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SENSOR/SIGNAL MONITORING AND PLANT MAINTENANCE

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SENSOR/SIGNAL MONITORING AND PLANT MAINTENANCE

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ABSTRACT

Nuclear Power Plant (NPP) availability is determined by the intended functionality of safety related system and components. Therefore, maintenance is an important issue in a power plant connected to the plant's reliability and safety. The traditional maintenance policies proved to be rather costly and even not effectively addressing NPP requirements. Referring to these drawbacks, in the last decade, in the nuclear industry reliability centered maintenance (RCM) gained substantial interest due to its merits. In the formal implementation of RCM, apparently, predictive maintenance is not considered. However, with the impact of modern real-time and on-line surveillance and monitoring methodologies, the predictive maintenance procedures like sensor/signal verification and validation are to be included into RCM.

INTRODUCTION

Reliability of safety equipment in power plant is an important issue in operation. The role of maintenance in increasing nuclear power plant reliability and availability is currently an important concern under consideration for nuclear utilities. An effective (i.e., cost effective) maintenance procedure for this purpose is the RCM (reliability centered maintenance) which is based on system's and/or subsystems' reliability considerations. In a general application, RCM is a static assessment procedure identifying the importance of system's and subsystems' functionality on a reliability basis and determines the relevant appropriate maintenance procedures. For a critical component, the reliability of the component is so designed that the probability of the system operability complies with the existing standards. In these considerations, however, the predictive maintenance demands are not formally or explicitly included. Relatively lately, predictive maintenance together with RCM was articulated in a general industrial predictive maintenance conference (EPRI 1992) and was recommended in a pilot feasibility study for the maintenance of heat power computing instrumentation (Ciftcioglu et al. 1992). For a reactor safety equipment, the RCM guidelines are not adequate as they are static assessments. In operational conditions, verification and validation of the various sensors and safety instrumentation is necessary in order to achieve enhanced maintenance and reliability in plant operation. These can be integrated into the RCM procedures for the system and subsystems identified to be critical in the RCM terminology. This integration can include the concept of real-time surveillance into RCM which eventually implies the predictive maintenance procedures like monitoring, early fault detection diagnosis and prognosis in RCM activities. The major advantage of this integration is that for critical system and subsystems in RCM the reliability considerations are effectively made use of and the required high reliability of the system is maintained by continuous inspections coordinated with the other system components, rather than excessive redundant component and/or related provisions. Such a methodology is especially very effective for common mode failures among which sensor failures

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are in the first place, in safety system information processing systems. Although in a design, individual reliabilities of the system and subsystems can comply with the requirements and at the same time the independent failure probabilities yield outcomes with a very improbable accident/incident cases, such assessments may suffer because of occasional common mode failures with severe consequences. In this respect, the integrity of sensory information is of primary concern and therefore verification and validation of sensor information on a continuous base is necessary as a part of the maintenance activities and can be accomplished by means of real-time sensor/signal monitoring. By doing so, the design reliability of the system is satisfied or even improved as this is forseen in the RCM.

A brief description of RCM and the integration of real-time sensor/signal verification and validation procedures into RCM is presented below.

RELIABILITY CENTERED MAINTENANCE

Nuclear power plant (NPP) availability is determined ultimately by the proper functioning of safety-related systems, subsystems and/or components. Therefore, the maintenance is an important issue in NPP operation together with plant's reliability and safety.

The traditional maintenance methods proved to be rather costly and even not efficiently addressing the NPP requirements. This is because the traditional methods are based essentially on time-directed maintenance and partly on condition-directed maintenance procedures which are known to be planned maintenance and breakdown maintenance. However, in NPP operation maintenance issues are related to the environmentally qualified lifetimes, such as fuel-cycle as well as the operational conditions requiring augmented fixed maintenance intervals. Additionally, the traditional maintenace programs do not adequately address new issues, like safety system functional inspections, real-time monitoring and diagnostics.

The traditional maintenance methods are essentially within the category of preventive maintenance (PvM) relying on component reliabilities and therefore the activities are component oriented. However an alternative approach can be conceived as system oriented identifying the importance of each component on a system-based perspective. Accordingly, each component is classified considering its significance in the safety related functions and the significance is evaluated by means of component's failure modes and effects analysis (FMEA). This concept enables different maintenance requirements for different components, depending on their importance to system's function. Such an approach is called (RCM). By classifying components according to their safety function and safety significance as related to keeping the overall system performance, replacement life and maintenance requirements are established. The execution of this maintenance program provides one with data called performance indicators which are, in a feedback link, used to update the maintenance program in the form of input data.

Hence, RCM is a systematic methodology for identifying applicable and effective preventive maintenance tasks. Thus, it is an evaluation approach for developing and optimizing a maintenance program. RCM utilizes a decision logic tree to identify the maintenance requirements of equipment according to the safety and operational consequences of each failure and the degradation mechanism responsible for failure so that the design reliability of the system is satisfied or even improved. Component reliability and mean-time between failures can be quantified.

An RCM program includes the following steps.
- define system's and subsystems' boundaries,

- identify important system functions to address,
- perform functional failure analysis, determine the functional failures,
- identify dominant failure modes for functional failures,
- identify critical failure modes using functional Failure Mode and Effect Analysis (FMEA),
- apply RCM fault-tree methodology, identify criticality of each functional failure at component level,
- apply RCM event-tree and decision-tree methods,
- determine efficient (applicable) and effective preventive maintenance (PM) tasks
- implement tasks,
- prepare final documentation.

The schematic representation of the RCM program is given in Fig.1.

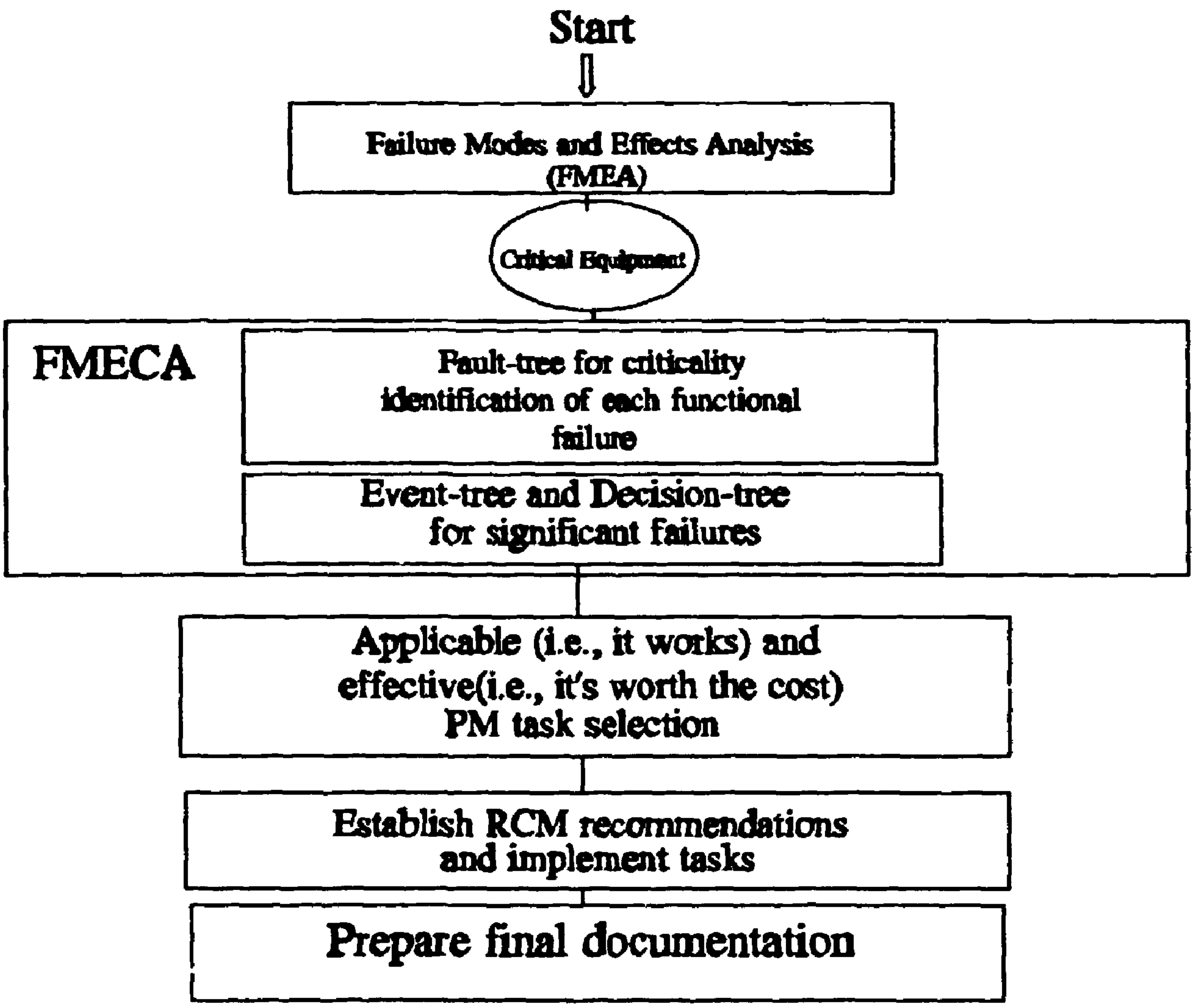

Fig.1 : Essential components of the RCM Methodology

Some basic definitions in the terminology of RCM program above, are as follows.

BOUNDARY - A boundary is a demarcation between two or more subsystems subject to RCM analysis where other systems are not included in the analysis. A boundary delineates the system and its subsystems to help identify in and out interfaces, as well as subsystem functions.

CONDITION MONITORING - Continuous or periodic tests, inspections, measurement or trending of the performance or physical characteristics of a component to indicate current or future performance and the potential for failure.

CRITICAL COMPONENT - A critical component is a component that, if it fails by a specific mode, could or would cause effects significant in failing an important system function. To be considered a critical component one or more of the following criteria must be met. a) have both significant functional effects (plant effects) and a high probability of failure b) have a medium probability of failure and a determination of criticality by the analyst based on engineering judgement c) have a significant condition monitoring (CM) history. In addition, some non-critical components will be evaluated as critical because of extenuating features, i.e., physical size, unavailability during normal plant operations, replacements (time/$), consequences of failures, etc.

CRITICAL FAILURE MODE - A critical failure mode is a dominant failure mode having significant effects on plant safety or availability and having a high likelihood of occurence.

DOMINANT FAILURE MODE - A dominant failure mode is a component failure mode likely to occur during the life of the plant based upon generic plant data or experience.

EVENT-TREE AND DECISION-TREE ANALYSES - Event-tree and decision-tree are inductive logic methods for identifying the various possible outcomes of a given initiating event. In an event-tree the outcomes depend only upon the laws of science. In a decision-tree the outcomes are also influenced by human control.

FAULT-TREE ANALYSIS - Fault-tree analysis is a technique by which many events that interact to produce other events can be related using simple logical relationships AND, OR etc. These relationships permit a methodical building of a structure that represents the system.

FAILURE MODES AND EFFECTS ANALYSIS - A failure modes and effects analysis (FMEA) is a reliability technique that investigates the local, system and plant effects of a given component failure. Typically, the FMEA will be organized by functional failures identified in the FFA (functional failure analysis). FMEA is a tool to systematically analyse all contributing component failure modes and identify the resulting affects on the system. Thus, FMEA will include the failure mode and failure probability of the component. Additionally, the FMEA is used to document whether the component is critical such that it is desirable to develop a preventive maintenance task to prevent the failure. FMEA considers ony one failure at a time and not multiple or common cause failures. FMEA components are functional failures, dominant failure modes, local effects, system effects, probability of failure modes, compensating provisions.

FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS - A failure modes, effects and criticality (or consequences) analysis (FMECA) method is similar to FMEA except that the criticality of the failure is analyzed in greater detail. The objective of this task is to identify components whose failure consequence must meet at least one of the following criteria: a) the failure has a high probability of effecting plant and/or personnel safety b) the failure has a significant economic impact c) the failure is a hidden function item that increase the plant's exposure to multiple failures d) the failure affects instrumentation used for operational decisions.

FUNCTIONAL FAILURE ANALYSIS - A functional failure analysis (FFA) documemts the system functions to be analyzed for failure. The FFA consists of a listing of functions, out-interfaces, in-interfaces and functional failures. An FFA is developed for each identified subsystem. Additionally, the FFA is used to identify which type of analysis technique will be used to investigate functional failures.

IN-INTERFACE - An interface that is provided by another system or subsystem.
OUT-INTERFACE - An interface that is provided by the system or subsystem under consideration to another system or subsystem.

LOCAL EFFECTS - Local effects are those impacts or outcomes, physically at the location of the component associated with a component failure. Local effects focus on the outcome of component failures at the immediate location of the failure and do not consider system or plant effects resulting from the failure.

PREVENTIVE MAINTENANCE - Periodic and planned maintenance actions taken prior to component failure to maintain the component within design operating conditions by controlling degradation or failure.

SUBSYSTEM - A subsystem is a combination of components grouped for convenience in performing RCM analysis. Typically a subsystem will include like components or components performing a similar function or a variety of components that share a common function.

The status of RCM in the nuclear industry has been reported by IAEA (1990).

MONITORING AND PREDICTIVE MAINTENANCE

Safe and reliable operation is a well recognized issue of prime importance in NPPs. Additionally, from the economic considerations viewpoint, system availability is another factor playing important complementary role. In this respect, monitoring of a plant is an important concept during the operational conditions where monitoring includes failure detection and identification (FDI) which concerns not only failures of the sensory information but also system and/or subsystems oriented failures. As a generic name, the monitoring activities involving system and/or subsystem in a plant for early fault detection, diagnosis and prognosis (fault evolution forecasting) are collectively referred to as predictive maintenance (PrM). These activities aim at condition monitoring of the system subject to maintenance on a continuous basis desirably in real-time and on-line. After reliability based considerations, the RCM program dictates the maintenance procedures making use of the available extensive reliability data so that the outcomes are the result of static computations. Therefore, the resulting procedures are effective from the viewpoint of preventive maintenance. The various maintenance procedures involved in the maintenance technology is schematically represented in Fig.2.

Although the traditional maintenance programs have contributed significantly to attain high level safety of NPPs, they are by no means perfect. The limitations of the traditional programs were dramatically disclosed by the accident at Three Mile Island-2. The maintenance activities of Borssele NPP and TMI-accident directed backfitting is described by Boer (1986). Recognizing the success of RCM in airline industry since late 1960, in the last decade RCM is identified to be a technology to be transferred to nuclear industry (Gaertner 1989; Zwingelstein 1992). Referring to the RCM program as a systematic approach for the implementation of an effective preventive maintenance program, with the developments in the computer technology in the last decade the on-line real-time monitoring and FDI should be integrated in this maintenance scheme as as a part of a preventive maintenance program. By means of this, system reliability, safety and availability is enhanced. The integration of the PrM task selection into RCM is accomplished together with the PvM task selection as shown in Fig.1. Hence the critical subsystem(s) having been determined as

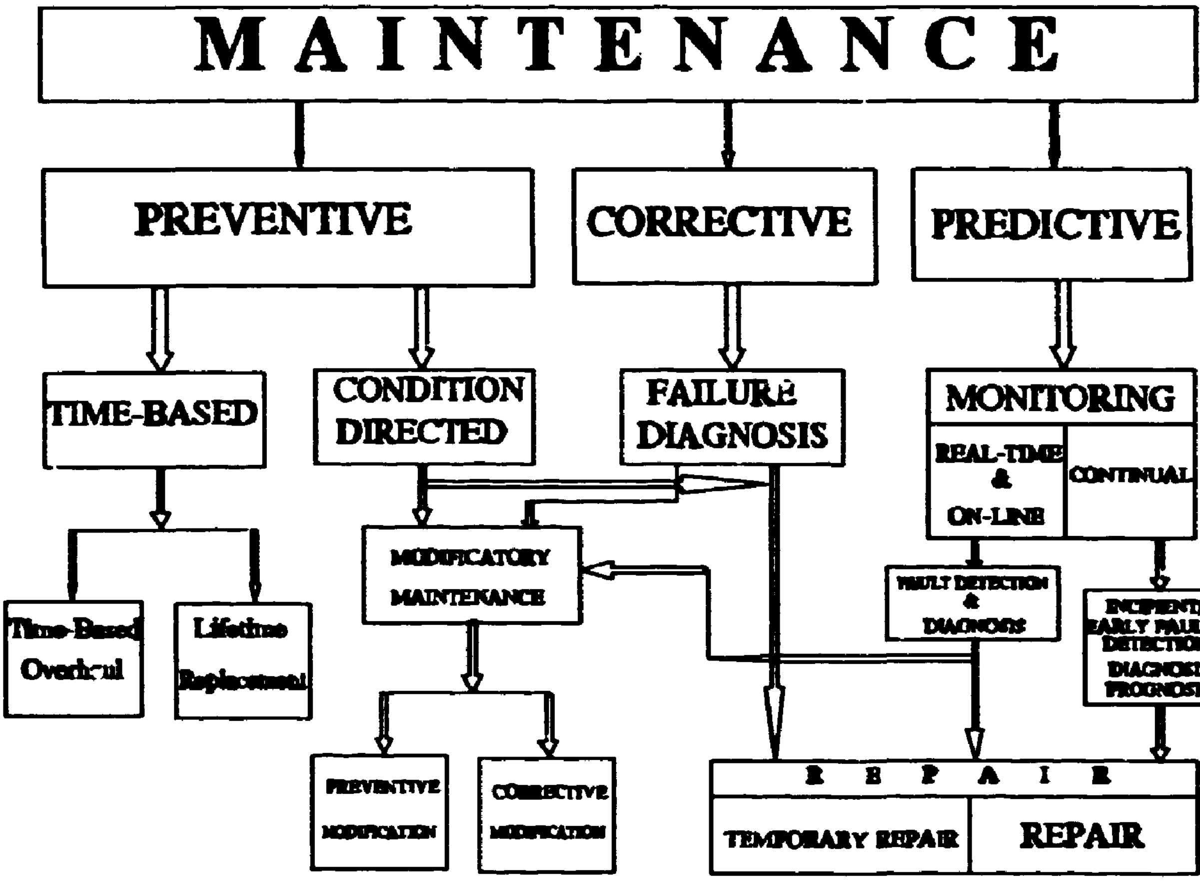

Fig.2 : Schematic representation of the maintenance paradigm

result of FMECA analysis, these systems can be real-time monitored forming the base for preventive maintenance and hence to achieve the followings.

(a) - fault detection before getting to the failure stage
(b) - fault localisation and diagnosis
(c) - forecast of fault evolution
(d) - potential reconfiguration
(e) - preventive maintenance procedures

Making use of the advancements in computer technology, real-time monitoring and fault detection for preventive maintenance can be carried out by means of modern workstation and/or enhanced single-user based computers known as WS and PC. In real-time monitoring several different approaches for surveillance, fault detection are used. They can broadly be grouped as dynamic stochastic modelling, dynamic deterministic modelling and neural networks as they are briefly described below in the context of predictive maintenance in relation to the Borssele NPP in the Netherlands.

Dynamic stochastic modelling - In dynamic stochastic modelling emphasis is laid on FDI-information extraction from fluctuating components, called noise, inherently observed in the process signals rather than the information extraction from signals themselves. Parametric modelling techniques are used as a unified approach to alleviate the difficulty in determining physical model for wide range operating conditions. Typically an ongoing process within the system and/or subsystem(s) is characterized by a certain number of state variables whose knowledge permits the prediction of the process behaviour in the immediate future of observations. The relationship between the observed variables can be obtained by a mathematical model which is represented by a certain number of parameters referred to as structural parameters. The actual values of these parameters can be obtained through system identification methodologies. A change of value of these parameters signifies a structural change which implies a fault. Faults often appear in the order of

- unsteady faults in the form of random structural changes
- steady faults or failures
- catastrophic faults or failures.

The progressive deterioration can lead to catastrophy especially when an automotic control compensates for it. The analyses made through the utilization of noise signals are commonly referred to as noise analysis.

These analyses are carried out in frequency domain as well as in time domain. In frequency domain, power spectral density approach is used for (Türkcan et al. 1991)

- neutron detector's degradation estimation in the form of detector efficiency
- rms noise for global information as the noise power is dependent on the Boron concentration
- spectral decomposition for the analysis of the spectral peaks by discomposing the noise spectrum to the contributing spectra from different phenomena the approach being particularly in use for the analysis of core barrel motion and internal vibrations
- temperature sensor's performance measurements as rms and response time delay (RTD) estimation
- core exit thermocouple's measurements for overheating identification in the channel
- primary system pumps' vibrations estimation, the vibration amplitudes together with the information from in- and ex-core detectors being indicative of primary system integrity
- primary system pressure effects for the estimation of standing waves

Above mentioned analyses are also performed by stand-alone enhanced PC/DSP (digital signal processing module) systems designed as DSA-1 BWR stability monitoring system; DSA-2 general 8-channel spectrum monitoring system; DSA-3 primary system integrity monitoring and core barrel motion analyser. Similar analyses are performed in time domain using the signal modelling methodologies such as AR (autoregressive) and its multivariate counterpart MAR, recursive optimal algorithm using Kalman filtering.

By means of these real-time plant surveillance methodologies, predictive maintenance is exercised throughout the plant in the form of

- continuous monitoring of component conditions and plant operation by diagnostic monitors and sensors
- use of on-line analysis tools that utilize updated plant data, equipment records and data bases
- automated assessment of component remaining life, wear and tear and specification of different operational condition limits.

Dynamic deterministic modelling - The dynamic deterministic modelling implemented is essentially for EFD (early failure detection). The EFD system (Sørensen 1990) is based on the plant's subsystem models, in the form of coupled balance equations solved in real-time using the data from the sensors. Some of the process variables used are power, mass-flow, temperature, pressure and they are determined by the system model as well as obtained from the sensors. Actual measurements are compared with the corresponding model outcomes for model verification as well as fault detection and diagnostic information in the case of failure conditions (Türkcan, Ciftcioglu 1993).

Neural Networks - Artificial feedforward neural networks serve as a computational model of system modelling the signals of state variables in a dynamic process. In this respect, among others, the outstanding useful properties are that neural network does not require a physical model and can model the non-linearities in the process as well. Therefore, it is an emerging technology, and has potential merits for the applications in the nuclear industry. Utilization for the enhancement of V&V for NPP is demonstrated in a real-time application by Ciftcioglu and Türkcan (1993). The potential application areas for maintenance in power plant is especially conspicuous for concerning the preventive maintenance demands. Some areas of interest can be stated as
- general monitoring and fault detection
- check-valve monitoring
- heat-rate monitoring
- sensor/signal and system/subsystem verification and validation
- eddy-current tests
- early failure detection based on physical model with the deterministic state variables.

SENSOR/SIGNAL VERIFICATION AND VALIDATION

Safe, reliable and cost effective operation of a plant is mainly dependent on the quality of signals obtained from the sensors and/or measuring instrumentation where after the initial phase of data and signal processing, the information processing systems pave the way for optimal decisions. In this respect, before the sensory information is used in major time critical functions i.e., monitoring, diagnostics and control, it has to be verified and validated. Although verification and validation (V&V) is rather comprehensive concept (NATO 1992), in simple terms verification is to provide confidence in the resulting information processing subject to the recognition of the plant's operational conditions. Validation is to provide confidence in that the implemented techniques and methods are right to perform the intended function. This terminology implies that verification provides confirmation to the design on one hand and validation provides confirmation to the specifications and requirements, on the other. The reliability of the verification and validation method is enhanced by the implementation of the concept of redundancy together with diversity in this process so that the monitoring basically serves for obtaining confidence in the integrity of the sensory information.

There are several approaches to the design of instrumentation systems to ensure their reliability in spite of eventual sensor failures. These methods are commonly addressed as instrumentation failure detection (IFD). It is the purpose of the IFD subsystem to detect any instrument fault which could seriously degrade the performance of the control system. Some of these methods require redundant sensors with the IFDI (instrumentation failure detection and isolation) subsystem acting as a monitor to detect a fault which causes one of the redundant sensor outputs to deviate from its unfailed conterparts. This is known as hardware redundancy. Another sensor failure detection method is known as functional or analytical redundancy. In such applications conventionally a system or subsystem model can be used to obtain the redundant signals, in a way from analytically emulated (virtual) sensors, to compare with the outcomes of the instrumentation system where Kalman filtering is mainly used for system modelling. Kalman filtering is an optimal method for the estimation of the of a linear dynamic system using measurements of process variables. It is a time-recursive algorithm and can be used for system response, prediction and for estimating nonmeasurable state variables. The method can be extended to nonlinear dynamics and dynamics for uncertainties. Because of its time-recursive structure, it is applicable for both steady-state and transient conditions. For the analytical redundancy, the number of Kalman filters needed is equal to the number of system states in the dynamic model developed. Each filter receives measured signals. However, each filter is made insensitive for one of the particular signal and this signal is estimated by that desensitized filter using other measured signals by the help of system model.

Hence any inconsistency between one of the redundant sensors and its estimated counterpart which is apparently redundant and obtained by analytical means, is identified to be a sensor failure. This approach is used for Borssele steam generator's waterlevel, steam pressure, feedwater flow, steam flow sensors in Borssele NPP in the Netherlands and the effectiveness of the method is demonstrated (Türkcan, Ciftcioglu 1991) by means of emulated fault imposed on the actual plant data. This approach at the same time serves as a means or the verification and eventual validation of the steam generator model and therefore it is referred to as FDE (failure detection and estimation) approach (Frank 1990;Isermann 1984). Among other approaches for the analytical redundancy mention may be made of parity-space representation (Tsai,Chou 1993; Massoumnia,Velde 1988; Chow,Willsky 1984; Ray,Desai, Deyst 1983). Methods of detecting changes in signals is given by Basseville (1988) in a survey paner and instrument fault detection methods are discussed by Watanabe and Himmelblau (1982). As an emerging technology, neural networks are getting growing interest and their actual real-time utilization for sensor/signal failure detection and system V&V are reported (Nabeshima,Türkcan,Ciftcioglu 1993).

The real-time monitoring based on signal modelling and ensuing statistical measure of Mahalonobis distance is described earlier (Ciftcioglu, Türkcan 1991a). In this approach real-time data from the sensor is modeled by means of time series analysis techniques known as autoregressive analysis special form of which is referred to as lattice filtering (Friedlander 1982). Filter parameters are estimated recursively by Kalman filtering in adaptive form and afterwards a statistical Mahalonobis distance measure is formed. By means of this information, a statistical χ^2 test is applied for classification. The decision-making for failure is based on the sequential decision reliability concept (Ciftcioglu, Türkcan 1990) treating the statistical distance measure with predetermined confidence level as a detection processor whose failure-rate parameter for the reliability assessment is determined by false-alarm and alarm-failure probabilities. This approach is used for the monitoring of steam-flow loop1 and loop2 signals of Borssele nuclear power plant (Ciftcioglu, Türkcan 1991b).

CONCLUSIONS

An optimized maintenance program is one which minimizes total plant maintenance costs, while achieving target values of safety, reliability, availability and performance. In this respect RCM is effective that it improves an inadequate PvM program, eliminates unnecessary PvM activities, improves plant reliability and safety, optimizes maintenance sources. By means of inclusion of PrM into RCM the superiorities of the RCM program is enhanced, as the predictive maintenance itself has outstanding merits relevant to maintenance technology. It increases operator safety, reduce maintenance cost, increases availability, increases maintenance productivity and effectiveness, and increases product quality. Added to this, as the safe plant operation is primarily dependent on the quality of the sensory information, sensor/data verification and validation is imperative. To carry out this task in the frame of RCM program in real-time and on-line basis provides improved maintenance performance, in particular, against occasional as well as time critical failures and enhances the existing maintenance superiorities of RCM as the task effectively becomes condition monitoring of sensory information on which plant's operation rely.

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