MAINTENANCE AND TEST STRATEGIES TO OPTIMIZE NPP EQUIPMENT PERFORMANCE

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Abstract

This paper proposes an approach to maintenance optimization of nuclear power plant components, which can help to increase both safety and availability. In order to evaluate the benefits of preventive maintenance on a quantitative basis, a software code has been developed for component performance and reliability simulation of safety related nuclear power plant equipment. A three state Markov model will be introduced, considering a degraded state in addition to an operational state and a failed state.

Introduction

In the field of safety culture, maintenance activities are more and more considered to play a major role. The past history has shown that in many cases nuclear power plant equipment failures could have been avoided with an appropriate maintenance schedule. Avoiding failures means not only an increasing state of safety, but also reducing costs due to forced component outage times and repairs. The following paper shows a possible approach to maintenance optimization of nuclear power plant components, which can help increasing both safety and availability.

In standard reliability and probabilistic safety assessment (PSA) modeling, only two states for each component are considered: success and failure. Yet in many cases there is no immediate transition from a success state to a failed state. Components may show significant degradation, indicating a more serious failure to occur. Component degradation can, however, in many cases be detected and corrected. Thus a total loss of function, which could seriously impact plant reliability and safety, can be avoided. With the inclusion of degraded states, especially scheduled, preventive maintenance activities turn out to have remarkable benefits regarding component performance. Preventive maintenance can be seen as a scheduled periodic activity with the objective to repair any degraded or failed equipment and to assure the proper functioning of the equipment after it has been maintained.

In order to evaluate the benefits of preventive maintenance on a quantitative basis, a software has been developed for component performance and reliability simulation of safety related nuclear power plant equipment. A three state Markov model will be introduced, considering a degraded state in addition to an operational state and a failed state. The degraded state occurs when the component's performance degrades below some threshold value defining normal designed performance.

The three state Markov model allows not only the immediate transition from an operational state to a failed state, but also the transition from an operational state to a failed state through a degraded state. The component may of course remain in a degraded state, depending on the degradation mode. With the inclusion of a degraded state, the advantages of preventive maintenance actions can be explicitly quantified.

The application of this three state Markov model is, however, not restricted to components in standby; simulations for running components may also be performed. Whereas for standby components catastrophic failures only can be detected through demand, test or maintenance, it can be assumed that for running components in most cases catastrophic failures will be detected immediately. But for both standby and running components, a degraded state may remain undetected for a certain amount of time. In such a case, preventive maintenance can correct degradation before the transition to a catastrophic failure.

Once a degraded state is defined, optimal preventive maintenance intervals can be evaluated, depending on the components' reliability parameters. This is one of the main objectives of the reliability simulation. In order to simulate the three state Markov model, the following reliability parameters need to be known or estimated:

- catastrophic failure rate;
- degraded failure rate;
- average repair time;
- (allowed) outage time due to preventive maintenance.

The application of the reliability simulation to safety related pumps show the state probabilities and the availability depending on the reliability parameters and on the preventive maintenance interval

An interesting and also very important study is the dependence of component reliability and availability on failure detection probabilities. Whereas it can be assumed that a catastrophic failure will always be detected by preventive maintenance or by surveillance/test, the detection of degraded failures may not always be possible by surveillance/test, based, however, on the degraded failure modes. The inclusion of failure detection probabilities plays a major role for components with high degraded failure rates. It can be shown that a high detection rate of degraded failures increases both reliability and availability.

Another very important issue is a comparison between scheduled and unscheduled maintenance. It can be shown that planned maintenance activities lead to a significant higher operational state probability than unscheduled maintenance activities, even if the scheduled and the unscheduled maintenance activities have the same cumulative outage time for a certain time period. This emphasizes the importance of an appropriate periodic maintenance schedule, which should be determined depending on the failure history over the past operating period.

As an extension, this model can also be applied to power production systems, where a degraded state can be defined in terms of lower output. In this case the economical consequences of the components' reliability parameters can be shown quantitatively.

The equipment performance and reliability simulation was applied to nuclear power plant safety related standby pumps. The data available from the maintenance records are the total operating period, the number of catastrophic failures, the number of degraded failures and the average repair time. The allowed preventive maintenance outage times were assumed to be in the range of the average repair times. The range of the operating periods is long enough to yield reasonable results (5 – 11 years). However, future investigations may show changes in pump reliability performance, which may also be based on changing maintenance procedures.

Operational State Probabilities

In the following the operational state probability for various standby pumps are compared. For graphical reasons, the complementary probability, 1 - operational state probability, is plotted in Fig. 1 and Fig. 2.

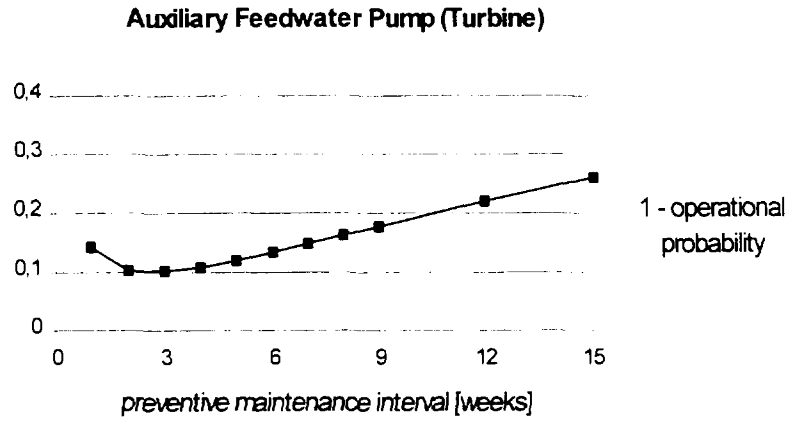

Fig. 1. Operational state probability of the auxiliary feedwater pump (turbine) of Plant I. For graphical reasons, the complementary probability, 1 - operational state probability, is plotted. It can be seen that after the maximum of the state probability at a preventive maintenance interval of 3 weeks, the operational state probability decreases only slightly with increasing preventive maintenance interval.

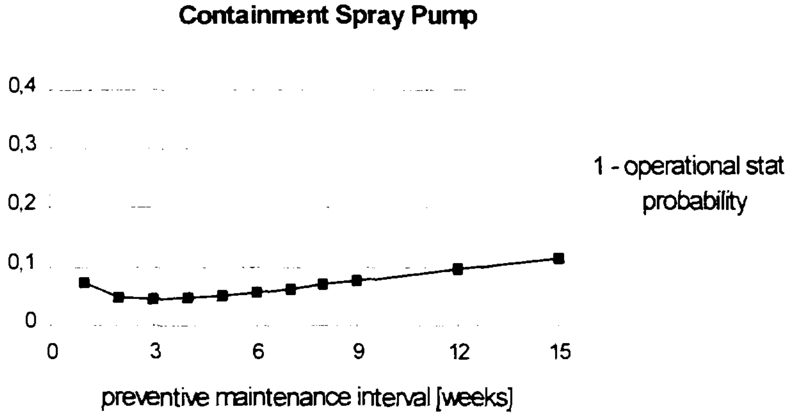

Fig. 2. Operational state probability of the containment spray pump of Plant 1. For graphical reasons, the complementary probability, 1 - operational state probability, is plotted. It can be seen that the operational state probability decreases slightly with increasing preventive maintenance interval.

Availability

During one preventive maintenance interval plus the planned outage due to preventive maintenance activities, the maximum availability which is achievable is:

$$\frac{\textit{maintenance interval}}{\textit{maintenance interval} + \textit{preventive maintenance outage time}}$$

In this case it is assumed that no outages due to failures occur within one preventive maintenance interval.

Taking into account pump failures and in the case of failure the unavailability to perform its function upon demand, the pump availability can be written in the form:

$$\frac{\textit{maintenance interval} - \textit{time in failed state}}{\textit{maintenance interval} + \textit{preventive maintenance outage time}}$$

Figures 3 and 4 show the maximum availability and the availability taking into account the outage time due to failures of sample pumps. The gap between the maximum availability and the "real" availability is shown, depending on the preventive maintenance interval. With constant maintenance duration, the maximum availability is always increasing with preventive maintenance. The "real" availability shows a maximum, indicating the optimum balance between planned preventive maintenance outages and outages due to failures. The following decrease of the availability is caused by the increasing influence of the failure outages. As can be seen in the following figures, a high failure rate is reflected by a rapid decrease in the availability.

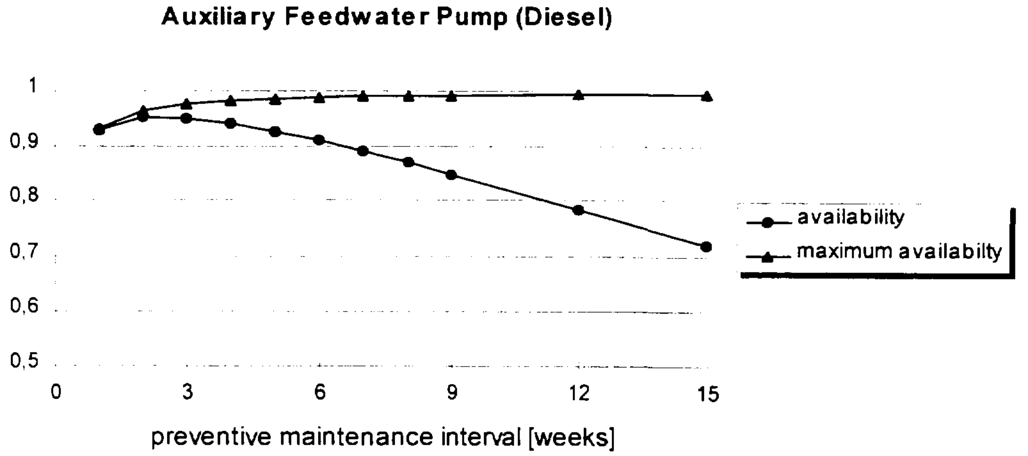

Fig. 3. Availability of the auxiliary feedwater pump (diesel). The maximum availability considers only outages due to preventive maintenance activities. In addition to preventive maintenance outages, the "real" availability also takes into account outages due to failures. The rapid decrease of the availability reflects the high pump failure rate.

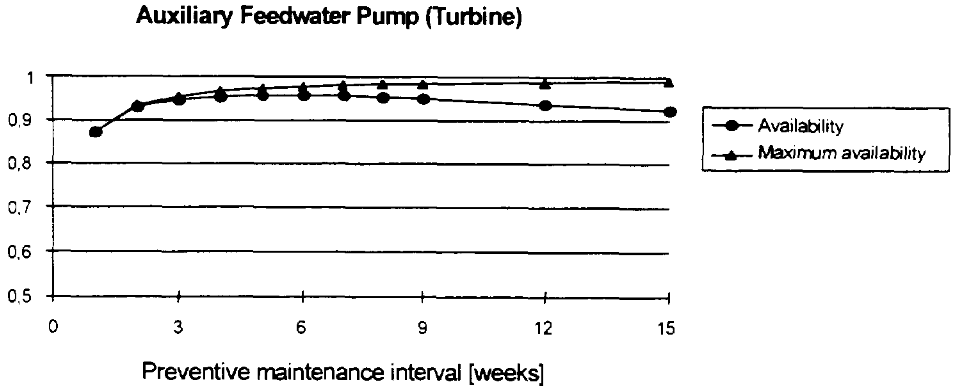

Fig. 4. Availability of the auxiliary feedwater pump (turbine). The maximum availability considers only outages due to preventive maintenance activities. In addition to preventive maintenance outages, the availability also takes into account outages due to failures. The slow decrease of the availability reflects the low pump failure rate.

Tests between Preventive Maintenance Activities

Under certain circumstances it is valuable to perform tests between preventive maintenance activities. In most cases, tests are much easier to perform and less time consuming than preventive maintenance activities and are therefore more cost-effective. The inclusion of regularly performed tests may allow the extension of the preventive maintenance interval, thereby hardly affecting equipment reliability and availability.

Tests are in most cases less costly than maintenance activities. Benefits obtained through an appropriate inclusion of tests within a regular preventive maintenance interval are therefore not only of probabilistic nature, improving the component's reliability performance, but also of financial terms. Allowing the extension of the preventive maintenance interval through the inclusion of tests, financial resources could be saved and allocated for spare parts or improved training courses for maintenance personnel. However, tests performed too frequently may also have a negative impact on plant reliability performance, as a higher number of demands, either due to tests or emergency, may accelerate component aging. In our work, we concentrate on probabilistic safety assessment calculations and do not consider financial aspects. A future extension of this work might be to include financial considerations in addition to probabilistic calculations of component reliability performance.

In our model, tests are assumed to be capable of failure detection, but not of detecting equipment degradation. Fig. 5 shows a possible trajectory for equipment that undergoes regular preventive maintenance with a predetermined maintenance interval and with tests performed within each preventive maintenance interval.

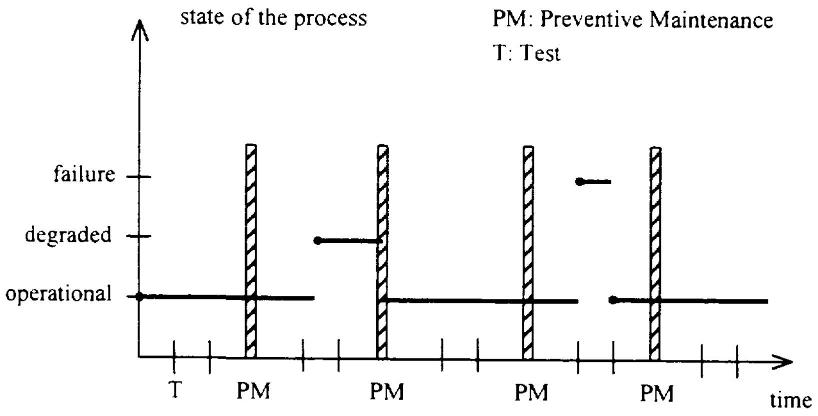

Fig. 5. A possible trajectory of equipment with the states operational, degraded and failed is shown for a Markov process that is interrupted not only by preventive maintenance, but also by tests performed during the preventive maintenance interval. In our model, tests are assumed to be capable of failure detection, but not of detecting any kind of degradation.

We assume that a test is capable of detecting a failed state. This assumption is reasonable because the main objective of performing tests is to identify the functional performance of a component. For the time being, any kind of degradation will in our model not be detected through a test:

$$\textit{Test:}\ \begin{cases} \textit{operational state} & \rightarrow\ \textit{operational state} \\ \textit{degraded state} & \rightarrow\ \textit{degraded state} \\ \textit{failed state} & \rightarrow\ \textit{operational state} \end{cases}$$

One of the most remarkable benefits obtained by tests performed between preventive maintenance activities is the reduction of the failed state probability and the increase in the component's availability.

In order to show the effect of regularly performed tests within each preventive maintenance interval, 2 pumps were selected for the numerical simulation, quantifying changes in component reliability performance compared to a maintenance strategy not considering tests:

- *the Auxiliary Feedwater Pump (Diesel) of Plant I,*
- *the Fire Pump of Plant II.*

In Table 1 and Table 2 the pump input parameters for the numerical reliability performance simulation are listed.

Table 1 shows the 2 selected pumps' transition rate from the operational state to the failed state, denoted by the catastrophic failure rate, the transition rate from the operational state to a degraded state, denoted by the degraded failure rate, and the transition rate from a degraded state to the failed state, denoted by the degraded to catastrophic failure rate.

Standby Pump	catastrophic failure rate	degraded failure rate	degraded to catastrophic failure rate
	/ 1,000,000 h	/ 1,000,000 h	/ 1,000,000 h
Plant I: (operating period = 5 years = 43800 h)			
Auxiliary Feedwater Pump (Diesel)	23.0	757.8	803.8
Plant II: (operating period = 6 years = 52560 h)			
Fire Pump	19.3	159.3	197.9

Table 2 shows the 2 selected pumps' average repair duration and average preventive maintenance duration. The average preventive maintenance durations were estimated to be in the range of the respective pump's average repair durations.

Standby Pump	average repair duration [h]	average preventive maintenance duration [h]
Plant I: (operating period = 5 years = 43800 h)		
Auxiliary Feedwater Pump (Diesel)	6.6	12.0
Plant II: (operating period = 6 years = 52560 h)		
Fire Pump	6.7	12.0

For the 2 pumps it is assumed that the test duration is 3 hours.

Auxiliary Feedwater Pump (Diesel) of Plant I

Test Interval = 3 Weeks

As already stated, the reduction of the failed state probability and therefore a higher operational state probability and an increase in the pump availability are among the tangible benefits regarding the inclusion of tests within the preventive maintenance interval. In Fig. 6, the two component reliability performance approaches, case (a), considering only preventive maintenance activities and case (b), including tests performed every 3 weeks within the preventive maintenance interval, are compared with respect to the pump's failed state probability. As can be seen, the reduction of the failed state probability through the inclusion of tests is a remarkable positive impact obtained by the regular performance of tests. With tests performed every 3 weeks, the increase in the failed state probability with the extension of the preventive maintenance interval becomes almost negligible. However, it should be noted that tests performed too frequently may effect component performance, an aspect which is not taken into consideration in our calculations.

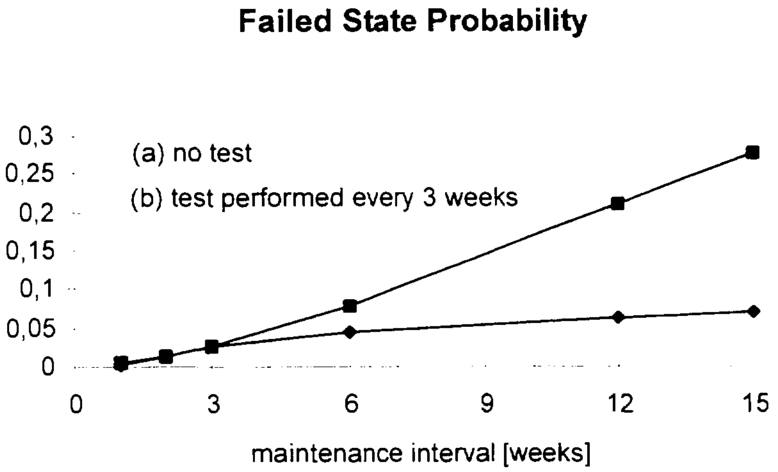

Fig. 6. Failed state probability for 2 two component reliability performance strategies: In case (a) only preventive maintenance activities are considered, whereas in case (b) tests performed every 3 weeks within the preventive maintenance interval are included. It can be seen that the inclusion of tests significantly reduces the failed state probability, thus allowing the extension of the preventive maintenance interval without a major increase in the failed state probability.

The reduction of the failed state probability is equal to an increase in the probability that the pump will be found at the operational state upon demand. This can be seen in Fig. 7, where the operational state probability is compared for the 2 cases (a) and (b). With the preventing maintenance interval exceeding 6 weeks, the gap between the operational state probabilities becomes significantly large, indicating that for the auxiliary feedwater pump the inclusion of tests would contribute to a better component reliability performance.

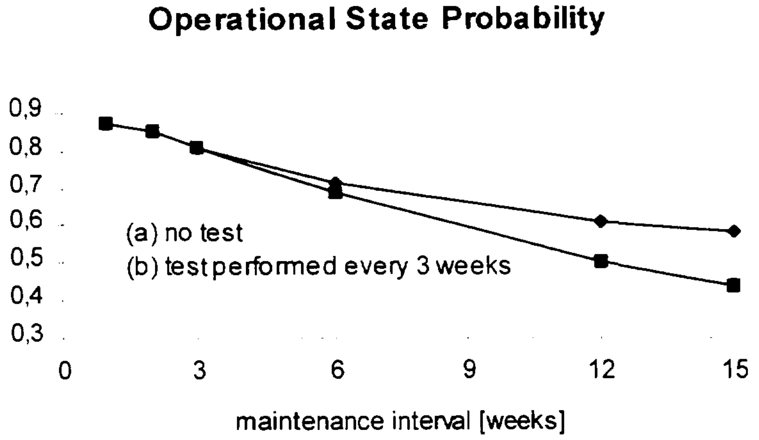

Fig. 7. Operational state probability for 2 two component reliability performance strategies: In case (a) only preventive maintenance activities are considered, whereas in case (b) tests performed every 3 weeks within the preventive maintenance interval are included. It can be seen that the gap between the state probabilities becomes significantly large with the preventive maintenance interval exceeding 6 weeks.

An interesting issue is the availability of the auxiliary feedwater pump depending on the component performance strategies. Comparing the availability for case (a) and case (b), it can be seen that through the inclusion of tests, the availability stays almost constant with increasing preventive maintenance interval, whereas a dramatic decrease in the availability occurs for the performance strategy not considering the regular performance of tests. As already mentioned, the increase in the pump's availability through the inclusion of functional tests is consistent with the decrease in the failed state probability. The auxiliary feedwater pump availability, compared for case (a) and case (b), can be seen in Fig. 8.

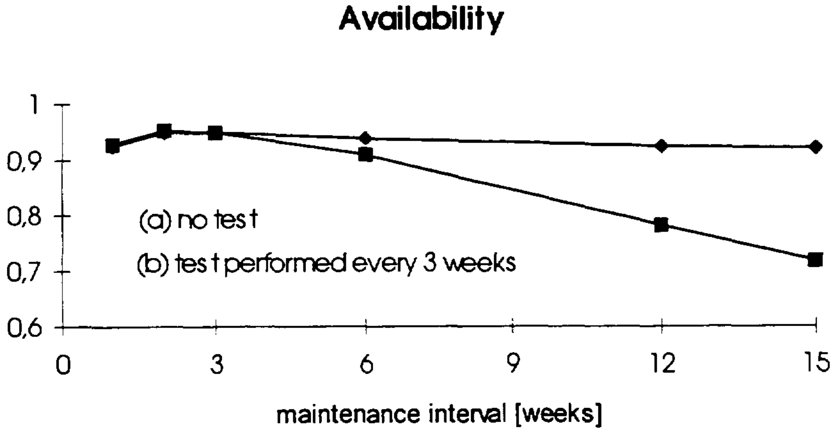

Fig. 8. Comparison of the availability of the auxiliary feedwater pump of plant I for case (a) and case (b). In case (a) only preventive maintenance activities are considered, whereas in case (b) tests performed every 3 weeks within the preventive maintenance interval are included. The difference is significant, emphasizing the benefits obtained by the inclusion of tests within the preventive maintenance interval.

Comparison of Different Test Strategies

We have now compared 2 different test strategies to improve reliability performance of the auxiliary feedwater pump of plant I. We have shown that the inclusion of tests within the preventive maintenance interval contributes significantly to a better pump reliability performance, increasing the pump's operational state probability and availability.

In addition to the 2 test strategies we have already evaluated, a test interval of 6 weeks is now considered. In the following we directly compare 3 different test strategies for the auxiliary feedwater pump of plant I. For this purpose the preventive maintenance is kept constant, being 12 weeks. The test interval of the 3 different test strategies ranges from 3 to 6 weeks:

(1) Test Interval = 3 Weeks

(2) Test Interval = 4 Weeks

(3) Test Interval = 6 Weeks

Comparing the failed state probability in Fig. 9, it can be seen that with the test interval extending from 3 to 6 weeks, the failed state probability becomes twice as high, increasing from 0,06 to 0,12.

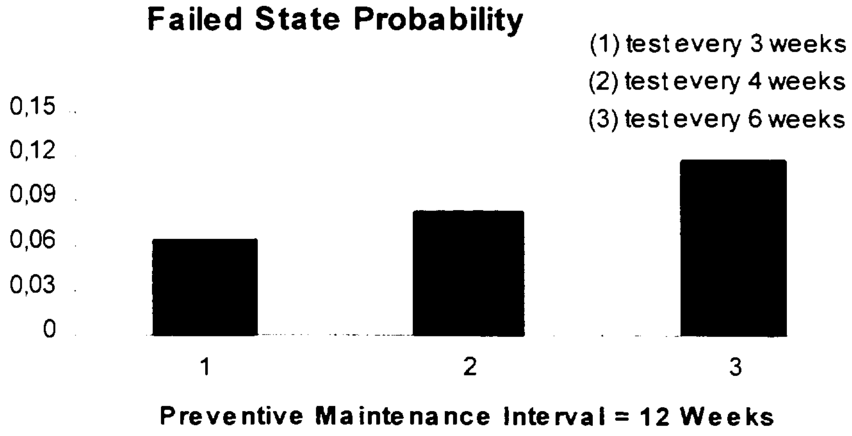

Fig. 9. Compares the failed state probability of the auxiliary feedwater pump of Plant I for 3 different test intervals. It can be seen that with the test interval extending from 3 to 6 weeks, the failed state probability becomes twice as high, indicating that the variation of the test interval remarkably influences reliability performance of the auxiliary feedwater pump.

In Fig. 10 the operational state is compared for the 3 different test intervals at a preventive maintenance interval of 12 weeks. It can be seen that the operational state probability decreases with the extension of the test interval.

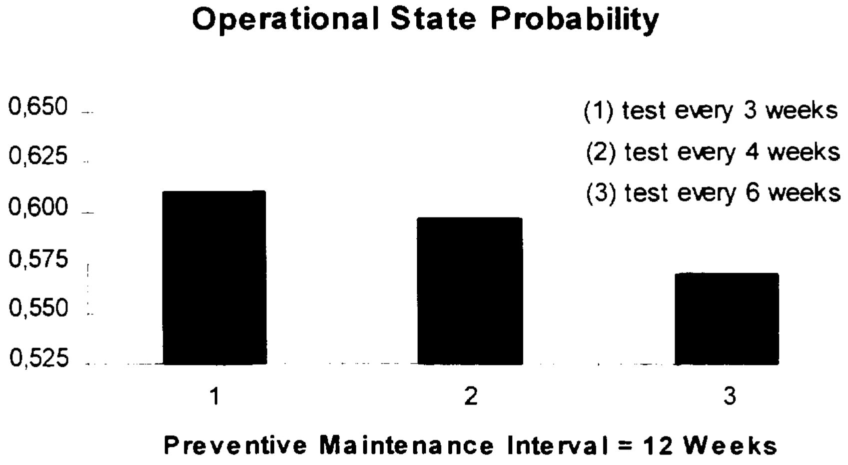

Fig. 10. Compares the operational state probability of the auxiliary feedwater pump of Plant I for 3 different test intervals It can be seen that with the extension of the test interval, the operational state probability increases, caused by the increase of the failed state probability.

The increase in the failed state probability directly affects pump availability, which can be seen in Fig. 11. Comparing the availability for the 3 different test intervals at a preventive maintenance interval of 12 weeks, one observes that the availability decreases with the extension of the test interval. Summarizing the effects of the extension of the test interval on component reliability performance, it can be stated that the higher the failed state probability, the more beneficial is the inclusion of tests into a maintenance optimization strategy.

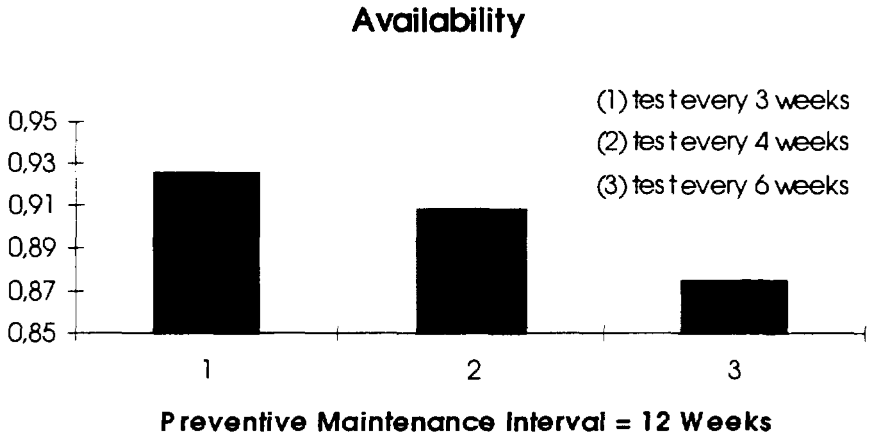

Fig. 11. Compares the availability of the auxiliary feedwater pump of Plant I for 3 different test intervals It can be seen that with the extension of the test interval, the availability decreases, caused by the increase in the failed state probability shown in Fig. 9.

Tests with the Capability of Detecting Component Degradation

In the previous chapter we have included the performance of tests within the preventive maintenance interval. We assumed that tests are only capable of detecting component failures. However, for some kinds of degradation this assumption may not be true. Based on the degradation mode, a component degradation may or may not be detected.

In order to include the possibility of detecting component degradation through tests, we will introduce degradation detection probabilities through tests. Thus it is possible to correct a degraded state through tests, bringing the component back to the operational state.

For the auxiliary feedwater pump (diesel) of plant I, we compared 2 different cases:

- *25% degradation detection probability through test*
- **50%** degradation detection probability through test

25% Degradation Detection Probability Through Tests

In Fig. 12 the effect of including a degradation detection probability through tests is shown on the degraded state probability. Tests being capable of detecting pump degradation with a probability of 25%, denoted by case (a), are compared with tests not being capable of detecting a degraded state, denoted by case (b). The test interval is kept 4 weeks in our numerical simulations. The difference between the degraded state probabilities is obvious, indicating a higher efficient component reliability performance through the inclusion of degradation detection probabilities through tests.

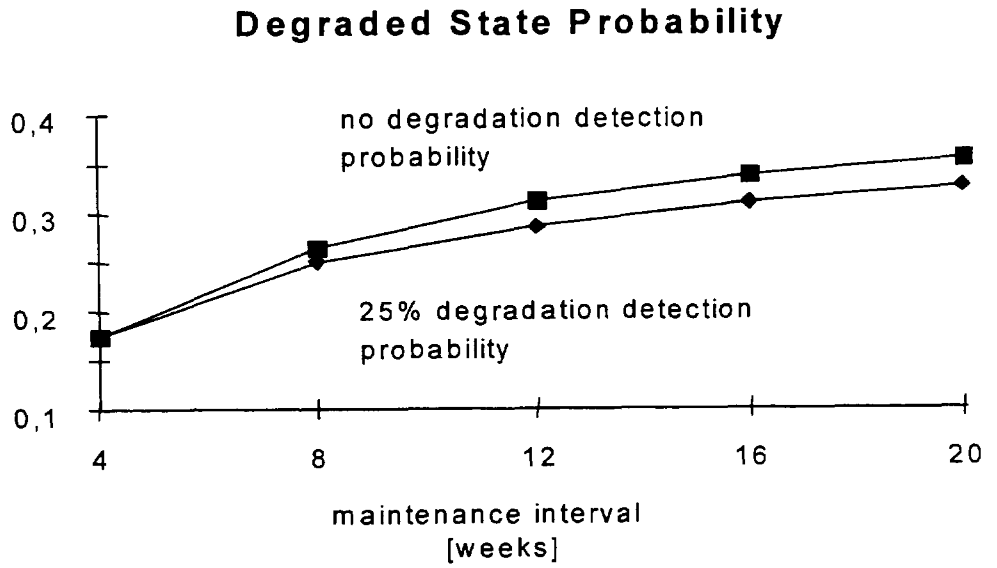

Fig. 12. Comparison of the degraded state probability of the auxiliary feedwater pump of plant I: In case (a), tests are capable of detecting a degraded state with a probability of 25%, whereas in case (b) tests are not capable of detecting any mode of degradation. The test interval is 4 weeks. The difference between the degraded state probabilities is significant, being 5% at a preventive maintenance interval of 20 weeks.

In Fig. 13 the operational state probability is compared for case (a) and case (b).

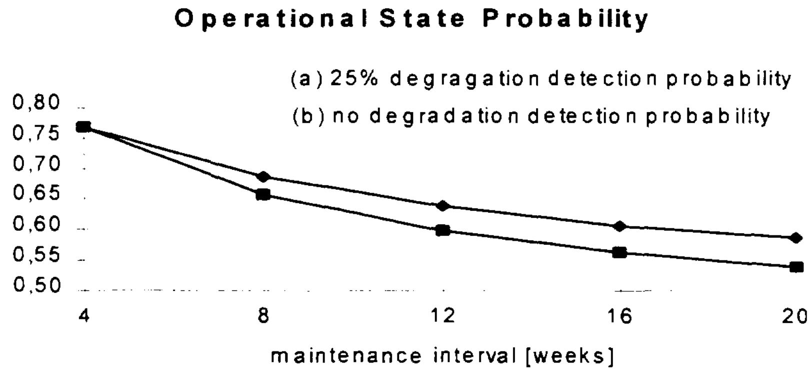

Fig. 13. Comparison of the operational state probability of the auxiliary feedwater pump of plant I: In case (a), tests are capable of detecting a degraded state with a probability of 25%, whereas in case (b) tests are not capable of detecting any mode of degradation. The test interval is 4 weeks. The increase in the operational state probability reflects the decrease in the degraded state probability shown in Fig. 12.

In Fig. 14 the failed state probability is compared for the 2 cases (a) and (b). The difference between the failed state probabilities is not so obvious compared to the degraded and the operational state probabilities shown in Fig. 12 and Fig. 13. The rather small influence on the failed state probability is an indirect benefit obtained by the possibility of detecting degradation through tests, thus decreasing the probability of the pump transiting from a degraded state to the failed state.

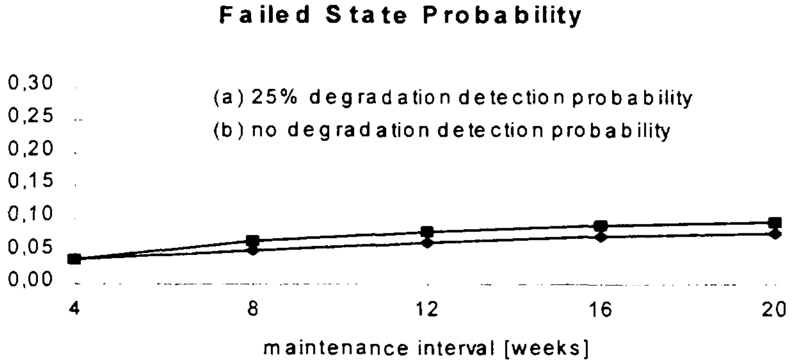

Fig. 14. Comparison of the failed state probability of the auxiliary feedwater pump of plant I: In case (a), tests are capable of detecting a degraded state with a probability of 25%, whereas in case (b) tests are not capable of detecting any mode of degradation. The test interval is 4 weeks. The difference between the failed state probabilities is an indirect benefit of the inclusion of degradation detection probabilities through tests, thus decreasing the probability of the pump transiting from a degraded state to the failed state. However, the effect is not very significant.

The effect on the pump availability is almost negligible, as can be seen in Fig. 15. In this connection it should be mentioned that being in a degraded state, the pump is assumed to be still available. As the inclusion of degradation detection probabilities through tests mainly affects the degraded state probability, the availability does not show major changes.

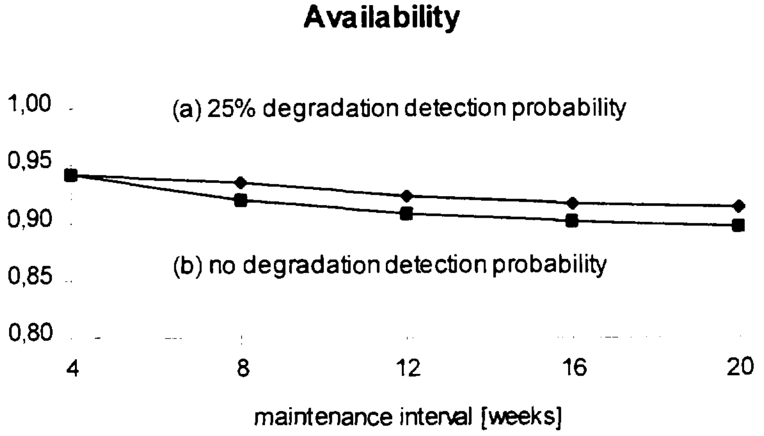

Fig. 15. Comparison of the availability of the auxiliary feedwater pump of plant I: In case (a), tests are capable of detecting a degraded state with a probability of 25%, whereas in case (b) tests are not capable of detecting any mode of degradation. The test interval is 4 weeks. The difference between the availabilities is rather small, as the inclusion of degradation detection probabilities through tests mainly affect the pump's degraded state probability.

50% Degradation Detection Probability Through Tests

Let us now increase the degradation detection probability to 50%, being equal of detecting every second pump degradation. Again we will evaluate the effect of the inclusion of a degradation detection probability through tests on component reliability performance. We of course expect now a greater influence on the state probabilities, especially on the degraded and the operational state probability. In Fig. 16 the degraded state probabilities are shown for tests being capable of detecting pump degradation with a probability of 50%, now denoted by case (a), and for tests not being capable of detecting a degraded state, denoted by case (b). The test interval is again 4 weeks.

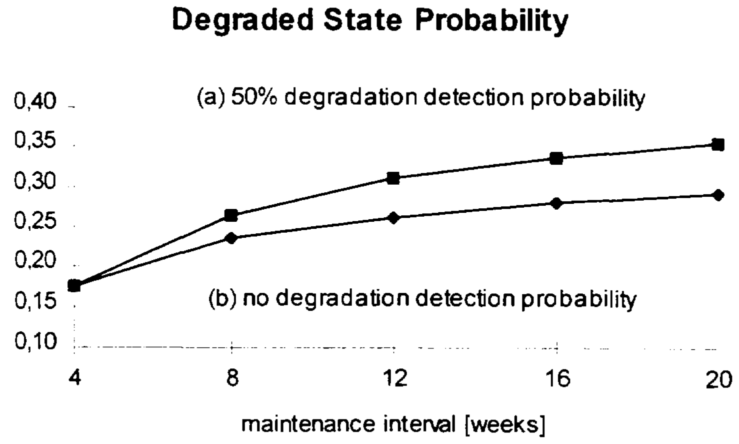

Fig. 16. Comparison of the degraded state probability of the auxiliary feedwater pump of plant I: In case (a), tests are capable of detecting a degraded state with a probability of 50%, whereas in case (b) tests are not capable of detecting any mode of degradation. The test interval is 4 weeks. The difference between the degraded state probabilities is even more significant than in the case of tests being capable of detecting pump degradation with a probability of 25%, shown in Fig. 12. At a preventive maintenance interval of 20 weeks, the difference between the degraded state probabilities is already 10%.

In Fig. 17 the operational state probability is compared for case (a) and case (b). As can be seen, with the inclusion of tests being capable of detecting degraded states with a probability of 50%, the operational state probability becomes significantly higher. The increase in the operational state probability reflects the decrease of the degraded state probability shown in Fig. 16.

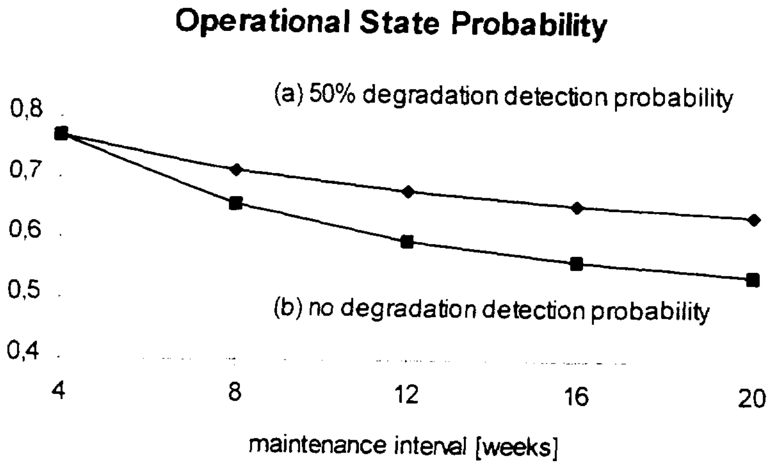

Fig. 17. Comparison of the operational state probability of the auxiliary feedwater pump of plant I: In case (a), tests are capable of detecting a degraded state with a probability of 50%, whereas in case (b) tests are not capable of detecting any mode of degradation. The test interval is 4 weeks. The increase in the operational state probability, now even more remarkable than for tests being capable of detecting degradation with a probability of 25%, reflects the decrease of the degraded state probability shown in Fig. 16.

Again, the failed state probability is compared for the 2 cases (a) and (b), as can be seen in Fig. 18. The difference between the failed state probabilities is not so obvious compared to the differences between the degraded and the operational state probabilities shown in Fig. 16 and Fig. 17. However, the difference between the failed state probabilities has increased due to the higher probability of degradation detection through tests, thereby decreasing the probability of the transiting from a degraded state to the failed state.

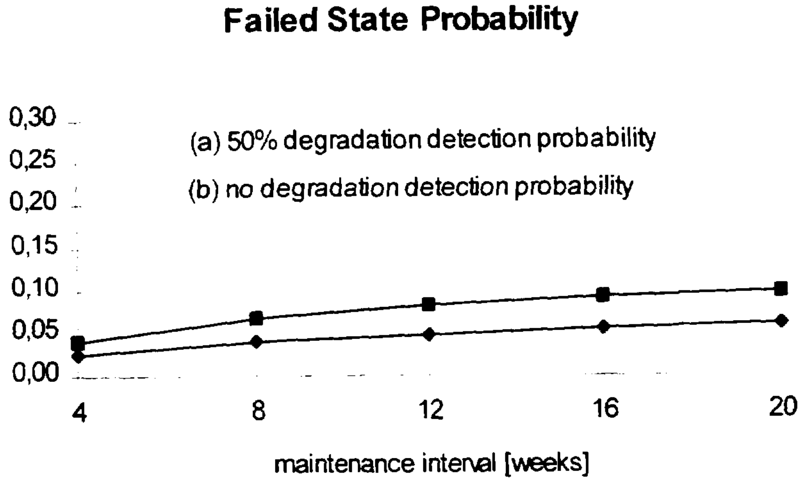

Fig. 18.Comparison of the failed state probability of the auxiliary feedwater pump of plant I: In case (a), tests are capable of detecting a degraded state with a probability of 50%, whereas in case (b) tests are not capable of detecting any mode of degradation. The test interval is 4 weeks. The difference between the failed state probabilities, now more significant than in the case of a degradation detection probability of 25% through tests, is an indirect benefit of the inclusion of degradation detection probabilities through tests, thus decreasing the probability of the pump transiting from a degraded state to the failed state.

Comparing the pump availabilities for the 2 cases (a) and (b), it can be seen in Fig. 19 that the difference between the availabilities is now more significant, which reflects the changes of the failed state probability shown in Fig. 18.

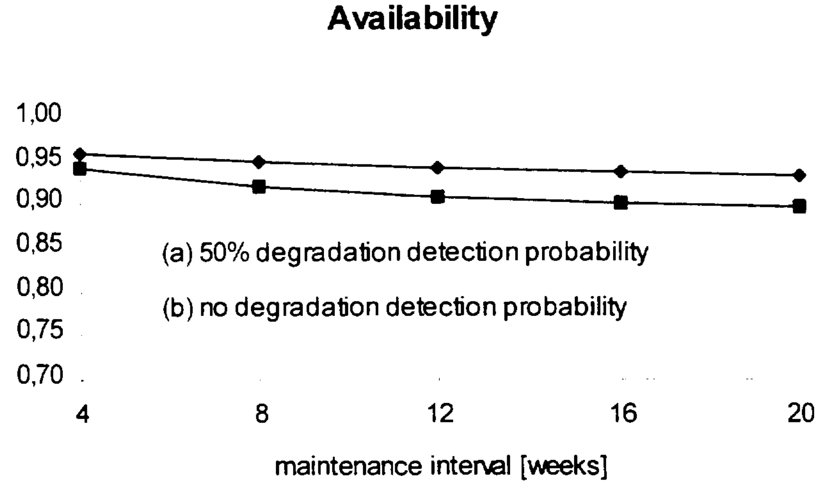

Fig. 19. Comparison of the availability of the auxiliary feedwater pump of plant I: In case (a), tests are capable of detecting a degraded state with a probability of 50%, whereas in case (b) tests are not capable of detecting any mode of degradation. The test interval is 4 weeks. The difference between the availabilities is still small, but more significant than in Fig. 15, where the degradation detection probability through tests is only 25%.

Let us now summarize the effects of the inclusion of degradation detection probabilities through tests: Keeping the preventive maintenance interval constant to be 20 weeks, Fig. 20 shows the degraded state probability for (1) tests not capable of detecting any degraded states, (2) for tests with a degradation detection probability of 25% and 50%. The differences are significant and indicate the benefits that could be obtained with increasing degradation detection probabilities through tests.

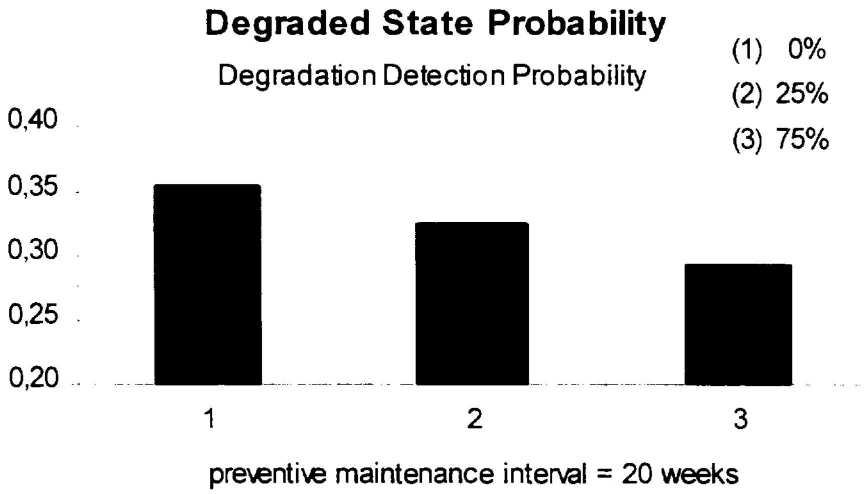

Fig. 20. Degraded state probability of the auxiliary feedwater pump (diesel) of plant I at a preventive maintenance interval of 20 weeks for (1) tests not capable of detecting any degraded state, (2) tests with a degradation detection probability of 25% and (3), tests with a degradation detection probability of 50%. The test interval is 4 weeks. The differences are significant, thus indicating the benefits that could be obtained with increasing degradation detection probabilities.

Comparing the pump availability for tests not capable of detecting any degraded state and for tests with a degradation detection probability of 25% and 50%. It can be seen in Fig. 21 that the differences between the availabilities are less significant than the differences between the degraded state probabilities in Fig. 20. As already mentioned, the increase in the pump availability is an indirect benefit obtained by the inclusion of degradation probabilities through tests, thus decreasing the probability of pump failure after being in a degraded state.

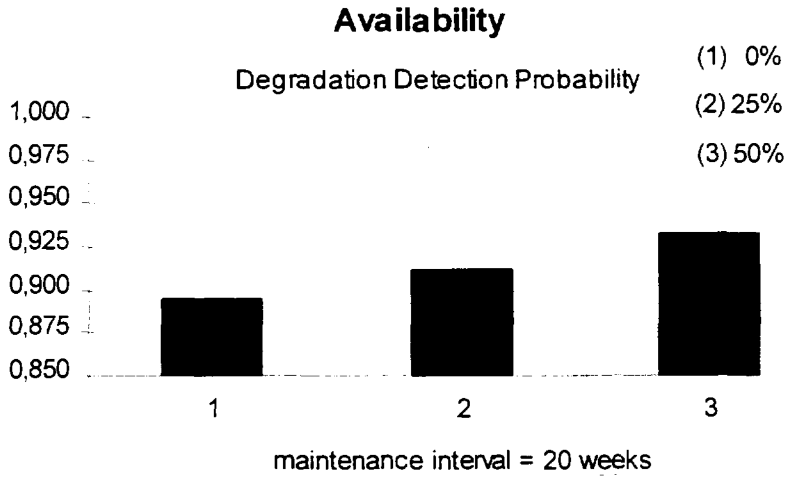

Fig. 21. Comparison of the availability of the auxiliary feedwater pump (diesel) of plant I at a preventive maintenance interval of 20 weeks for (1) tests not capable of detecting any degraded state, (2) tests with a degradation detection probability of 25% and (3), tests with a degradation detection probability of 50%. The test interval is 4 weeks. Compared to the differences between the degraded state probabilities in Fig. 20, the difference between the availabilities is smaller, caused by the assumption that the pump is still available in a degraded state.

Unscheduled Maintenance Activities

In this chapter we want to compare component reliability and availability performance for scheduled preventive maintenance activities and for unscheduled maintenance activities. The objective of this comparison is to show that a scheduled maintenance strategy yields to higher component reliability and availability than a randomly distributed performance of maintenance, comparing both maintenance approaches for the same average maintenance interval and the same maintenance duration.

For our unscheduled maintenance activities, the maintenance intervals are exponentially distributed. With p_m being the probability that a component will be maintained, and λ_m being the inverse of the average maintenance interval, we can write

$$p_m = e^{-\lambda_m \cdot t} .$$

Each maintenance interval is determined through a random number generator, with the average maintenance interval being the inverse of λ_m

$$\text{average maintenance interval} = \frac{1}{\lambda_m}.$$

The occurrence of maintenance is according to the theory of Markov processes. However, we assumed the maintenance duration to be constant and not being exponentially distributed.

In the following figures the 2 maintenance performance strategies are compared for the containment spray pump of plant I. In case (a) preventive maintenance is performed regularly, keeping the interval between preventive maintenance activities constant. In case (b) the maintenance intervals are exponentially distributed. It should be emphasized that for unscheduled maintenance activities both the average maintenance interval and the maintenance duration are the same as for a scheduled preventive maintenance performance.

To explicitly show the effect of unscheduled maintenance activities compared to scheduled preventive maintenance, a maintenance interval of 15 weeks is chosen in Fig. 22 to compare the operational state probability. For a scheduled maintenance strategy, the operational state probability is 8% higher than for unscheduled maintenance activities.

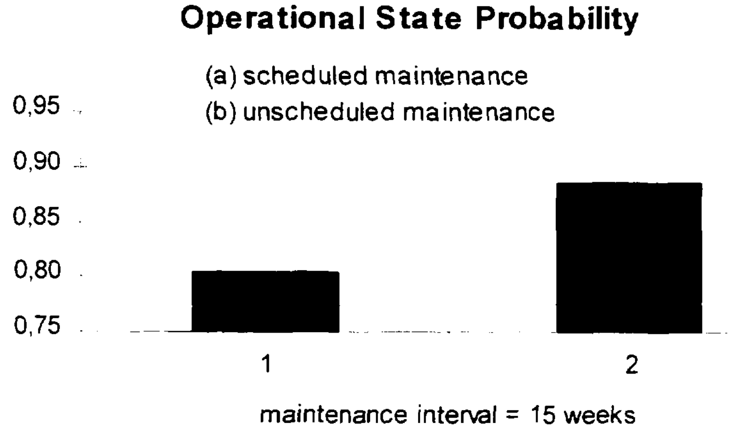

Fig. 22. Comparison of the operational state probability of the containment spray pump of plant I of scheduled and unscheduled maintenance performances at an maintenance interval of 15 weeks. In case (a) preventive maintenance is performed regularly, keeping the interval between preventive maintenance activities constant. In case (b) the maintenance intervals are exponentially distributed. In the case of regular preventive maintenance, the operational state probability is 8% higher, thus indicating the advantage of regular preventive maintenance over unscheduled maintenance activities.

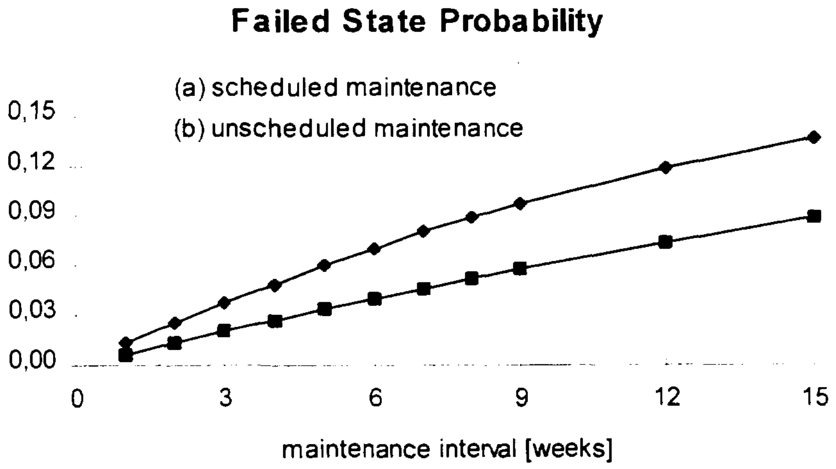

Fig. 23. Comparison of the failed state. The difference between the state probabilities for scheduled and unscheduled maintenance performance is significant.

Comparing the degraded state probability for scheduled and unscheduled maintenance performances, one can see in Fig. 24 the increasing difference between the state probabilities with increasing preventive maintenance interval. The degraded state becomes significantly lower in the case of scheduled maintenance activities and once again emphasizes the advantage of performing regular preventive maintenance.

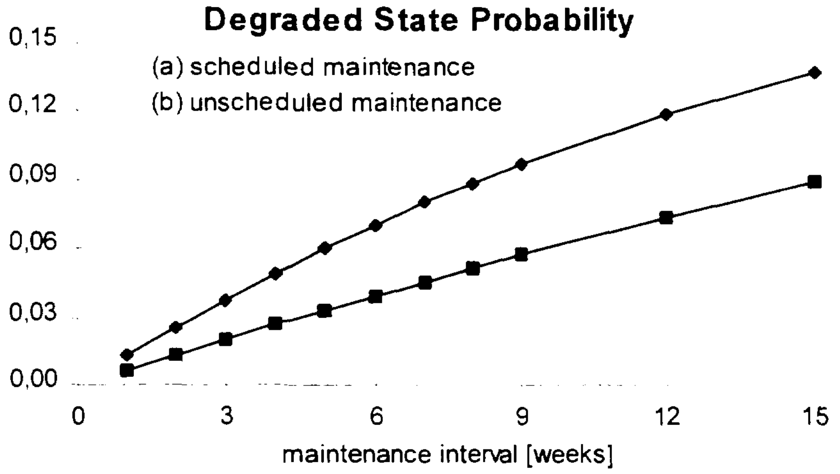

Fig. 24. Comparison of the degraded state probability of the containment spray pump of plant I for scheduled and unscheduled maintenance performance strategies. In case (a) preventive maintenance is performed regularly, keeping the interval between preventive maintenance activities constant. In case (b) the maintenance intervals are exponentially distributed. Comparing the degraded state probability, one can see that the difference between the state probabilities becomes significantly large with increasing maintenance interval.

CONCLUSIONS AND RECOMMENDATIONS

The results show that particularly in large-scale and complex technical facilities appropriate maintenance schedules contribute substantially to equipment and plant reliability, availability and safety. The studies focused primarily on the role of preventive maintenance activities in the optimization of both equipment reliability and availability performance, considering different preventive maintenance frequencies and durations.

An essential role in the optimization process of preventive maintenance is the information available from the databases. Data records should include, *inter alia*, failure frequency and mode, repair time, average repair time, maintenance frequency and duration, test interval and duration. Comprehensive data records are essential for establishing appropriate policies to improve plant performance.

Needless to mention that also economic considerations have to be included in any processes of maintenance optimization. In any maintenance policies, the cost of maintenance personnel, spare parts, repairs as well as maintainability on component and system level play a vital role. However, the recent past has shown that appropriate preventive maintenance has become a substantial contribution to plant reliability, availability and safety.