SYSTEMATIC REPORTING AND TRENDING OF FINDINGS ON SSC: PREREQUISITE FOR ENHANCEMENT OF SAFETY PERFORMANCE IN NPPs

Duško Kančev [1, a], Jens-Uwe Klügel [1, b], Stefan Heussen [1, c], Thomas Kozlik [1, d]

[1] *NPP Goesgen-Daeniken AG, Kraftwerkstrasse CH-4658 Daeniken, Switzerland*
[a] dkancev@kkg.ch, [b] jkluegel@kkg.ch, [c] sheussen@kkg.ch, [d] tkozlik@kkg.ch

As a result of the effort to enhance safety in NPPs, incidents and accidents are progressively decreasing in number and significance. This means that in accordance with international reporting requirements the amount of collected data becomes less sufficient to draw meaningful statistical conclusions. This is where the collection and trend analysis of low level events, near misses and various defects/disturbances/findings on selected structures, systems & components can prove to be very useful. These trends can show which of the safety barriers are weak or are failing more frequently. This paper addresses the development of a concept for systematic evaluation and trend assessment of such trouble report events in NPP Goesgen-Daeniken. The trends are investigated on a general level, i.e. the development of the total number of all reported SSC deviations/findings in time, as well as on specific levels, i.e. the development of the number of reported deviations per category defined. The results of the trend investigation on general level implicate, in general, a constant rate of occurrence of the reported deviations in time, i.e. no increasing trend of reported SSCs deviations is to be detected. Additionally, all the reportable (to the authorities) and internal events of higher safety significance in the period 1998-2016 are also subjected to trend analysis. This too shows no increasing trend of these reportable and internal significant events occurrences.

I. INTRODUCTION

Systematic reporting, evaluation and trending of low level events (LLEs), near misses (NMs) and identified plant issues and findings on selected structures, systems & components (SSCs) will help to prevent major incidents because latent weaknesses can be timely identified and corrective actions undertaken to prevent recurrence. Systematic and risk-informed assessment of these findings with impact on the plant safety/availability based on plant-specific PSA models and trend assessment of such events should be performed.

A case study, based on a newly-developed concept, is performed at NPP Goesgen-Daeniken (KKG). A selected set of systematically reported defects and/or findings on various SSCs as well as human- and organizational-related events (*trouble reports* further in the text) is designated as data input for the case study. This set of selected data is first being categorized according to pre-defined categories. These categories are defined such that they correspond, in general, to the WANO coding scheme. Subsequently, the data are being subjected to statistical analysis. Due to the page number limitations of this paper, only two categories are studied: affected systems and relevant direct cause. The main focus of the analysis herein is the trend investigation, i.e. the possibility of existence of trends given the reported trouble reports is investigated. Since the systematic collection and analysis of the trouble reports is a relatively new process at KKG and began in January, 2016, this analysis encompasses the trouble reports in the period 01.01 - 30.5.2016. In addition to the statistical analysis for the trouble reports, the plant database comprising the reports of more safety significant events, i.e. the reportable (to the authorities) and internal events is also being subjected to trending analysis for the purpose of this paper. The timeframe relevant for these significant events was set since the beginning of the last periodic safety review (PSR), i.e. from 1998 to 2016. Visual inspection tests (Nelson-Aalen indicator), non-parametric (Mann-Kendall, Laplace tests) as well as parametric (Weibull) tests are performed.

II. METHODOLGY

The various LLEs, NMs and reports on SSCs defects and findings, which may reach several thousand per reactor operating year, need to be treated by the organizations as learning opportunities. A system for capturing these low level events and near misses truly needs to be an organization-wide system in which all levels of the organization, including contractors, participate[1]. In this direction, an effort was made at KKG to develop a concept for centralized collection, categorization and analysis of all these LLEs, NMs and reports on SSC defects and findings.

Firstly, the already existing input data information channels were identified. Then, potential new input data sources were additionally designated. Subsequently, a concept for long-term collection, categorization and analysis of all these LLEs, NMs and reports on SSC defects and findings was established. This is an ongoing-project at KKG.

For the purposes of this paper, a case study based on one of the envisaged input sources is presented. Namely, the so-called trouble reports system at KKG is already established and well-acknowledged system for reporting of various finding, defects, irregularities related to both the equipment-related as well as human- and organizational-related events. These trouble reports are being subjected to trending analysis. Additionally, events with higher safety significance - the reportable and internal events - are also being subjected to trending analysis for the purpose of this paper. Acknowledged and widely-applied methods and techniques for trend testing (Nelson-Aalen indicator, Laplace test, Mann-Kendall test) are used for the statistical analysis and potential trends diagnosis.

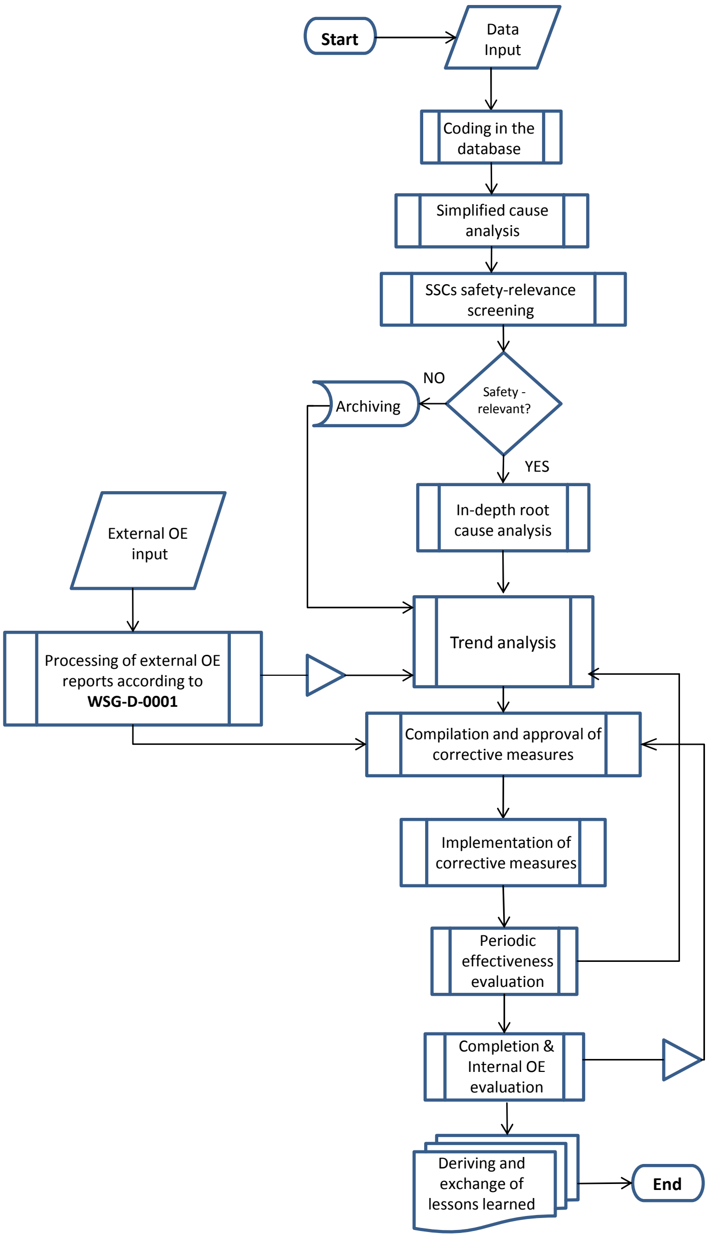

Fig. 1. Flowchart of the developed concept.

II.A. Process flow and concept description

Figure 1 presents the flowchart of the developed concept for systematic and centralized collection, categorization and analysis of the LLEs, NMs and reports on SSC defects and findings.

The process begins with the input from the relevant information sources. Various input data channels have been established as relevant for reporting the LLEs, NMs and various SSCs defects data sources at KKG, e.g.: Trouble reports; Operations log; Management in field; Periodic testing & reporting results; Ageing management program.

The reporting threshold is quite important as an initial step of the flowchart. Experience shows that the causes of significant events are usually the same as those of LLEs and NMs. Therefore, it is important that the identification and reporting threshold be established at an appropriate level of detail to identify any unwanted or undesirable situation, or any unintended occurrence (including NMs), which may be useful in preventing reoccurrences and improving plant and personnel safety, reliability and performance[2]. The reporting thresholds may include a full spectrum ranging from day to day plant defects, event reports and NMs through to accidents. The advantage of this type of arrangement is that all data can be contained within one database, allowing for extensive and consistent trend and pattern analysis. The LLE and NM process will include issues identified in any of the following key areas: plant systems and equipment, human and organisational factors (HOF). Each single person from the general personnel is encouraged to report an LLE and/or NM. In order to enable the recording of the data (LLEs, NMs and regularly monitored plant equipment/findings on SSCs) a new database/adaptation of the existing is to be set up by the department IT. Direct & root cause analysis for the collected reported events are to be conducted. This should include prioritization according to safety significance, i.e. not all reports will be subjected to root cause analysis. Subsequently, the department for safety will perform a filtering of the supplied reports based on the safety-relevance of the affected SSCs. Detailed, in-depth trend analysis is to be performed for the collected reports. Based on identification of non-favourable trends, suitable corrective measures to cope against these trends are to be defined. Appropriate corrective measures will be compiled accordingly. A periodic effectiveness monitoring of the implementation process of the delegated corrective measures is to be established. Both the results from the implementation of the corrective measures and the periodic effectiveness assessment of this implementation should be considered in the process of internal OE assessment. The main objectives of this internal OE assessment are: Avoidance of re-occurrence of observed failures; Detecting precursors that could lead to more severe accidents; Assessing whether the plant behaviour and equipment reliability are consistent with the design assumptions. This provides additionally actual equipment reliability data needed for PSA. As a result of the internal assessment, derivation of KKG-specific lessons learned (LL) is expected and encouraged. The impact of the external OE should also be accounted for.

II.B. Statistical data assessment and trend diagnosis

This subchapter briefly discusses the methodology applied for the statistical data examination for the case study presented within this paper. The trouble reports, as one of the credible input data discussed earlier in the description of the concept, are used as basis for this case study. The trouble reports are a set of reports, being done on daily basis and are related to reporting of various unavailabilities and irregularities of SSCs as well as HOF-related events. They are found as a comprehensive database that practically covers all ranges of possible failures and irregularities of plant systems and equipment as well as human performance. Thus, they were selected as a sample data input for the purpose of this case study.

A systematic collection, processing and categorisation of the trouble reports are being conducted at KKG since 01.01.2016. The trouble reports are being categorized according to the WANO coding scheme as well as according to the internal KKG nomenclature. Additionally, each of the trouble reports is being screened for nuclear safety relevance.

The aim of the case study within this paper is to examine the trend of occurrence of the trouble reports. Specific trouble reports categories as well as the total set of all the reported trouble reports in the period 01.01.2016 – 31.05.2016 are subjected to statistical non-parametric tests that are aimed at diagnosis of a possible trend (increasing or decreasing) of the occurrence rate of the trouble reports. Additionally, all the reportable (to the authorities) as well as internal events KKG data base are studied. A set of all these events from 01.01.1998 to June, 2016 is also subjected to statistical tests.

II.B.1. Nelson-Aalen Indicator

The Nelson-Aalen Indicator is a special form of the Kaplan-Meier Indicator with respect to testing the assumption of an exponential distribution with a constant failure rate. This indicator is an estimator for the cumulative hazard function dependent of time[3]:

$$H(t) = \sum_{\{i=1,n;t_i \le T\}} \frac{1}{n-i+1} \qquad (1)$$

where the index *i* corresponds to the number of the failure event, *T* is the total observation time, *ti* is the point in time since the observation start when the i^{th} event took place and *n* is the total number of observed failures. The graph of this function should be a straight line and run through the origin of the coordinate system to prove the assumption of an exponential distribution with a constant failure rate as a valid model.

II.B.2. Laplace Test

The Laplace test, also known as the centroid test, is a measure that compares the centroid of observed arrival times with the mid-point of the period of observation. It is a simple and powerful test for distinguishing between a constant rate at which events are occurring and an increasing rate of occurrence of such event[4]. The Laplace test statistic is defined as:

$$U_L = \frac{\frac{1}{m}\sum_{i=1}^{m} T_i - \frac{t_f}{2}}{t_f \cdot \sqrt{\frac{1}{12 \cdot m}}} \qquad (2)$$

Under constant rate of event occurrence, the arrival times to fault will occur randomly around the midpoint of the length, *tf/2*. Therefore, the sample mean of the Ti's will be approximately equal to *tf/2*; hence the test statistic U_L will be small. If events are occurring more frequently towards the end of the interval, however, the sample mean will be large. If U_L is larger than the z-value of the standard normal distribution, $Z_{\alpha/2}$, there is evidence at a significant level α that the event occurrence indicates the trend of increasing possibility of imminent fault. The z-value for 95% confidence level (α=0.05) is 1.96. In other words, test statistic U_L greater than zero means that there is an upward or increasing trend, and a test statistic U_L less than zero means there is downward or decreasing trend. When the test statistic U_L is greater than (less than) +1.96 (-1.96), we are at least 95% confident that there is a significant trend upward (downward). A test statistic U_L of zero means the trend is a horizontal line.

II.B.3. Mann-Kendal Test

The purpose of the Mann-Kendall (MK) test[5, 6] is to statistically assess if there is a monotonic upward or downward trend of the variable of interest over time. A monotonic upward (downward) trend means that the variable consistently increases (decreases) through time, but the trend may or may not be linear. The MK test can be used in place of a parametric linear regression analysis, which can be used to test if the slope of the estimated linear regression line is different from zero.

The MK test tests whether to reject the null hypothesis (H_0) and accept the alternative hypothesis (*Ha*) where: H_0 – No monotonic trend; *Ha* - Monotonic trend is present.
The initial assumption of the MK test is that the H_0 is true and that the data must be convincing beyond a reasonable doubt before H_0 is rejected and *Ha* is accepted.

The procedure of the MK test is as follows:

1. List the data in the order in which they were collected over time, $x_1, x_2, \ldots, x_n$, which stand for the measurements obtained at times 1, 2, …, *n*.
2. Let $\mathrm{sgn}(x_j - x_k)$ be an indicator function that takes on the values 1, 0, or -1 according to the sign of $x_j - x_k$, i.e. :

$$\mathrm{sgn}\left(x_j - x_k\right) = \begin{cases} 1, if\left(x_j - x_k\right) > 0 \\ 0, if\left(x_j - x_k\right) = 0 \\ -1, if\left(x_j - x_k\right) < 0 \end{cases}, \quad \text{then compute parameter S:} \quad S = \sum_{k-1}^{n-1} \sum_{j-k+1}^{n} \mathrm{sgn}\left(x_j - x_k\right) \qquad (3)$$

3. For n > 10, compute the variance of S, VAR(S), is as follows:

$$VAR(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p-1}^{g} t_p (t_p - 1)(2t_p + 5) \right] \text{, then the test statistic } Z_{MK} = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}}, if\ S>0 \\ 0, if\ S=0 \\ \frac{S+1}{\sqrt{VAR(S)}}, if\ S<0 \end{cases} \quad (4)$$

where *g* is the number of the tied groups and *tp* is the number of observations in the p^{th} group; A positive (negative) value of Z_{MK} indicates that the data tend to increase (decrease) with time.

4. To test the H_0 (no trend) versus *Ha* (increasing or decreasing monotonic trend), at an error rate α (or, at a significance level α), H_0 is rejected and *Ha* is accepted if $| Z_{MK} | \geq Z_{1-\alpha}$, where $Z_{1-\alpha}$ is the Z-value of the 100 (1- α)th percentile of the standard normal distribution.

III. ANALYSIS AND RESULTS

The trouble reports are being categorized according to the WANO Coding Scheme. Two of these groups: the affected systems and the direct cause are being investigated herein. Also, all the trouble reports reported within the observation period 01.01.2016 – 31.05.2016 are subjected to a Mann-Kendall test in order to investigate a possible trend in the occurrence of the trouble reports at KKG, in general. Additionally, all the reportable (to the authorities) as well as internal events at KKG in the period from 01.01.1998 to June, 2016 are also subjected to statistical analysis.

III.A. Statistical analysis of the trouble reports

There are 673 trouble reports reported in the period 01.01.2016–31.05.2016. They are subjected to the Mann-Kendall test.

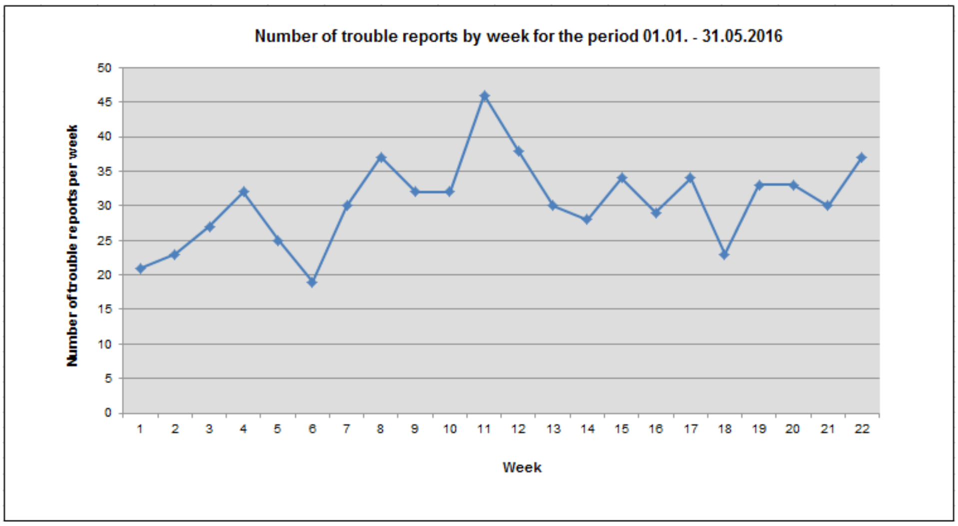

Fig. 2. Chronology of the trouble reports in the period 01.01.2016 – 31.05.2016.

After conducting the Mann-Kendall test, the following values are obtained: S = 69 => VAR (S) = 1257.67 => Z_{MK} = 1.92 which smaller than Z-value for normal distribution, i.e. $| Z_{MK} | < Z_{95\%} = 1.96$. Consequently, we can conclude that, on a 95% confidence level the H_0 hypothesis (no trend) cannot be rejected.

Two of the WANO categories groups for these trouble reports are also studied. As Figure 3 shows, the most affected systems in the period Jan. – May, 2016, were the electrical systems (22%); the feedwater, steam, condensate and power conversion systems (21.6%) and the service auxiliary systems (18.7%). Given the direct cause statistics, the biggest part of the 673 trouble reports was related to mechanical deficiencies (51.6%). The I&C (20.6%) and electrical (17.5%) deficiencies follow. The HOF-related trouble reports constitute only 3.2% of all the 673 trouble reports.

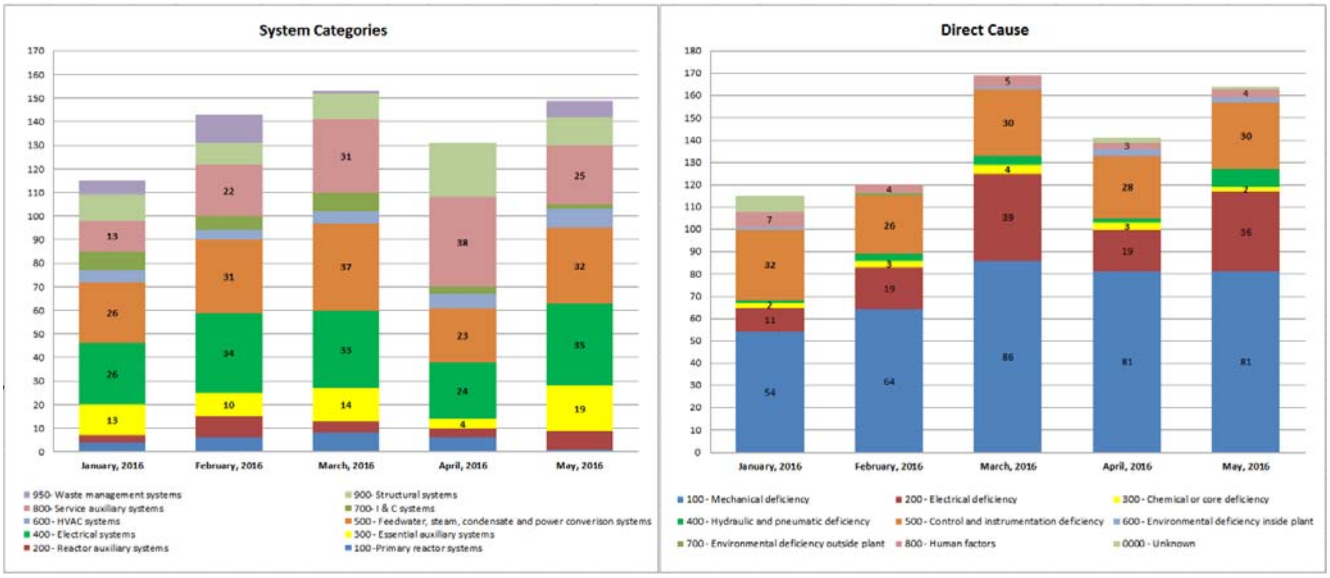

Fig. 3. Affected systems (left) and direct cause category (right).

III.B. Statistical analysis of the reportable and internal events

Next, the occurrence of all the reportable (to the authorities) as well as internal events at KKG in the period from 01.01.1998 to June, 2016 is also subjected to statistical analysis. Firstly, they are inspected by the Nelson-Aalen indicator (Figure 4). A comparative analysis is conducted between the data for the last PSR (1.1.1998 – 31.12.2007; 119 events) and the total number of events from 1.1.1998 to 30.06.2016 (272 events).

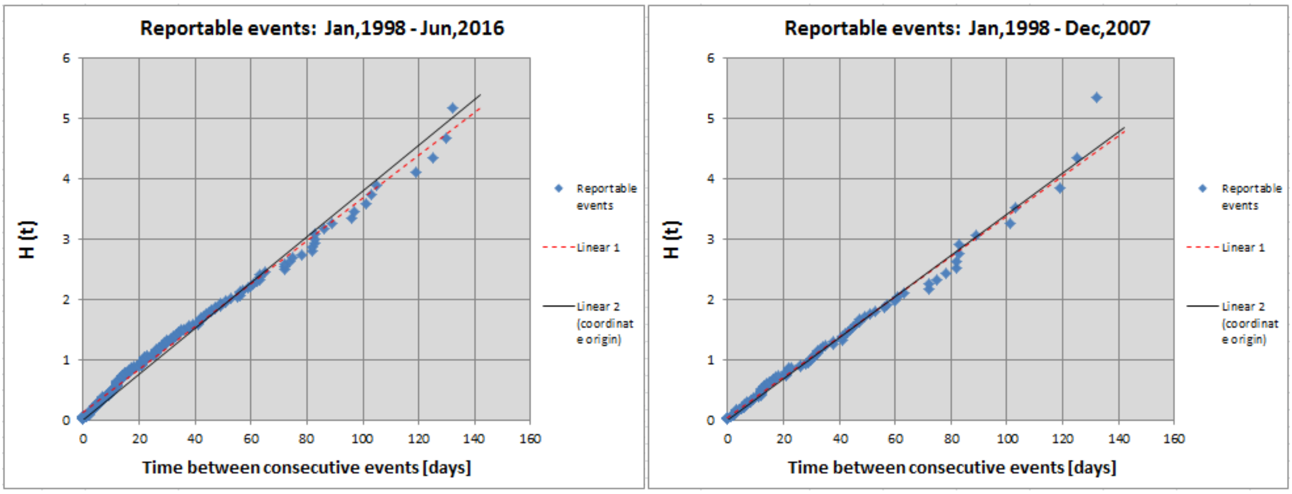

Fig. 4. Nelson –Aalen indicator visual test for all the reportable and internal events.

The evaluation by the Aalen-Nelson indicator is used to verify whether the chronological sequence of the occurrence of events (precursor events to a failure) can be defined by an exponential distribution with a constant rate of occurrence. This is the case when the dependency of the indicator from the time between two consecutive occurrences can be represented by a line extending through the coordinate origin. In that direction, by comparing the Nelson-Aalen test results presented on Figure 4, one can see a slight, negligible deviation of the trend line of the indicator (Linear 1) vis-à-vis the trend line that is constrained to extend through the coordinate origin. This implicates the fact that, although some very slight, increasing trend can be theoretically derived, it is practically and statistically insignificant. This fact is additionally confirmed and verified with the Laplace test. Namely, the Laplace is run for both the data sets discussed above. The Laplace test statistic for the events: 1.1.1998 to 30.06.2016 is $U_{L1} = 0.0121$, and for the events: 1.1.1998 to 31.12.2007 is $U_{L2} = 0.0009$. This implicates the fact that, at a 95% confidence level a constant occurrence rate (no trend) cannot be rejected for both the cases. The results of the Laplace test also implicate that if the two cases are to be compared to each other, then a slight worsening (i.e. relative increase of the occurrence rate) can be derived for the "second half" of the whole period (1.1.1998 to 30.06.2016) when compared to the "first half" (1998-2007).

In addition to the graphical visualization (Nelson-Aalen Indicator) and non-parametric tests (Laplace test), also a parametric testing is conducted. The parametric test is conducted with the specialized for reliability and life data analysis computer program WEIBULL ++ 7®[7]. Again, the focus is on the reportable and internal events that occurred at KKG during the years. The reportable events in the period: 1.1.1998 to 30.06.2016 are analysed. The results of the life data analysis to determine the average time period between two consecutive precursor events led to the conclusion that the model of the exponential constant occurrence rate of events best describes the present data. Figure 5 shows the cumulative probability distribution, including the two-tailed 95% confidence range.

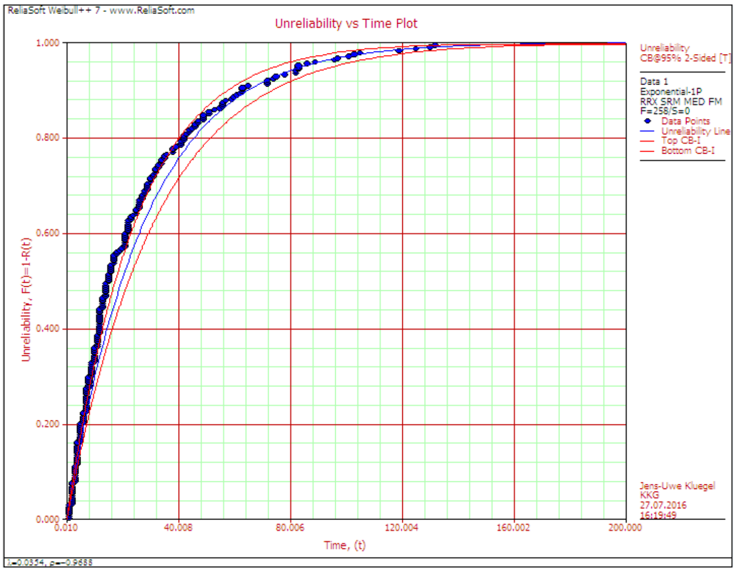

Fig. 5. Cumulative probability distribution for the times of two consecutive event occurrences (1998 - 2016).

Even with the naked eye (Figure 5) can be seen that this model describes the available data very well. This confirms the findings of the non-parametric tests. The two-sided confidence interval for the mean time period between two precursor events (MTBE, **M**ean **T**ime **B**etween Events) was determined as follows: $MTBE = (UB, Mean, LB) = (31.9, 28.2, 25.0)$. It means that, in average, one precursor per month has occurred. The life data analysis has been supplemented by a study using the power law model. The power law model is related to a non-homogeneous Poisson process (NHPP), which is non-stationary. The time to the first failure for a Power Law process has a Weibull distribution. For this reason, the Power Law model is sometimes called a Weibull Process. In case of power law model, the events occurrence rate ρ is given in the following form: $\rho(t) = \frac{\beta}{\eta^{\beta}} t^{\beta-1}$, where β is the shape parameter, and η is the scaling parameter of the two-parameter Weibull distribution, which describes the time to the first occurrence. In case of $\beta = 1$ the occurrence rate is constant, $\beta < 1$ the occurrence rate declines, and in case of $\beta > 1$ the rate of occurrence of the events increases, something that would be an indicator for an increased variability in the occurrence of the precursor events, which in turn would implicate a deteriorating safety performance at the plant. As it can be seen from Figure 6, it is obvious that the cumulative number of the reportable occurrences follows a straight line. The shape parameter takes the value of 0.9652, which is almost ideal case of constant occurrence rate of precursor events in KKG for the period: 1998 – 2016, i.e. the value of 0.9652 is quite close to $\beta = 1$.

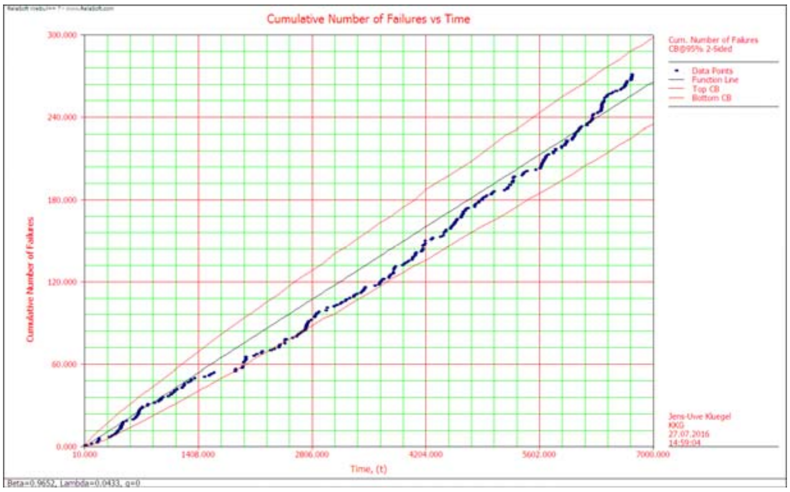

Fig. 6. Cumulative number of the reportable occurrences – power law model (Weibull process) 1998 – 2016.

IV. CONCLUSIONS

The research in this paper is related to the development of a concept for systematic evaluation and trend assessment of LLEs, NMs and identified plant issues and findings on various SSCs in NPP Goesgen-Daeniken.

The flowchart of the developed concept for systematic and centralized collection, categorization and analysis of these LLEs, NMs and reports on SSC defects and findings is presented and the separate steps discussed. Then, a case study is being conducted based on one of the data input channels of the developed concept, i.e. the trouble reports - systematically reported defects and/or findings on various SSCs as well as HOF-related events. All the trouble reports in since the application of the new concept (Jan-May, 2016) were subjected to trend analysis. The results of the Mann-Kendall test implicate that the null hypothesis of no trend cannot be excluded. Subsequently, two groups of the categorized trouble reports – the affected systems and the direct cause categories – were studied. The results indicate that the most affected systems in the period Jan. – May, 2016, were the electrical systems (22%); the feedwater, steam, condensate and power conversion systems (21.6%) and the service auxiliary systems (18.7%). Given the direct cause statistics, the biggest part of the 673 trouble reports was related to mechanical deficiencies (51.6%). The HOF-related trouble reports constitute only 3.2% of all the 673 trouble reports.

In addition to the statistical analysis for the trouble reports, the plant database comprising the reports of more safety significant events, i.e. the reportable (to the authorities) and internal events was also subjected to trending analysis for the purpose of this paper. Namely, the occurrence of all the reportable as well as internal events at KKG in the period from 01.01.1998 to June, 2016 is also subjected to statistical analysis. They were subjects to graphical visualization tests (Nelson-Aalen Indicator), non-parametric (Laplace test) as well as parametric (Weibull) tests. The results of all tests, in general, suggest that a constant rate of occurrence (no trend) of these reportable and internal events cannot be rejected.

ACKNOWLEDGMENTS

The Goesgen Nuclear Power Plant supported this research.

REFERENCES

1. IAEA, *Trending of low level events and near misses to enhance safety performance in nuclear power plants,* IAEA-TECDOC-1477, Vienna, (2005).
2. IAEA, *Low Level Events and Near Miss Process for NPPs: Best Practices*, IAEA-Safety Report Series No.73, Vienna, (2012).
3. J-U. KLUEGEL, "Investigation of time-dependent trends in failure data of active components," *Proc. Title*, Knoxville, Tennessee, 7-11 September 2008, ISBN: 978-1-61567-008-6, PSA (2008).
4. C. J. KIM, "Identification of Symptom Parameters For Failure Anticipation By Timed-Event Trend Analysis," *IEEE Power Engineering Review*, **20**, 9, pp. 48-50 (2000).
5. H. B. MANN, „Non-parametric tests against trend," *Econometrica,* 13:163-171 (1945).
6. M. G. KENDALL, *Rank Correlation Methods,* 4th edition, Charles Griffin, London, (1975).
7. Life Data Analysis Reference, WEIBULL++7®, ReliaSoft Publishing, Tucson, AZ, USA, (2007).