A vgbe & DNV project

Reliability Indicators with KISSY new data 2009 to 2020

Utilities

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SUMMARY

Failures of a power plant can be costly and efforts should be directed to prevent such failures. Methods using Reliability Analysis Maintainability (RAM) tools are well known to answer questions on target values for Reliability and Availability of a plant, capacity expansion planning, optimum redundancy, maintenance optimisation, spare parts etc.. However, such RAM tools need high quality reliability data. These data are scarce for power plant components.

In the report reliability data such as a failure rate (1 / Mean Time Between Failures, 1 / MTBF) and an average repair time (the time equipment is unavailable) are derived from raw events in the vgbe KISSY database using data over the period 2009 – 2020 on KKS breakdown level. The report follows the VGB 361 R&D project with data over the period 2002 – 2011 using almost identical methods and standardised reports. However, automatically outliers are indicated now and trends are calculated without such outliers.

In Annex A some applications are given using RAM data. Overall results for the vgbe KISSY data in this report are given in Annex B – D, while Annex F – H contains standard reports and plots for the plant categories CCGT and coal / lignite fired plants. Example calculations are given using the data for a CCGT plant.

1 INTRODUCTION

There is a use for high quality reliability data for power plants. These data can be used to optimise plant configurations, for benchmarking, maintenance optimisation, etc.. Such reliability data are preferably given as a failure rate (1 / Mean Time Between Failures, 1 / MTBF) and an average repair time (Mean Time to Repair MTTR, the time equipment is unavailable). The required level of detail is dependent on the use of the data: A high level of detail (subsystem level or deeper) is required for spare parts analysis or maintenance optimisation and a lower level of detail (system or subsystem level) for the systems design of new plants.

However, these data are scarce for power plants. In 2013 DNV KEMA (now DNV) carried out the VGB research project 361 [1] (now vgbe) in which failure rates and average repair times were derived from the vgbe KISSY database using data over the period 2002 – 2011 on subsystem level. The present report contains data derived from KISSY over the period 2009 – 2020 using almost identical methods and standardised reports. Compared to 361, the standardised reports now automatically indicate outliers using methods from [2] and as a result trends are calculated without such outliers.

Similar sources for other industries and applications can be found in alternative databases / reports. For instance, detailed data from the oil and gas industry are reported in OREDA, the latest Handbook with failure rates etc. from 2015 (also digital). Data from the nuclear power industry are present e.g. in the EIREDA report (extensive work of Henri Procaccia et all from EdF), the T-Book (Swedish nuclear plants) and in the ZEDB handbook (Zentrale Zuverlässigkeits- und Ereignisdatenbank, Reliability Data for Nuclear Power Plant Components, German nuclear plants). However these handbooks do not contain typical conventional power plant components such as large gas turbines, steam turbines, generators, evaporators, superheaters, coal mills, flue gas ventilators etc.. EPRI has its data base (called EPRI PM = Preventive Maintenance) in which data from expert judgement are reported. NERC GADS has its database and software to derive failure rates and repair times called pc-GAR going back to 1982. Requests for pc-GAR versions from organizations outside the United States are evaluated and approved on a case-by-case basis. Alstom has been known to operate a database with data from Alstom plants. Both the EPRI and Alstom data are not easily available. In the interest of the power industry therefore DNV and vgbe decided to publish the present report. The TG Performance indicators group has allowed the use of the data for the project. As per the Inception Report [3], the project is carried out with guidance from the vgbe Working Group “Application”.

The KKS designations (Function Keys) used in this project have been described in an understandable but abbreviated form, as the original designations are too long for the graphs or Excel cells and cannot be displayed. The original designations are described in Reference VGB-S-811-01-2018-01-EN, Key Part.

The report, in addition to the information in the VGB Research Project 361, with the aforementioned reliability data, is intended to be of use for companies working with power plants (new and existing). In Annex A some applications are given using reliability data from vgbe as well as from some power plants derived in DNV projects. The new report has the same structure as the VGB 361 report, explaining the data and the methods to derive failure rates, etc.. It is extended with a description on how to derive outliers. We have given an example calculation for a CCGT plant.

2 LIMITATIONS USING KISSY DATA

The vgbe KISSY database contains the raw material for deriving failure rates and repair times. In KISSY engineers and operators working at power plants and other personnel at utilities record the unavailability of power plants and the components that cause it. Power plant information in KISSY is made anonymous when handing over to third parties. The systems, sub-systems and components are indicated with the Kraftwerk-Kennzeichensystem (KKS[1]), mainly on 3 letter coding pinpointing to subsystems. One can derive the following failure data from KISSY:

- Subsystem data for evaporators, superheaters, etc. since such failures often cause full plant outages. Still, one has to know how many boilers (a so-called duo block has 2 boilers and 1 steam turbine) are present to calculate the failure rate of a boiler, superheater, etc.. Similar for gas turbines, generators, step-up transformers, etc..

  Data for flue gas fans can be derived since failures of such components cause both partial outages and full outages of the plant and again one must know how many fans are present. For the VGB Research Project 361 [1] both an enquiry for the plant configuration was sent out to the engineers inputting data in KISSY as well as checking the raw text and amount of loss when failed. For the present analysis, only the raw text and partial outages versus full outages was checked. As there are both partial failures and full plant outage failures in the database, it is easy to derive so-called common cause coefficients that show the fraction where both (or more) components fail at the same time.

- Component failure data for fully redundant feed water pumps etc. cannot generally be derived from KISSY unless they cause full outages due to so-called common cause failures. However, turbine driven feed water pumps normally are accompanied by smaller electromotor driven pumps. When such a turbine driven pump fails, it causes a partial outage. Therefore, by assessing the partial outages of plants that are sure to have a turbine driven feed water pump, the failure rate and repair time of that pump can be derived.

It should be noted that these reliability data are not found in the annual KISSY reports since for instance the number of ventilators is not taken into account in these reports. The standard KISSY reports do show which systems and components are dominant, either on the number of failures per year and per block basis on a forced unavailability basis. Therefore, low failure rates are not reported, while some systems may have HILP (High Impact Low Probability) failures with an important contribution to plant unavailability.

[1] The KKS codes in this report mentioned are informal translations. Reference is made to the appropriate handbooks as found on the vgbe website (KKS Identification System for Power Stations (ISBN 978-3-96284-271-0; 978-3-96284-270-3; 978-3-96284-269-7; 978-3-96284-268-0)

3 METHOD TO ARRIVE AT RELIABILITY DATA

The plant characteristics are shown in Figure 3-1, whereas the raw KISSY failure information in Excel is shown in Figure 3-2 (next page). Plants have been made anonymous and the plant size has been grouped by vgbe head office to make plants anonymous. Columns in light-green in Figure 3-1 were calculated by DNV, the other columns contain the basic information from vgbe.

Power Plant Unit	Type of Power Plan	First Fail	Last fail	Years in database	Fuel	Average Starts / yr	Capacity net [MW]	Age max in database	Average Operating Hours	Years in database as ResKV
1	Mono fossil fired unit	2009	2019	5	Hard Coal	42.7	400 - 599 MW	35	2821	1
2	CCGT	2009	2019	11	Hard Coal	36.7	200 - 399 MW	23	5212	0
3	gas turbine jet	2014	2020	7	Oil	22.0	until 99 MW	47	32	0
4	Mono fossil fired unit	2009	2013	5	Hard Coal	19.0	600 - 999 MW	35	6366	0
5	Mono fossil fired unit	2009	2013	5	Hard Coal	1.0	600 - 999 MW	28	8067	0
6	Mono fossil fired unit	2009	2012	2	Hard Coal	18.8	until 99 MW	53	3442	0
7	Mono fossil fired unit	2009	2018	10	Hard Coal	41.0	600 - 999 MW	39	4376	0
8	Mono fossil fired unit	2009	2009	1	Hard Coal	0.0	600 - 999 MW	33	3781	0
9	Duo fossil fired unit	2009	2020	11	Lignite	7.0	400 - 599 MW	42	7767	0
10	Duo fossil fired unit	2009	2020	12	Lignite	5.6	400 - 599 MW	40	7953	0
11	Mono fossil fired unit	2009	2020	12	Lignite	10.2	600 - 999 MW	20	7811	0
12	Mono fossil fired unit	2013	2020	8	Lignite	16.1	600 - 999 MW	9	6935	0
13	Mono fossil fired unit	2009	2013	5	Hard Coal	24.3	600 - 999 MW	30	6786	0
14	Mono fossil fired unit	2009	2011	3	Hard Coal	13.8	600 - 999 MW	29	6900	0
15	Mono fossil fired unit	2014	2014	1	Hard Coal	15.2	600 - 999 MW	30	7187	0
16	Mono fossil fired unit	2009	2014	5	Hard Coal	17.0	600 - 999 MW	28	7103	0
17	Mono fossil fired unit	2009	2013	5	Lignite	0.0	200 - 399 MW	34	5744	0
18	Mono fossil fired unit	2009	2012	4	Gas	36.0	600 - 999 MW	43	2181	0

Figure 3-1 Anonymous plant information derived from vgbe KISSY

Figure 3-1 shows the type of plant, fuel, over how many years it has been present in the period analysed (2009-2020), the age of the plant at end of the dataset and the average operating hours per year. Starts per year are given as well, but they have not always been reported as this was mandatory only for gas turbines. However, in recent years all plants have provided their annual starts. In the last column (years in database as ResKV), it is shown whether the plant is operated as a reserve plant to strengthen the grid on request of the regulator (so called ResKV plant). As such plants do not operate much and they are not in the electricity market, their behaviour might be very different from plants that are active on the electricity market. In Excel a filter was built to either take all data, data without ResKV years or ResKV only years in account. The failure data overviews per KKS code in Annex B to C were calculated without ResKV years.

4 SELECTION OF PLANTS

As per the Inception Report [3], in the spreadsheet the following plant types, fuels and plant sizes can be selected:

- Conventional plants for 4 fuel types (hard coal, lignite, oil and gas fired).
- Combined cycles (called Kombi in Germany) and CCGT plants. These are plants equipped with gas turbines. Most CCGT plants have heat recovery, non-fired, boilers.
- Mono plants versus Duo plants (several boilers to 1 steam turbine)
- Plant size in the same classes as per the VGB 361 R&D project
- ResKV (grid reserve) plants included, not included or selected.

In the VGB 361 R&D project, a differentiation was made into modern (< 10 years old), midlife (10 – 25 years old) and aged ((>25 years old) plants. In line with the Inception Report [3], this difference is skipped as ageing effects can be directly read from the standard plots. Furthermore, a plant that might be midlife in VGB 361 could now be aged. As the failure characteristics per plant may differ substantially, this influences the results per class.

Examples of standard layouts are shown in Figure 4-1 and Annex E. It is recommended to use such layouts for benchmarking purposes as for instance benchmarking for the number of times a plant is fully out of operation not taking into account a single shaft configuration with 1 GT + ST + generator versus a multi shaft configuration with for instance 2 GTs, 1 ST, 3 generators make no sense. The single shaft configuration will have a full outage more often due to its layout.

5 SELECTION OF KKS CODES

As per the Inception Report [3], only KKS codes that are dominant with regard to forced unavailability are analysed, in line with Pareto's 80-20 rule It makes little sense to analyse a code with only a few failures since statistically the average number of failures per hour and the average repair time is very inaccurate[2]. We have calculated Pareto's for CCGTs, for coal fired plants and for lignite fired plants. Compared to the thousands of failures present in these Pareto's, a Pareto for ResKV coal plants (70 failures) and ResKV CCGTs (35 failures) will be sensitive to chance and therefore is not reported.

For the Pareto of CCGTs in Figure 5-1 & 5-2. the dominance of GT failures with MB = gas turbine is shown causing 20 % of the energy related to outages, followed by other rotating equipment items. Interestingly, HAD = evaporator is only at place 9, therefore HAD for heat recovery boilers is clearly less dominant compared to conventional fossil fired boilers.

For the Pareto of hard coal plants in Figure 5-3 & 5-4 the HAD = evaporator, HAH = superheaters and HAJ = reheaters are dominant components which have been in Pareto's for decades. Interestingly however also present is MKA = generator stator & rotor (place no. 3) as well as LAC = feed water pumps (place no. 4). For the Pareto of lignite plants in Figure 5-5 & 5-6, similar to hard coal plants, HAD = evaporator, HAH = superheaters and HAJ = reheaters are the dominant components.

For each KKS code that is dominant in the Pareto analysis, standard reports were made as per Annex F to H together with some additional standard reports for components that allow to compare for instance GT bearings with ST and generator bearings, etc..

As some power plants systematically code at 2 letters KKS only, these plants are automatically de-selected when a component level is chosen on 3 letters. When selected the result would be that the failure rate is too low when taking operating hours of such plants into the equation.

[2] The spreadsheet for analysis however can enter any valid KKS code and calculate the failure rate and repair time.

6 FAILURE RATE AND REPAIR TIME

The calculation of failure rate and average repair time is straightforward. The failure rate is defined as the average number of failures per unit of time per component (KKS code). For time, plant operating time was chosen as it can be expected that with less operating time the number of failures becomes lower. The number of components (subsystems) is either taken from a help-file in which the number of components is estimated or, for those plants that have reacted to VGB's 361 R&D project questionnaire on plant layout, have been recorded.

As an example: plant no. 159 had 7 GT failures (EMS-code A1 and A2) on its 2 GTs. The plant was operated on average 5400 hrs per year and is present for 7 years in the database. The failure rate per GT is 7 / (5400 * 7 * 2) = $9.2x10^{-5}$ hr^{-1} (which is rather low compared to the average of $9.71x10^{-4}$ hr^{-1}). It is recognized that if 1 GT operates significantly less than the other one, the failure rate can be underestimated. However, gathering operating hours for separate subsystems requires significantly more input data. For some plants this may be present in KISSY as some companies have inputted such data in order to follow individual GTs, but this was not taken into account.

The repair time is defined as the average duration of the failures. It is not possible in the present data structure to subdivide failure duration into active repair time, waiting time (cooling, spares, etc.). This would also require substantial data efforts for the people that input the data since this is not generally recorded in the same database. The free text field usually gives insufficient clues to long waiting times however the free text field allows to record special events like delivery problems, a turbine rotor being delayed in transport, etc..

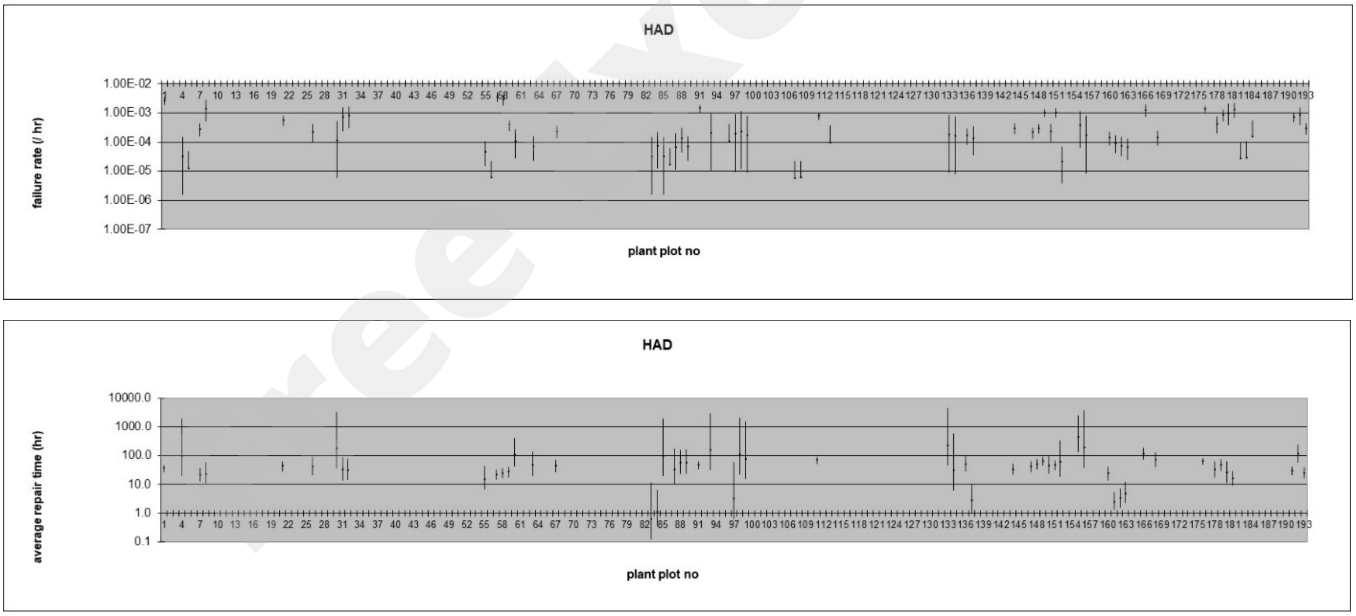


Figure 6-1 failure rate and repair time of HAD = evaporator, coal fired plants

The uncertainty in failure rate is calculated using a Chi2-distribution with Excel. For a number of failures larger than 50, a normal distribution with standard deviation equal to the square root of the mean value was used.

A plot of the failure rate per plant in Figure 6-1 on a logarithmic basis shows which plants have a higher than average fail rate. When 0 failures are present, classical Bayesian statistics are applied to estimate the uncertainty in failure rate by inputting 0 for the 5 % lowest and 1 ("a failure happens tomorrow") as the 95 % highest value with 0.5 failure as mean estimate. This only holds when a substantial exposure (operating) time is present. If only a few failures are present for a subset of plants, each of these plants might show a "high" failure rate, while this need not be the case.

7 UNCERTAINTY DUE TO DIFFERENCES BETWEEN PLANTS

The calculation of uncertainty in the average value if the whole population of plants would be homogeneous is small given a large number of failures. However, it is generally known that differences between plants spoil this small uncertainty making it substantially larger. How to calculate this is not yet state of the art. However, an approximation for this was found in the OREDA Handbooks [4] for example in that of 2015. If we use the same method, we arrive at the following numbers. We refer to the OREDA Handbook 2015 section: estimation procedures for “multi-Sample Problems” for the precise formulas and procedures.

Initial estimate for failure rate				uncertainty for homogeneous set of plants		
lambda	2.56E-04	/ hr		5% lower	2.39E-04	
stdeviation	6.79E-04			95% upper	2.74E-04	
OREDA multi sampling for non-homogeneous sets				uncertainty for NON-homogeneous set of plants		
estimate lambda	4.39E-04			5% lower	2.80E-06	/hr
stdev	7.91E-04			95% upper	2.74E-03	/hr

Figure 7-1 Uncertainty in failure rate

The uncertainty in failure rate in Figure 7-1 ranges from $2.39 \times 10^{-4} < X < 2.74 \times 10^{-5}$ with 602 failures if differences between plants are not considered. When differences are considered (the population is inhomogeneous) the range is $2.80 \times 10^{-6} < X < 2.74 \times 10^{-3}$.

Figure 6-1 seems to indicate the same when reading the uncertainties. Therefore, it appears that differences between plants should be taken into account more systematically, for instance in plant improvement projects. Figure 7-1 also indicates that the average may differ for the selection of plants and KKS code when differences between plants are taken into account (compare cell initial estimate failure rate vs multi sampling failure rate).

8 DETECTION OF OUTLIERS

Outliers may be present in data and may spoil patterns, regression lines, etc. when no outliers are considered. The type of statistics to handle such outliers is called Robust Statistics and is discussed for example by Rousseuw [2]. In the paper, practical procedures are given to deal with outliers.

If the classical average differs much from the median (the 50 % value), outliers may be present. Rousseuw proposes in such cases to use the median being a robust estimator, unlike the arithmetic average which is sensitive to outliers. In the printout of the database in Annex I therefore also the GEOMEAN is shown.

Secondly, in statistics a Gaussian distribution, a bell-type distribution is often used. Very few distributions in the practice of reliability engineering are perfectly Gaussian. The standard deviation, applicable for a Gaussian distribution, again is non-robust being sensitive to outliers. Therefore, Rousseuw proposes to use;

$$MAD = 1.483 \cdot median[x_j - median(x_i)]$$

With j = 1,… n and i = 1,… n

MAD stands for <u>m</u>edian of <u>a</u>bsolute <u>d</u>istances from the sample median.

The coefficient 1.483 is a correction factor to make the estimator consistent with the spread in a Gaussian distribution.

Now, an outlier is a value which differs from the majority of points. As a measure for this, the standardised distance (z-score) is calculated using the sample median T and MAD:

$$z_i = \frac{x_i - T}{MAD}$$

For the classical Gaussian distribution, the probability that abs(z_i) > 2.5 is very small (< 1 %). Similarly, we can use the cut-off value for outliers using abs(z_i) > 2.5 together with choosing the sample mean rather than the arithmetic average and the MAD variable rather than the standard deviation.

This was implemented in Excel by labelling all calculated outliers (using T, MAD and z_i) automatically with the code for plant involved and colouring them red. Subsequently, simple linear regression lines were calculated <u>without</u> outliers.

9 ANALYSIS OF AGEING

Due to differences in age of the plants and the number of years that plants have been contributing failure data to the database, the data for each plant does not cover the same period. This is called left and right censoring. Ageing is defined as the number of failures going up more than linearly with time. A simple model for ageing is the Crow [5] model, which takes into account both issues noted before. It is an ABAO (As Bad As Old) model, indicating that both repair and overhauls do not appear to influence the number of failures compared to the situation before a repair or overhaul, (although the derivative may decrease in time indicating an improvement).

The cumulative number of failures is given by:

$$N(t) = \alpha \cdot t^{\beta}$$

with

α = parameter for the number of failures per hr

β = coefficient to describe ageing

t = time (hrs)

For t, calendar time since the start of operation is chosen, not the time since the first failure in the databases as we are interested in the life cycle of the plant. The use of operating time for t has not been implemented as this would require an estimate of the operating time at each failure which is a substantial data effort. It should be noted however that for plants having been mothballed or having had a HILP (high impact, low probability), this period should be subtracted.

With β = 1, no ageing is present and N(t) is approximately a straight line. The coefficient α in that case is equal to the failure rate λ. With β > 1, N(t) curves upward and ageing appears to be present. With β < 1, the gradient of N(t) decreases, and teething problems appear to be present. The coefficient α in these cases, while having the dimension of failure rate, takes on values that can be orders of magnitude different from the classical failure rate as a function of β. In general, with increasing β, α will be smaller. The values of α and β are dependent on each other.

The calculations are shown in Figure 9-1 (only 4 out of 224 plants shown). For full formulas, reference is given to the original 1990 IEEE symposium publication or [5]. Figure 9-1 shows that plants 2 and 3 were not selected (setting hours in the database to 1, therefore very low) while some failure data have other KKS codes and are therefore not applicable (the log of failure time is left open). Furthermore, only failures further away in time than the cut-off criterion (set at 168 hrs or 1 week) were take into account, as per rows 245, 247, 248 and 250.

The calculation starts with an initial estimation of β and usually β = 1 is a good choice leading to convergence. By using the Goal Seek procedure in Excel, making the beta difference = 0, a value of β is calculated that fits the data best. The procedure does not always converge, for example when 1 power plant with many failure data is present, which spoils the pattern. Typical β-values would be lower than 0.4 or higher than 5. In these cases the analyst should keep the coefficient at β = 1. This is coloured orange in the overall data tables.

11 COMPLETE DATA REPORT

An example of a complete data report for coal, lignite, gas and oil-fired plants (no CCGTs) of KKS HNC (induced flue gas fans) is shown in the next figures. All data reports following from the Pareto analysis plus some extra are gathered in Appendix F to H. Some extreme data points were not plotted being extreme outliers making the magnitude of other data points difficult to read.

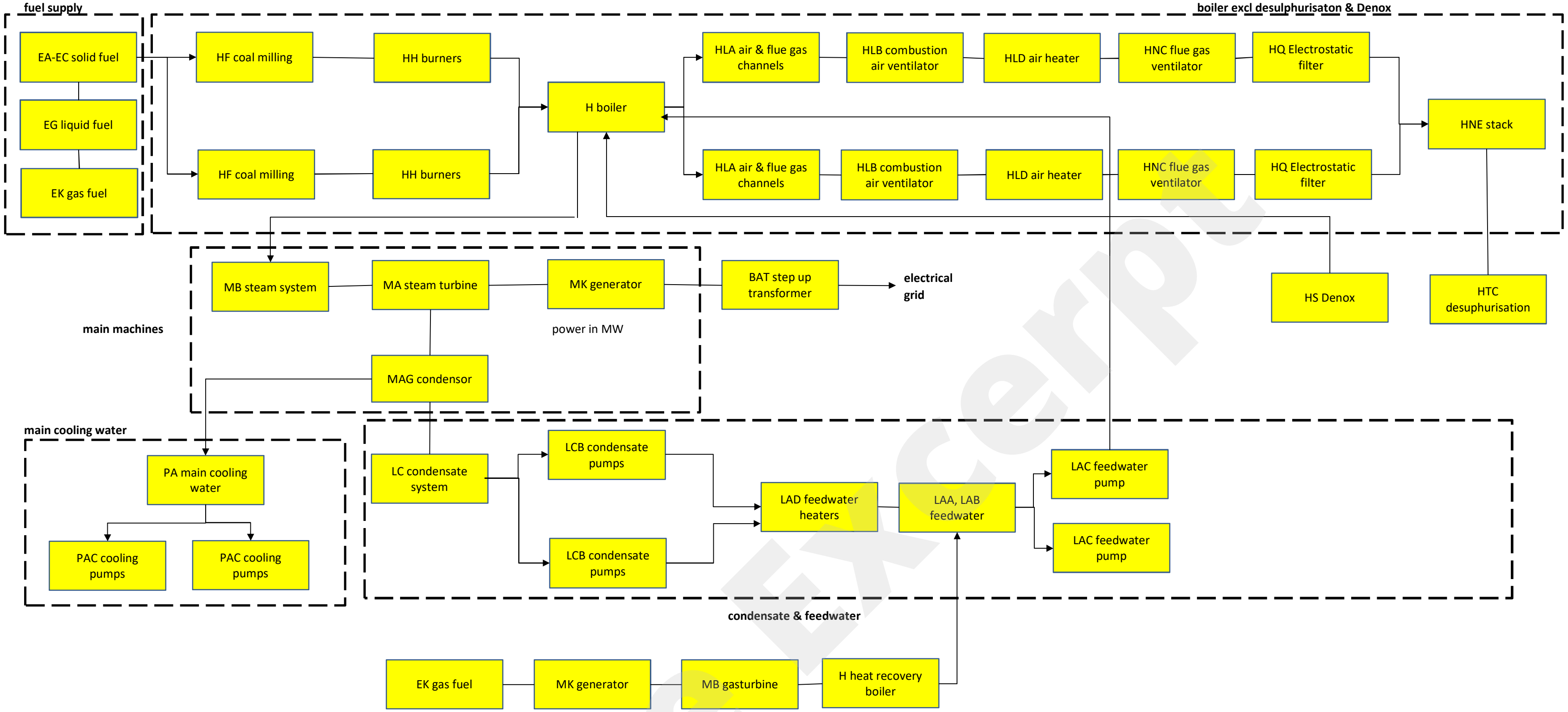
The standard reports for HNC are given in Figures 11-1 – 11-7.

Duo fossil fired unit Mono fossil fired unit	KKS Code	HNC	Level	KKS		Repeat filter: within	168
Hard Coal Lignite Oil		Induced flue gas fans					hrs
Excl. until 99 MW							

Plot no	Include	Power Plant Unit	Type of Power Plant	Fuel	Capacity net [MW]	Age max in database	Average Operating Hours	Years in database
1	1	1	Mono fossil fired unit	Hard Coal	400 - 599 MW	35	2821	5
4	1	4	Mono fossil fired unit	Hard Coal	600 - 999 MW	35	6366	5
5	1	5	Mono fossil fired unit	Hard Coal	600 - 999 MW	28	8067	5
7	1	7	Mono fossil fired unit	Hard Coal	600 - 999 MW	39	4376	10
8	1	8	Mono fossil fired unit	Hard Coal	600 - 999 MW	33	3781	1
9	1	9	Duo fossil fired unit	Lignite	400 - 599 MW	42	7767	11
10	1	10	Duo fossil fired unit	Lignite	400 - 599 MW	40	7953	12
11	1	11	Mono fossil fired unit	Lignite	600 - 999 MW	20	7811	12
12	1	12	Mono fossil fired unit	Lignite	600 - 999 MW	9	6935	8
17	1	17	Mono fossil fired unit	Lignite	200 - 399 MW	34	5744	5
21	1	21	Mono fossil fired unit	Hard Coal	100 - 199 MW	44	6182	6
25	1	30	Duo fossil fired unit	Hard Coal	200 - 399 MW	43	3576	6
26	1	31	Mono fossil fired unit	Hard Coal	200 - 399 MW	35	5387	6
30	1	37	Mono fossil fired unit	Hard Coal	200 - 399 MW	49	4436	2
31	1	38	Mono fossil fired unit	Hard Coal	200 - 399 MW	51	5860	1
32	1	39	Mono fossil fired unit	Hard Coal	200 - 399 MW	31	6416	1
33	1	40	Mono fossil fired unit	Oil	200 - 399 MW	47	456	12

180	1	210	Mono fossil fired unit	Hard Coal	100 - 199 MW	53	1539	5
181	1	211	Mono fossil fired unit	Hard Coal	100 - 199 MW	59	6346	3
182	1	212	Mono fossil fired unit	Hard Coal	100 - 199 MW	58	5982	3
183	1	213	Mono fossil fired unit	Hard Coal	600 - 999 MW	40	3406	1
184	1	214	Duo fossil fired unit	Lignite	100 - 199 MW	57	7865	4
185	1	215	Mono fossil fired unit	Lignite	100 - 199 MW	53	7281	4
186	1	216	Duo fossil fired unit	Lignite	200 - 399 MW	55	8080	11
187	1	217	Duo fossil fired unit	Lignite	200 - 399 MW	53	7647	11
188	1	218	Mono fossil fired unit	Lignite	600 - 999 MW	46	7548	11
189	1	219	Mono fossil fired unit	Lignite	600 - 999 MW	45	7516	11
190	1	222	Mono fossil fired unit	Hard Coal	200 - 399 MW	47	4169	8
191	1	223	Mono fossil fired unit	Hard Coal	600 - 999 MW	7	1419	6
192	1	224	Mono fossil fired unit	Hard Coal	600 - 999 MW	44	4866	12

Figure 11--1 Plants in standard report



MB gasturbine	no of gasturbines (not black start)	1
	technical ability to run block with ventilators Y/N	Y
H heat recovery boiler	no of heat recovery boilers	1
	E-capacity lost when 1 boiler fails	5%
HF coal milling	no of mills	5
	E-capacity lost when 1 mill fails	0%
HFE coal air	no of ventilators	2
	E-capacity lost when 1 mill fails	50%
HLB combustion air	no of ventilators	2
	E-capacity lost when 1 ventilator fails	50%
HLD air heater	no of air heaters	2
	E-capacity lost when 1 heater fails	50%
HNC flue gas ventilator	no of ventilators	2
	E-capacity lost when 1 ventilator fails	50%
HNC flue gas ventilator	no of ventilators	2
	E-capacity lost when 1 ventilator fails	50%

assumption: gasturbine supply heat to heat recovery boiler in MAIN boiler feedwater loop
other use of gasturbine please state:

PAC cooling water pumps	no of pumps	2	
	E-capacity lost when 1 pump fails	10%	
LCC condensate pumps	no of pumps	2	
	E-capacity lost when 1 pump fails	0%	
LAC feedwater pumps	no of turbine feedwater pumps	1	
	E-capacity when 1 turbine feedwater pump in operation		100%
	no of E-motor feedwater pumps	2	
	E-capacity when (only) 1 E motor pump in operation		30%

Duo fossil fired unit Mono fossil fired unit | KKS Code **BAT** | Level KKS | Repeat filter: within 168 hrs

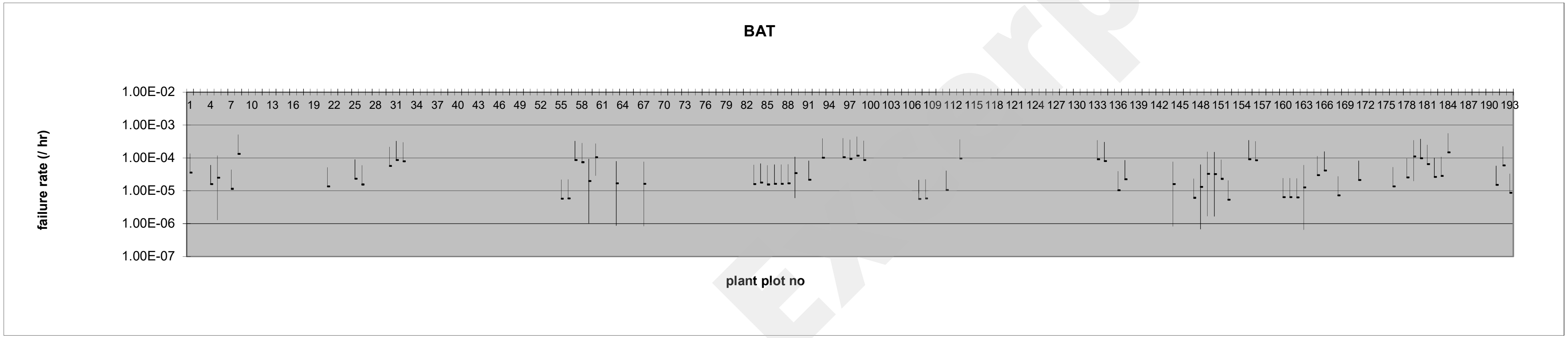
Hard Coal | Stepup transformer

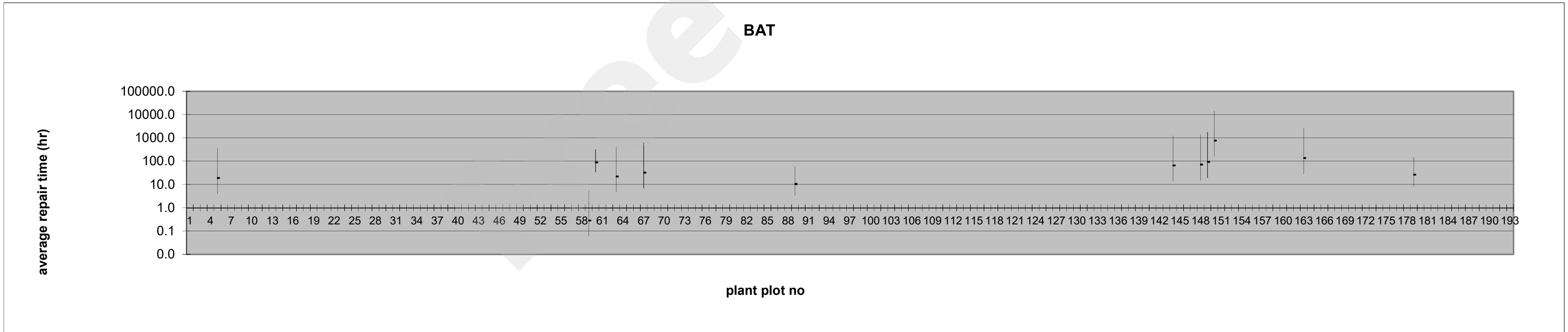
Excl. until 99 MW

Plot no	Include	Power Plant Unit	Type of Power Plant	Fuel	Capacity net [MW]	Age max in database	Average Operating Hours	Years in database
1	1	1	Mono fossil fired unit	Hard Coal	400 - 599 MW	35	2821	5
4	1	4	Mono fossil fired unit	Hard Coal	600 - 999 MW	35	6366	5
5	1	5	Mono fossil fired unit	Hard Coal	600 - 999 MW	28	8067	5
7	1	7	Mono fossil fired unit	Hard Coal	600 - 999 MW	39	4376	10
8	1	8	Mono fossil fired unit	Hard Coal	600 - 999 MW	33	3781	1
21	1	21	Mono fossil fired unit	Hard Coal	100 - 199 MW	44	6182	6
25	1	30	Duo fossil fired unit	Hard Coal	200 - 399 MW	43	3576	6
26	1	31	Mono fossil fired unit	Hard Coal	200 - 399 MW	35	5387	6
30	1	37	Mono fossil fired unit	Hard Coal	200 - 399 MW	49	4436	2
31	1	38	Mono fossil fired unit	Hard Coal	200 - 399 MW	51	5860	1
32	1	39	Mono fossil fired unit	Hard Coal	200 - 399 MW	31	6416	1
55	1	62	Mono fossil fired unit	Hard Coal	100 - 199 MW	31	7957	11
56	1	63	Mono fossil fired unit	Hard Coal	100 - 199 MW	31	7855	11
57	1	64	Mono fossil fired unit	Hard Coal	100 - 199 MW	55	974	6
58	1	65	Mono fossil fired unit	Hard Coal	100 - 199 MW	54	1135	6
59	1	66	Mono fossil fired unit	Hard Coal	600 - 999 MW	35	4594	11
60	1	68	Mono fossil fired unit	Hard Coal	600 - 999 MW	26	5735	5
63	1	71	Mono fossil fired unit	Hard Coal	600 - 999 MW	33	4963	12
67	1	75	Mono fossil fired unit	Hard Coal	600 - 999 MW	35	5619	11
83	1	91	Mono fossil fired unit	Hard Coal	200 - 399 MW	43	5204	6
84	1	92	Mono fossil fired unit	Hard Coal	200 - 399 MW	43	4700	6
85	1	93	Mono fossil fired unit	Hard Coal	200 - 399 MW	43	5388	6
86	1	94	Mono fossil fired unit	Hard Coal	200 - 399 MW	43	5146	6
87	1	95	Mono fossil fired unit	Hard Coal	200 - 399 MW	42	5147	6
88	1	96	Mono fossil fired unit	Hard Coal	200 - 399 MW	42	5008	6
89	1	97	Mono fossil fired unit	Hard Coal	200 - 399 MW	47	5896	10
91	1	99	Mono fossil fired unit	Hard Coal	200 - 399 MW	44	3922	6
93	1	102	Mono fossil fired unit	Hard Coal	400 - 599 MW	67	4941	1
96	1	105	Mono fossil fired unit	Hard Coal	200 - 399 MW	55	4809	1
97	1	106	Mono fossil fired unit	Hard Coal	200 - 399 MW	55	5380	1
98	1	107	Mono fossil fired unit	Hard Coal	200 - 399 MW	55	4317	1
99	1	108	Mono fossil fired unit	Hard Coal	200 - 399 MW	55	5825	1
106	1	121	Mono fossil fired unit	Hard Coal	100 - 199 MW	49	7472	12
107	1	122	Mono fossil fired unit	Hard Coal	100 - 199 MW	37	7186	12
110	1	125	Mono fossil fired unit	Hard Coal	600 - 999 MW	41	5938	8
112	1	130	Mono fossil fired unit	Hard Coal	100 - 199 MW	30	5262	1
132	1	151	Mono fossil fired unit	Hard Coal	200 - 399 MW	43	5605	1
133	1	152	Mono fossil fired unit	Hard Coal	200 - 399 MW	32	6281	1
135	1	154	Mono fossil fired unit	Hard Coal	400 - 599 MW	35	4444	11
136	1	155	Mono fossil fired unit	Hard Coal	600 - 999 MW	7	3787	6
143	1	163	Mono fossil fired unit	Hard Coal	400 - 599 MW	26	6250	10
146	1	168	Mono fossil fired unit	Hard Coal	200 - 399 MW	52	6840	12
147	1	169	Mono fossil fired unit	Hard Coal	200 - 399 MW	51	6347	12
148	1	170	Mono fossil fired unit	Hard Coal	200 - 399 MW	44	5105	6
149	1	171	Mono fossil fired unit	Hard Coal	200 - 399 MW	43	5189	6
150	1	172	Mono fossil fired unit	Hard Coal	600 - 999 MW	35	3639	6

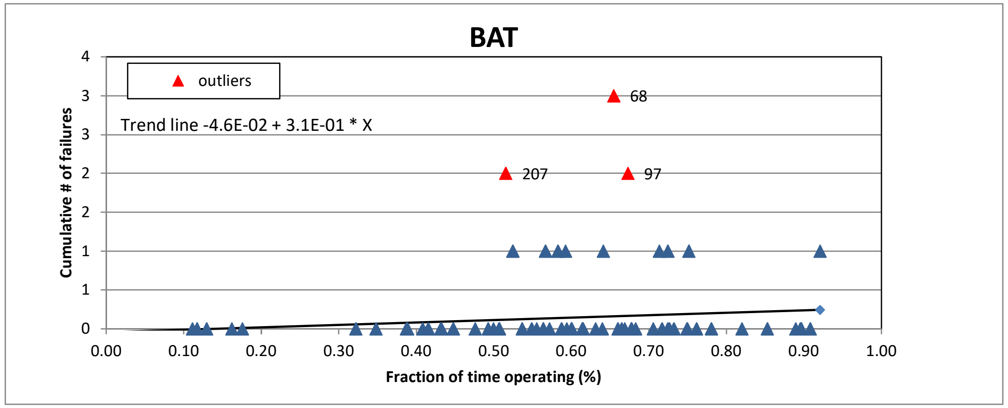
Initial estimate for failure rate					
				uncertainty for homogeneous set of plants	
lambda	6.92E-06	/ hr	5% lower	4.34E-06	
stdeviation	3.83E-05		95% upper	1.05E-05	

OREDA multi sampling for non-homogeneous sets					
				uncertainty for NON-homogeneous set of plants	
estimate lambda	7.42E-06		5% lower	1.26E-07	/hr
stdev	2.18E-05		95% upper	1.23E-04	/hr

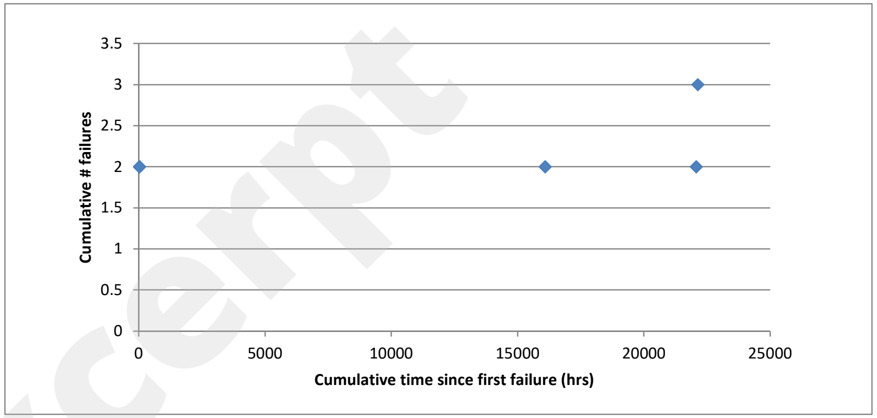




Cumulative failures versus fraction of time operating



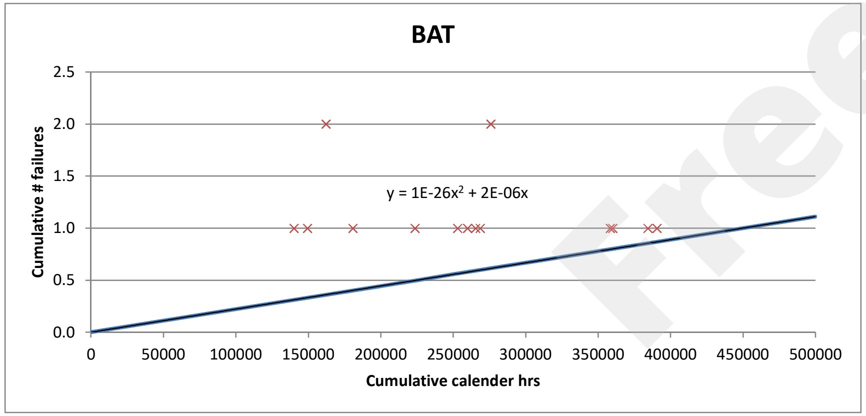
Cumulative failures versus time since first failure

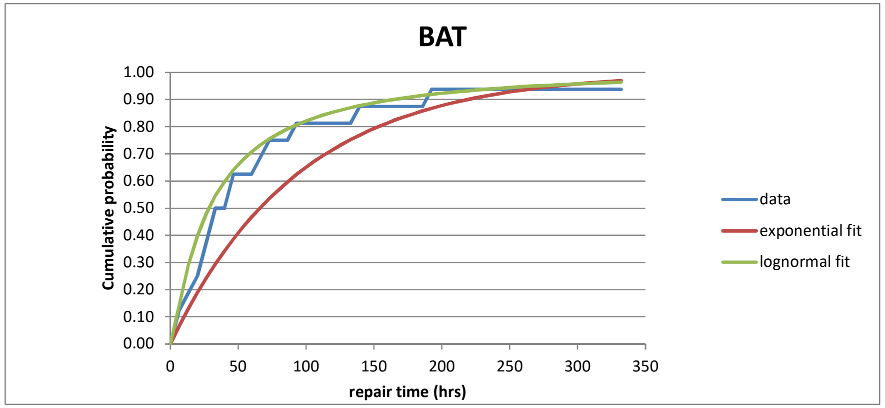


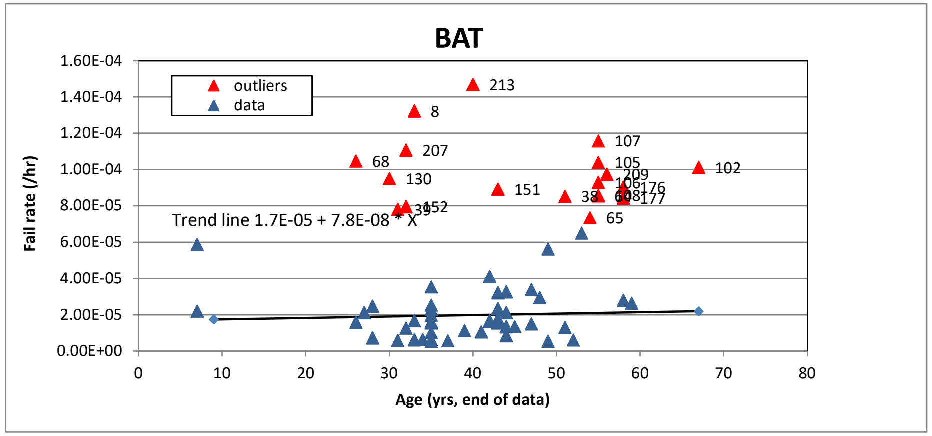
Fit of a Crow model to failure times				
lambda	2.22E-06	spare insert time	24
beta	1.00	>= spare	0.63
		avg >= spare	71.5
		avg < spare	12.4

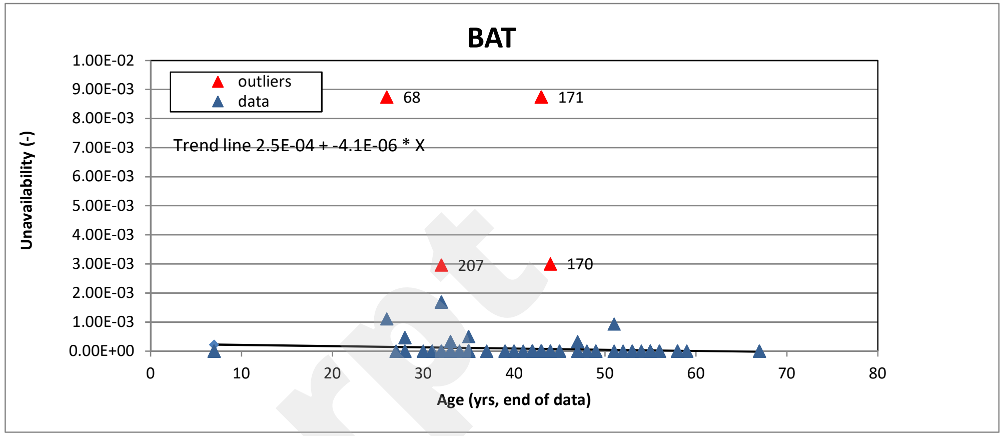
Fit of repair times

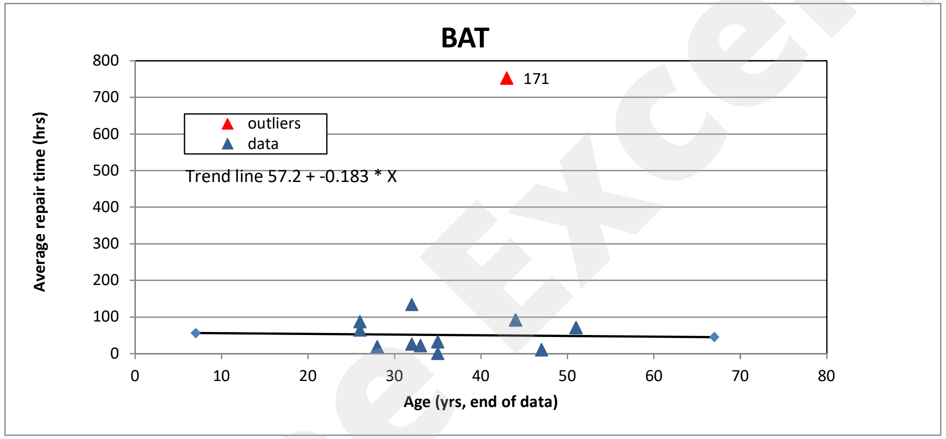
Repair time	all outages	full outages
average	95.1	58.2
5 % value	0.7	3.9
95 % value	332.4	160.2
lognormal average	164.7	110.3
lognorm stddev	941.1	417.4

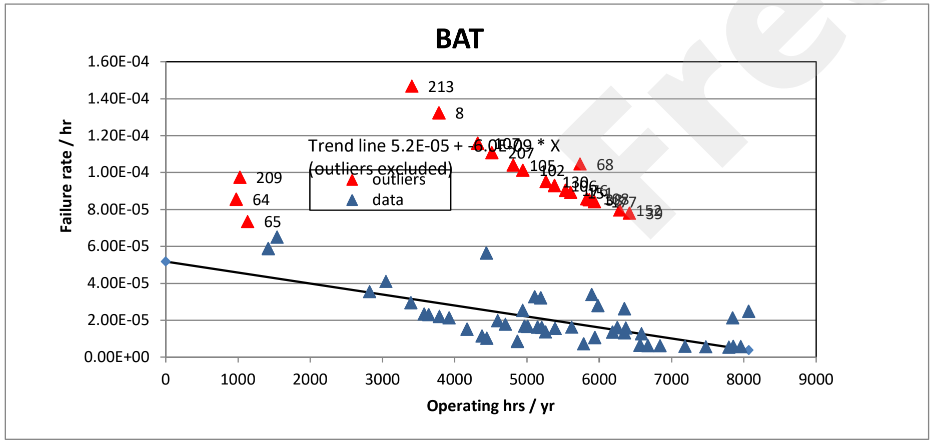


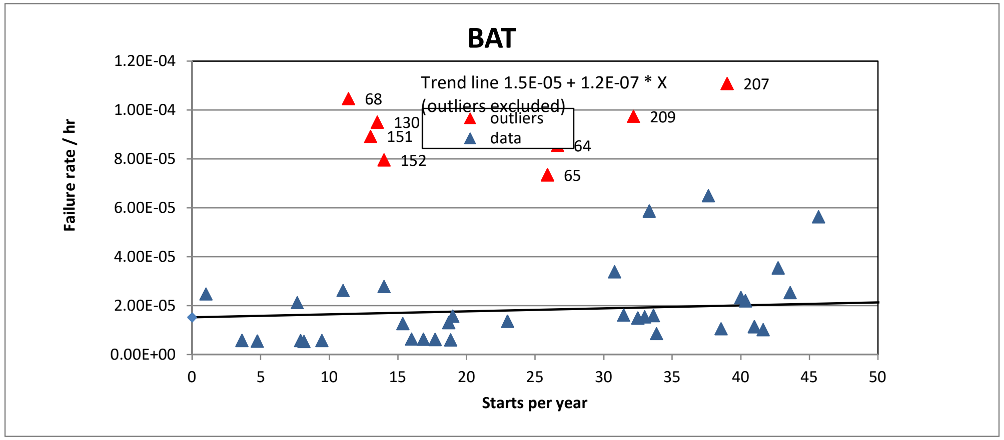


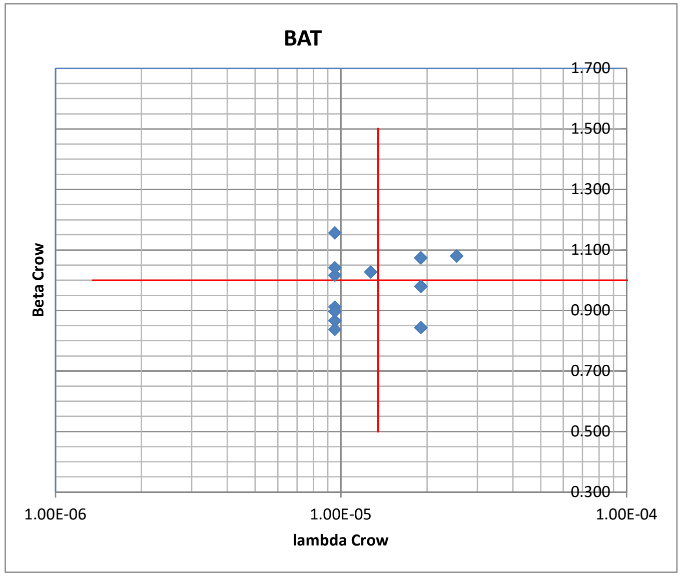

BAT
outliers
data
Trend line 1.7E-05 + 7.8E-08 * X
Fail rate (/hr)
Age (yrs, end of data)
1.60E-04
1.40E-04
1.20E-04
1.00E-04
8.00E-05
6.00E-05
4.00E-05
2.00E-05
0.00E+00
0
10
20
30
40
50
60
70
80
213
8
107
207
105
68
102
130
151
65


BAT
outliers
data
68
171
Trend line 2.5E-04 + -4.1E-06 * X
207
170
Unavailability (-)
Age (yrs, end of data)
1.00E-02
9.00E-03
8.00E-03
7.00E-03
6.00E-03
5.00E-03
4.00E-03
3.00E-03
2.00E-03
1.00E-03
0.00E+00
0
10
20
30
40
50
60
70
80


BAT
171
outliers
data
Trend line 57.2 + -0.183 * X
Average repair time (hrs)
Age (yrs, end of data)
800
700
600
500
400
300
200
100
0
0
10
20
30
40
50
60
70
80


BAT
213
8
209
64
65
68
outliers
data
(outliers excluded)
Failure rate / hr
Operating hrs / yr
1.60E-04
1.40E-04
1.20E-04
1.00E-04
8.00E-05
6.00E-05
4.00E-05
2.00E-05
0.00E+00
0
1000
2000
3000
4000
5000
6000
7000
8000
9000


BAT
Trend line 1.5E-05 + 1.2E-07 * X
(outliers excluded)
outliers
data
207
68
209
130
151
152
64
65
Failure rate / hr
Starts per year
1.20E-04
1.00E-04
8.00E-05
6.00E-05
4.00E-05
2.00E-05
0.00E+00
0
5
10
15
20
25
30
35
40
45
50


BAT
1.700
1.500
1.300
1.100
0.900
0.700
0.500
0.300
Beta Crow
1.00E-06
1.00E-05
1.00E-04
lambda Crow

DNV

vgbe ENERGY IS US

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