Trend analysis of input data to Nordic PSA

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Abstract: In Swedish and Finnish NPPs the ”T-book” is one common source for reliability parameters used in PSA. These parameters are calculated based on the assumption that component reliability does not change with time. This assumption is e.g. violated if components degrade, due to ageing effects, or improve, due to improvements in maintenance strategies. It is thus relevant to ask how PSA results may be affected by the time independence assumption. To approach an answer, a non parametric test method, the Wilcoxon rank sum test, was used to analyze how observations of malfunctions deviate from a Poisson-distributed set that represents the case when malfunctions are independent of each other and occur with a constant frequency. It was found that deviations from the Poisson distribution, trends, can be detected in the gathered data, and that corrections for reliability trends may affect the PSA results significantly.

Keywords: PSA, Reliability Parameters, Trend Analysis, Ageing

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1. INTRODUCTION

1.1 Background

Reliability data used to analyze the safety of Swedish and Finnish nuclear power plants, through PSA, is presented as reliability parameters for component groups. These reliability parameters, published in what is called the “T-book”, describe a frequency or probability of a specific failure mode for the component group. Reliability parameters are calculated from empiric information under the constraints of a set of assumptions and postulates. One postulate states “The reliability parameters are trendless“ - in other words, the true values of the components’ reliability parameters are unchanged with time. While physical components age and at some point become unusable, they are assumed to be replaced by new components or returned to ”mint” condition, resulting in a constant average failure frequency, or failure probability.

Parameters are estimated by analyzing observations of failure rates of components. For each parameter, as the number of observations increases, the probability distribution converges around a value close to the true reliability parameter value.

This study is an investigation of the validity of the postulate on absence of trends. In case this postulate is invalid for some or all of the T-book components, this may have an impact on the validity of the PSA results. If this postulate *is* valid, this opens a field for discussion on how to best analyze new component failure data. Given that the rate of convergence for the parameter estimates is slow, due to an already large pool of input data, one may consider changing focus to methods for early discovery of immerging trends due to e.g. changing ageing characteristics within the component group.

1.2 Reliability parameters in the T-book

The T-book updated regularly by the TUD-council (TUD-kansliet), which has a system of reporting failures that is connected to most of the Nordic NPPs. Every power plant is responsible for reporting its failures to the TUD-database. This process is described in the T-book [4].

The T-book presents components in groups of identical/similar components. For example one component group is “Centrifuge pump, MC-pump“ [4] (table 1.4.1). There exist a total of 66 components in this particular group, summed over all the covered nuclear power plants. The failures are assumed to be independent of each other, i.e. the components failure intensity is assumed to be unchanged through time. This leads to a Poisson-distribution of failures.

$$P(X = x|\lambda) = e^{-\lambda t} \frac{(\lambda t)^x}{x!} \quad (1)$$

Where $P(X = x|\lambda)$ is the probability of x events occurring given a rate parameter λ during the time t.

Further the T-book distinguishes between different component classes; stand-by and continuously running components. In the case of continuously running components the rate of failure is symbolized by λ_d [h^{-1}]. For stand-by components it is relevant to consider the time since the last activation as well as a probability of failure just after this activation. This is modeled with a so called "$q_0 + \lambda t$"-model. Here q_0 [use^{-1}] symbolizes the constant, i.e. time independent, base line probability of the component to fail on start and λ_s [h^{-1}] describes the increasing probability with respect to the time since the component was last tested. Each of the reliability parameters is presented individually.

Please note that failure modes attributed to stand-by components are in some cases presented as those for continuously running. An example of this case is failure mode "spurious stop" for a stand-by component, for this failure mode a measure of the number of uses is irrelevant as the component is in operation by definition. From here on out components defined as continuously running are components with failure modes characterized by one parameter, either λ_d or λ_s , because these types of components failures are dependent only on total running or stand-by time.

The reliability parameters are derived using a two-step Bayesian method [3]. In the first step the prior is updated using observations made for an entire component group, and in the second step plant-specific observations are accounted for. This method produces two "levels" of reliability parameters. Generic parameters adhere to a component group for all participating NPPs, while plant specific parameters describe the component group for each specific plant.

2. TREND ANALYSIS

As a first step in this study a method of data analysis was chosen. Four statistical test methods were compared en terms of efficiency and sensitivity on simulated random data. For an in-depths description of this analysis see [1]. It was found that the Wilcoxon Rank-Sum test (rank sum test) was best suited for the purposes of this study; this finding is in itself interesting. As stated in the discussion on appropriate test methods in [1]:

"During this stage a greater attention was paid to the choice of test methods rather than the input data. Probably the most interesting result was that the test method discussed in literature, the Z-test, was poor in comparison to the rank sum test. An explanation for this might be that the Z-test is in fact superior in efficiency when dealing with a single exact distribution but is sensitive to small variations in the input data and thus not compatible with the methodology of this thesis. This would give rise to an interesting question of exactly how sensitive this test method is, as a pure Poisson process is only the ideal case while real failure distributions surely deviate from it."

2.1 Strategy

In order to conclude whether PSA results need to be questioned, with respect to trend in reliability data, a detectable trend needs to be significant for the PSA results themselves. For reliability data where trends cannot be detected, this can e.g. be tested by postulating a barely detectable linear trend in reliability data and extrapolating reliability parameters in time to account for a change due to the time dependent trend. But in order to postulate a barely detectable trend in data that appears to be trendless one needs to find the magnitude of trends that can be detected.

To reach a conclusion on the validity of the postulate on absence of trends the study was divided into two consecutive steps. First the magnitude of theoretical trends that can be detected by the chosen test method was determined. Then actual data was tested for such trends.

2.2 Choice of studied components

Input data to the Rank-Sum test, the test method used in this project, must consist of two data sets. The test determines if the data sets originate from the same distribution. For the purpose of this study a data set, for example the observed distribution of failures, was compared to data sets simulated using a known rate parameter – containing a trend or trendless. If observed data compared to simulated trendless data yields a low probability of matching distributions, a trend is found in the observed data.

The data used in this study consisted of vectors containing 0’s and 1’s. Each position in the vector corresponded to a unit of time, 1 hour of operation for continuously running components or 1 use for stand-by components. Every non-zero element in a certain data set was interpreted as a failure – these were Poisson-distributed with a given rate parameter (λ in eq. 1). For distributions generated with an increasing rate parameter with time, in practice the rate parameter was increased for each entry in the data set.

In the study of actual component groups two stand-by and two continuously running components were chosen. Table 1 shows the chosen component groups and failure modes. The set of component groups were selected based on best available prior knowledge, and was verified - post analysis - to be a sufficient sample for the purpose of the study.

Table 1. Chosen component groups and failure modes.

Component group	Failure mode	Component type
Heat exchangers	Inadequate cooling capacity	Continuously running
Centrifuge pumps	Spurious stop	Continuously running
Diesel generators	Failure to start	Stand-by
Closing valves	Failure to maneuver	Stand-by

2.3 Detectability

To study the magnitude of hypothetical trends that can be detected by the rank sum test method, a set of distributions $\bar{X}_i$ were generated. These distributions represented each of the chosen components, matching the number of observations for each respective component with the length of the distribution. Further these distributions were generated using the constant reliability parameter given by the T-book.

A second set of distributions $\bar{Y}_{\alpha_i}$ were generated. These distributions also matched each component in number of observations but were generated using an increasing, trended, reliability parameter:

$$\lambda = \lambda_0 + \alpha\left(\frac{i}{I} - \frac{1}{2}\right) \qquad (2)$$

Where λ is the trended reliability parameter, λ_0 the trendless parameter, α the magnitude of the trend, i the position of the vector element and I the total length of the vector.

This specific trend model was chosen so that the trended parameter has a mean same mean value as the trendless parameter. The parameter α was increased until a trend could clearly be detected. “Clearly detected” in this case means that the p-value of the rank sum test is less than 0.05*.

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* The p-value is defined as the probability of observing the given data given that the null hypothesis is true. In this case translated into the probability of the two data sets originating from the same distribution.

Note that stand-by component groups are represented by two reliability parameters in the T-book. These two parameters were weighed into one, based on documented times between activations, as described in [1], chapter 3.2.

2.3.1 Results

Sets of simulations were made for each trend magnitude α. The results are presented in figures 1 and 2, as a mean p-value and variance for each tested magnitude. A summary of the results is presented in table 2.

Table 2. Summary of result of the detectability study.

Component group (failure mode)	Detectable trend magnitude
Heat exchangers (inadequate cooling capacity)	$1.9 \cdot 10^{-5}$ h^{-1}
Centrifuge pumps (spurious stop)	$3.5 \cdot 10^{-5}$ h^{-1}
Diesel generators (failure to start)	$3.9 \cdot 10^{-3}$ use^{-1}
Closing valves (failure to maneuver)	$5.9 \cdot 10^{-3}$ use^{-1}

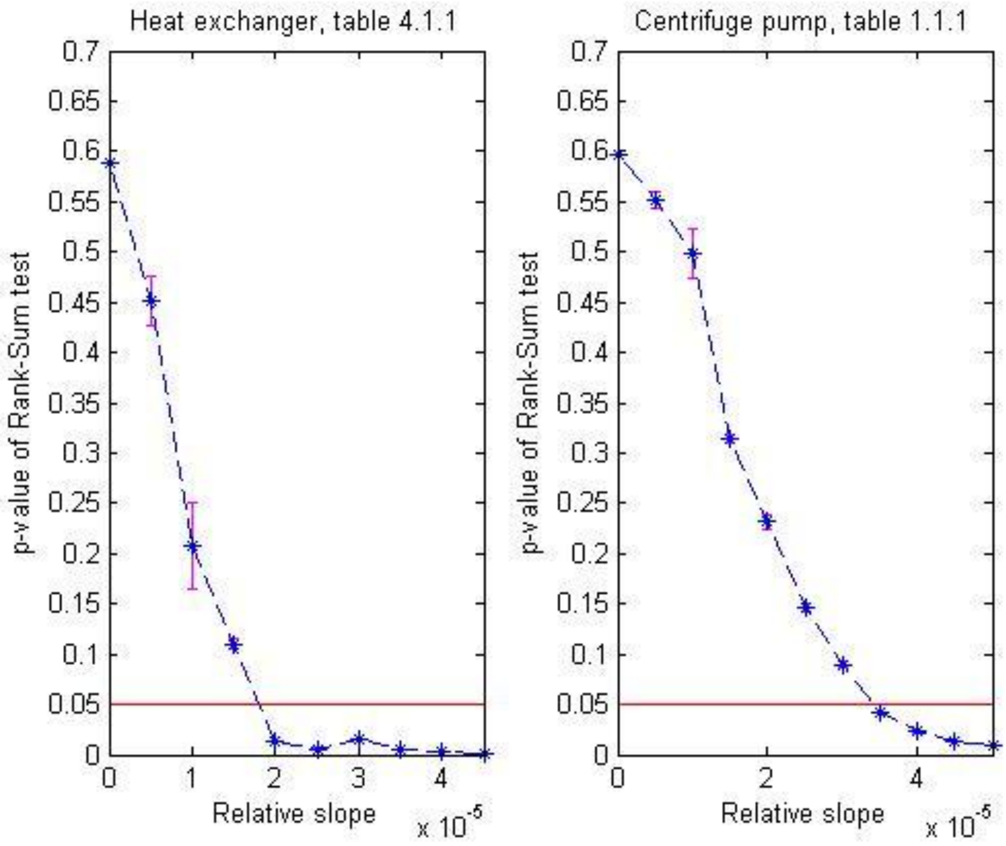

Figure 1: Simulations run on components presented in tables 1.1.1 (right) and 3.13.1 (left). Results are averaged from 10000 and 2000 simulations respectively. Bars indicate standard deviation 2σ.

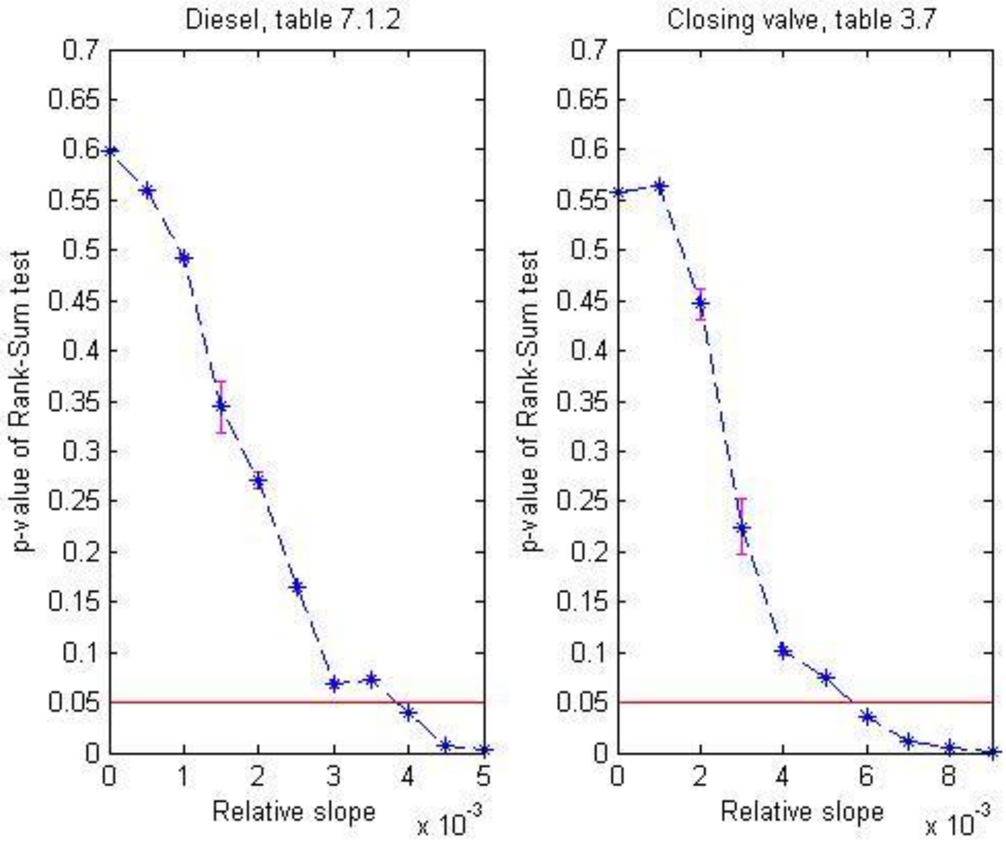

Figure 2: Simulations run on components presented in tables 3.7 (right) and 7.1.2 (left). Results are averaged from 30000 and 20000 simulations respectively. Bars indicate standard deviation 2σ.

2.4 Trend analysis

Because of the lack of actual distributions of the observed failures, the “real distributions” were approximated. This was done by placing the number of observed failures randomly in between the time interval when these failures were observed. Data on the number of observed failures at set time points was obtained from the different editions of the T-book [4], [5], [6] and [7].

When studying real distributions of failures the same approach was implemented as described in chapter 2.3. In this case the distributions $\bar{Y}_{\alpha_i}$ were exchanged to the actually observed distributions, and compared using the rank sum test to the randomly generated, trendless, distributions $\bar{X}_i$.

Using the same methodology as previously the approximation of the true time distributions were analysed. Input data to the rank sum test were: a distribution with the difference in number of observed failures between T-book version randomly distributed in the time intervals between the publishing's of T-books, and a distribution with the same total number of failures placed randomly in the total time interval. This procedure was performed several times to obtain an average p-value for each component versus the random distribution. Results of these calculations are presented in table 3. Pairs of sample distributions for each component group are shown in figures 3 and 4 to illustrate a possible difference in the distributions.

2.4.1 Results

Table 3: Summary of results of tests on actual data.

Component group	Average p-value	Trend suspicion
Centrifuge pump	0.6163	Trend highly unlikely
Closing valve	0.4965	Trend highly unlikely
Heat exchanger	ca. 0	Trend likely
Diesel generators	0.0128	Trend likely

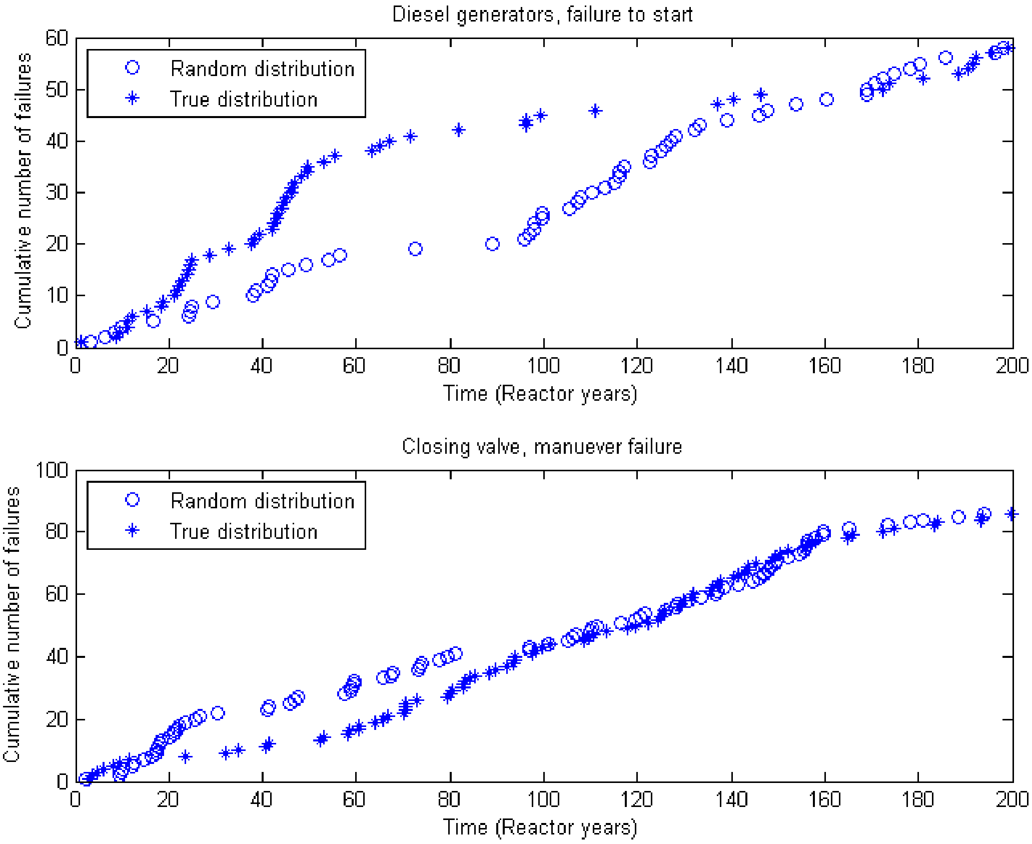

Figure 3: The approximations of the true and random distributions for the diesel generators and closing valve. The failures are presented cumulatively against time in reactor years.

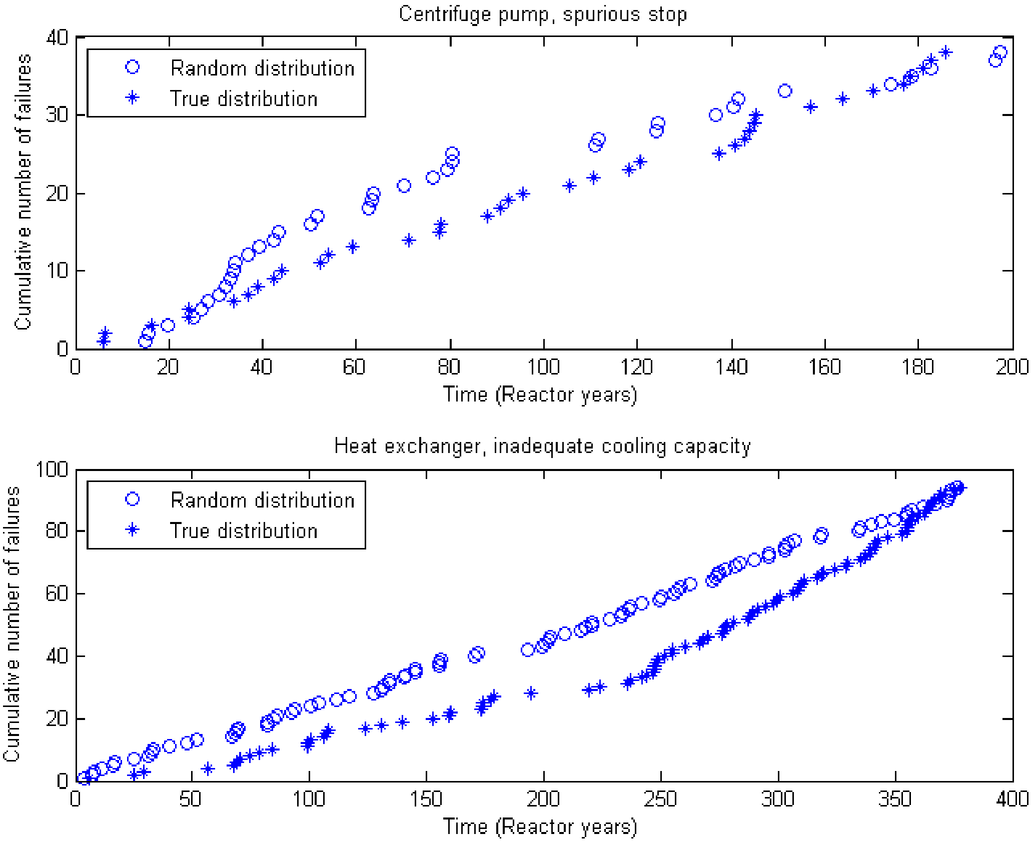

Figure 4: The approximations of the true and random distributions for the centrifuge pump and heat exchanger. The failures are presented cumulatively against time in reactor years.

As shown in Table 3 and Figures 3 and 4 trends were detected for diesel generators and heat exchangers. Further it is clear from the figures that one of each kind of trend, increasing and decreasing, can be observed by the test method. This result is interesting, as it implies that the analysis method is valid and can be used as a basis for the study of trends in reliability data.

2.5 Summary

This project proposes a methodology of screening observed component failures, in order to assess the validity of the postulate on absence of trends in reliability parameters based on these observed failures. The methodology is based on a statistical test method that determines whether two data sets are drawn from the same distribution. Assuming complete absence of trends in reliability data, component failures will ideally follow the Poisson-distribution. With a high number of observations, the average trendless parameter represents the rate parameter of a Poisson-distribution.

Thus, proving that a Poisson-distributed data set, generated with a certain rate parameter, is drawn from a different distribution than the observed failures attributed to the same reliability parameter, disproves trendlessness.

The rank sum test is in this paper shown to be able to detect trends in failure data.

3. DISCUSSION

3.1 Uncertainties

Some approximations were made in this project. Most of these originate in the fact that an exact time distribution of the observed failures is not available and approximate distributions were used. There is no way to estimate how precise these distribution are, therefore this is considered the largest source of uncertainty in the results. The way in which the time distribution was produced was however considered the best and only reasonable option given the available data.

For a more detailed discussion on this subject see [1].

3.2 Conclusion based on results

Even though many approximations were made, clear conclusions can be drawn from the results. It is apparent that trends can be observed in reliability data today. For the two component groups in which trends were detected the average p-values were 0.0128 (Diesel generators) and 0 (Heat exchangers).

P-value results should be interpreted as the probability of the two data sets being drawn from the same distribution. This means, as an example, that there is only a 1.28% probability that the observed failures of the diesel generators are Poisson-distributed, thus making the postulate on absence of trends invalid. The end user of this methodology is urged to decide before implementation the statistical limits on when the observed data is deemed to no longer be randomly distributed.

Applying the methodology proposed in this paper on all component groups presented in the T-book, or any other collection of operational experience, can show which components' or component groups' reliability parameters are subject to time dependency. Such knowledge may potentially have an impact on the PSA results for a nuclear power plant.

Figures 3 and 4 summarize the result visually. It is shown that trends can be both positive (increasing reliability) and negative (decreasing reliability), which is an unexpected result.. Based on the presented results the postulate on absence of trends can be rationalized, as two of the studied components show very good overlap with random distribution. Nevertheless the discovery of time dependent trends in some component in combination with a lack of trends in others validates the analysis method and motivated further study of reliability data.

The presence of positive trends opens the possibility of the postulate on absence of trends being conservative. This is possibly due to improved testing methods that lead to higher reliability of components. A new possible implication of the postulate is thus discovered, a possibility of over-conservatism that ads a new dimension to future studies.

Concluding this project, the trendlessness postulate may still be a sufficiently good approximation in general. However, it is also clear that there exist components for which the validity of this postulate may be questioned; this should be confirmed by a more detailed study. A preliminary investigation of the impact on PSA results - comparing nominal parameter values according to the T-book with values assuming barely detectable trends - points at the diesel generators as components where trends may have a significant impact. Based on this result, combined with a falsification of the trendlessness hypothesis in this case, it is reasonable to assume that PSA results need to be reevaluated. However, since the reliability of the diesel generators seem to be improving with time according to figure 3, the nominal PSA results are likely to be conservative. A more realistic reliability parameter estimate will in this case reduce the safety importance of the diesel generators, and reduce the overall core damage frequency for the PSA model.

The project recommends further study of time dependent trends, preferably in reverse order – starting with a parameter sensitivity study, followed by trend analysis of the identified parameters significant to PSA. If negative trends cannot be detected in reliability parameters most significant to PSA of a plant, the postulate on absence of trends is acceptable. The end user is also urged to account for positive trends, making an evaluation of the desired level of conservatism in future PSA.

3.3 Acknowledgements

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