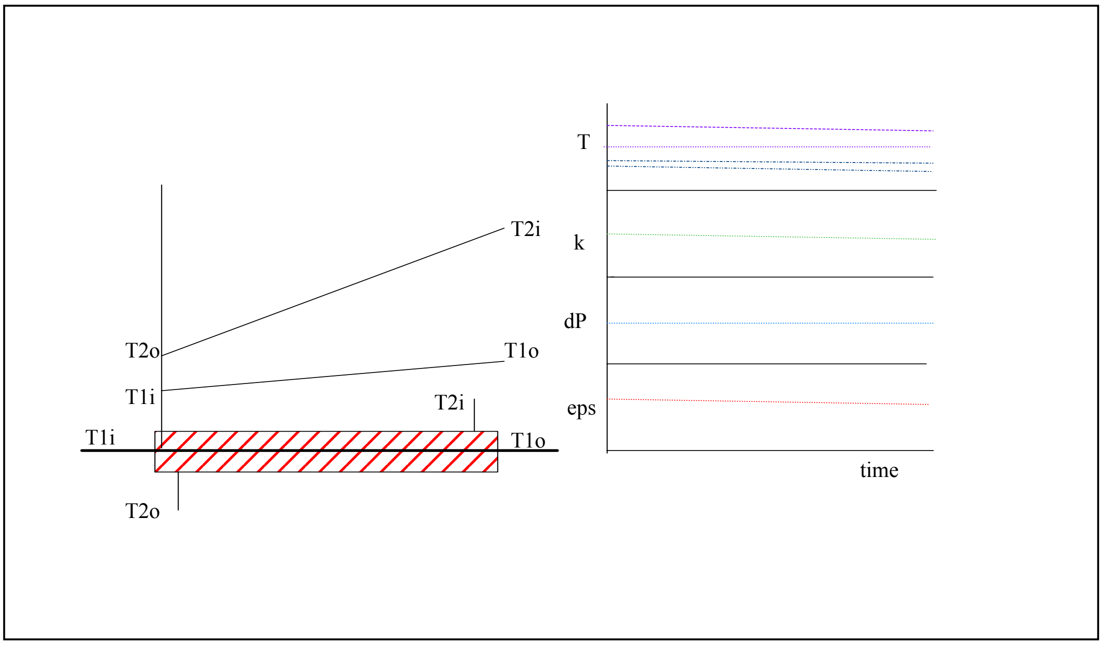


Figure 13. A condition display of a tube heat exchanger.

The decrease in the heat transmission coefficient is the most the dominant consequence of fouling. In tubes with small diameters the pressure drop dP can be the first indicator to observe fouling problems, while the pressure drop is proportional to the diameter in –5 (d^{-5}). The efficiency ε (eps) of the heat exchanger can be calculated too and observed as a function of time. On the display, there are shown on the one side the temperature increase on the primary side of the heat exchanger and the decrease on the secondary side. The measured variables T (temperature) and dP are shown as a function of time. The calculated condition parameters are also shown as a function of time and they need some design values to be shown too. The k value is an indicator for the materials' ability to transmit heat. The efficiency ε (eps) is a characteristics for the present design of the heat exchanger.

Turbine condenser

A condenser system for the turbine was considered as the first example in development of a display system of condition monitoring information. The efficiency of a power plant is significantly dependent on the condenser pressure, and thus it is important to follow the function and condition of the condenser. The strategy used in design of the condition monitoring display for the condenser looks as follows.

Table 7. Strategy for design of a condition monitoring display of turbine condenser.

What is the goal of the condenser?	Keep pressure low
What are the problems?	Temperature increase in the condenser Non-condensable gases in condenser
How do the problems occur?	Ejector problems Cooling problems Incoming air Fission gasses
How are the problems observed?	Increase in condenser pressure
How should they be presented for the users?	Actual working point and expected working point relative to the steam saturation curve

The display developed for condition monitoring of the condenser system is shown in the following figure.

Figure 14. A condition monitoring display on the turbine condenser.

The aim of the display system is to show deviations from the expected operating (working) point of the condenser and the actual operating point. Furthermore, the display should be able to show which type of degradation or fault has occurred. Cooling problems and fouling on the heat transmission (tube) surfaces give an increase of the temperature in the condenser and thereby in the condenser pressure, but the operating (working) point will still lie on the steam saturation curve. Non-condensable (NC) gases are expected to increase the condenser pressure in such a way that the operating point will lie above the steam saturation curve, but the gases will also give a smaller increase in steam temperature due to a decreased heat transmission. Fouling on the heat transmission surfaces is expected to increase the steam pressure in the condenser more slowly than the pressure increase due to failures in the ejector system or due to incoming leaks of air. Functional tests on a Danish power plant where the vacuum (ejector) system was stopped for half an hour showed a fast increase in the condenser pressure due to the increase of non-condensable gasses in the condenser.

The present display has importance for the operative maintenance planning of the condenser and for optimisation of the thermal performance of the plant. The display system has been implemented for tests at the Forsmark 3 simulator at the Halden Reactor Project in Norway. The idea of using the component characteristics and expected operating points is also used for condition monitoring of other types of components in the ongoing project. The tests of the displays will show, if this type of presentation is well understood by the operability personnel and if it sensitive enough to facilitate their observation of incipient faults. Replaying data from Barsebäck NPP has yielded promising tests. The development of a strategy for design of this type of visualisation will continue in the future.

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Author(s)	Kari Laakso[1], Tony Rosqvist[1] and Jette L. Paulsen[2]
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Key words	Condition monitoring, maintenance planning, decision making

Available on request from the NKS Secretariat, P.O.Box 30, DK-4000 Roskilde, Denmark.
Phone (+45) 4677 4045, fax (+45) 4677 4046, e-mail nks@catscience.dk, www.nks.org.