KAUNAS UNIVERSITY OF TECHNOLOGY

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DEPARTMENT OF APPLIED MATHEMATICS

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ANALYSIS OF SYSTEM UNAVAILABILITY AND TESTING CONSIDERING AGEING

Master Thesis

Supervisor
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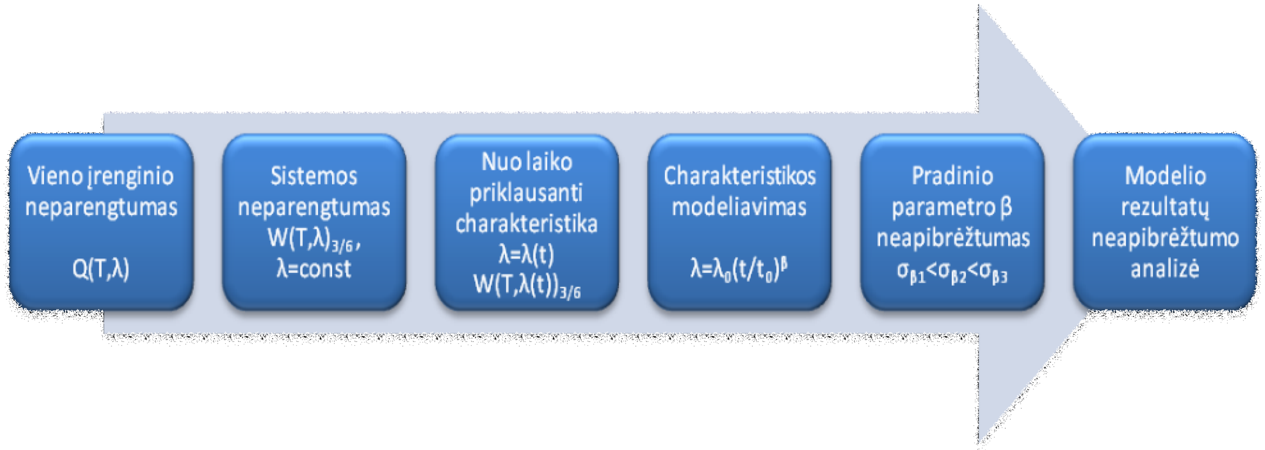
IŠPLĖSTINĖ SANTRAUKA

Darbe nagrinėjama avarinių saugos sistemų patikimumo problematika. Siekiant pratęsti besibaigiantį pramonės įmonių ir jėgainių įrangos eksploatacijos laiką, didžiulę reikšmę įgyja jos patikimumo vertinimas. Kadangi daugelis avarinių saugos sistemų nuolat yra budėjimo režime ir pradeda veikti tik pareikalavus, t.y. atsiradus tam tikroms sąlygoms, jų elementų parengtumas turi būti ypatingai didelis.

Šiame darbe buvo iškelti tokie uždaviniai:

- Išnagrinėti sistemos neparengtumo vertinimo tikimybinį modelį (1.3), susipažinti su pasaulyje naudojamomis mechaninių ir elektroninių prietaisų parengtumo (ang. Availability) ir patikimumo (ang. Reliability) vertinimo metodikomis (1.1);
- Parengti sistemos patikimumo duomenų analizės bei patikimumo parametrų kitimo vertinimo metodiką atsižvelgiant į įrenginių savybių kitimą dėl senėjimo (1.4);
- Atlikti Ignalinos atominės elektrinės (AE) dyzelinių generatorių (DG) neparengtumo modeliavimą, remiantis Ignalinos AE DG statistiniais duomenimis (2.2);
- Atlikti modelio neapibrėžtumo analizę (2.6), patikrinant, kaip kintant pradinių kintamųjų reikšmių neapibrėžtumui, kinta viso modelio rezultatų neapibrėžtumas;
- Parengti išplėtotų modelių ir priemonių taikymo rekomendacijas.

Darbo buvo vykdomas remiantis 1.1 schema:



1.1.pav. Darbo schema

Pirmiausia buvo išnagrinėti sistemos neparengtumo ir patikimumo kontrolės metodai. Kadangi įrenginio neparengtumą lemia skirtingos gedimų kritiškumo ir jų aptikimo rūšys (1.1 Lentelė), neparengtumo modelis, atsižvelgiant į tai, buvo sudaromas suskaidant jį į dedamąsias.

1.1 Lentelė

Įrangos, esančios laukimo būsenoje, gedimų būdai

Atsiradimo tipas	Gedimo pasekmė	
	Komponentas neveikia (V)	Komponentas tęsia darbą (D)
Aiškusis (A)	Aiškusis visiškas – AV	Aiškusis dalinis – AD
Nepastebimasis (N)	Nepastebimasis visiškas – NV	Nepastebimasis dalinis – ND

Bendrasis vieno įrenginio neparengtumas vertinamas sumuojant visas gedimų rūšis ir neparengumą, atsirandantį dėl testavimų, remiantis formule:

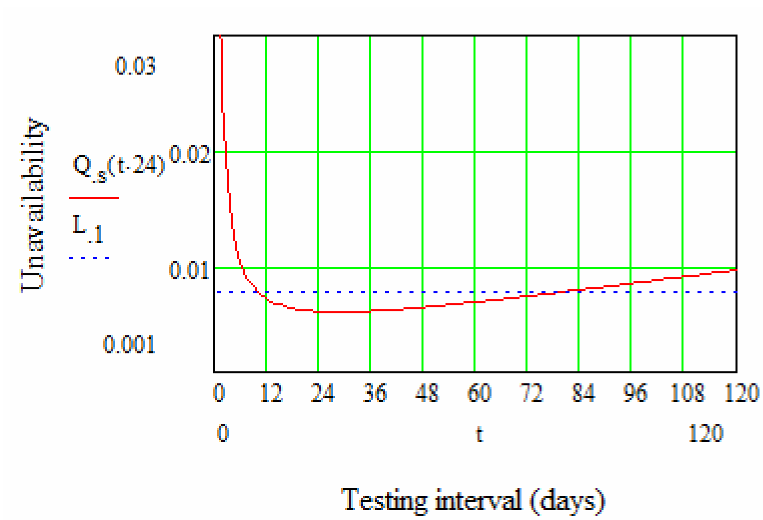
$$Q(T)=\left(\frac{1}{T}\int_0^T u(t)\,dt+\frac{u(T)a_{LC}}{T}\right)+\left(\lambda_{MC}a_{MC}\right)+\left(\lambda_{NC}a_{NC}\right)+\left(\frac{\tau}{T}E\right). \quad (1.1)$$

čia $U(t)=q_{NV}+(1-q_{NV})\cdot(1-e^{-\lambda_{NV}t})$ momentinis neparengtumas, q – nuo laiko nepriklausantis neparengtumas, λ – gedimų intensyvumas.

Atsižvelgiant į sistemai nustatytus sėkmės ir gedimo kriterijus, kombinatorinės formulės pagalba apibrėžiamas visos sistemos neparengtumo modelis:

$$U_{k/n}(T)=\sum_{m=k}^{n}\frac{n!}{m!(n-m)!}Q(T)^m\left(1-Q(T)\right)^{n-m}. \quad (1.2)$$

Toliau darbe nagrinėjamas neparengtumo modelis, priklausantis nuo testavimo intervalo, esant fiksuotoms patikimumo charakteristikų reikšmėms. Įrangos testavimui parenkama intervalo reikšmė, atitinkanti minimalų neparengtumą. Apžvelgiama galimybė keisti testavimo intervalą, neviršijant nustatytos neparengtumo ribos. Sutrumpinus intervalą tarp testavimų, įranga praranda parengtumą dėl per dažnų testavimų, o intervalą padidinus – sumažėja tikimybė gedimą aptikti iškart po jo atsiradimo. 1.2 paveiksle pateikiami testavimo intervalo kraštiniai kitimo rėžiai, bei didžiausią parengtumą garantuojantis testavimų dažnumas.



1.2.pav. Įrenginio neparengtumo modeliavimas

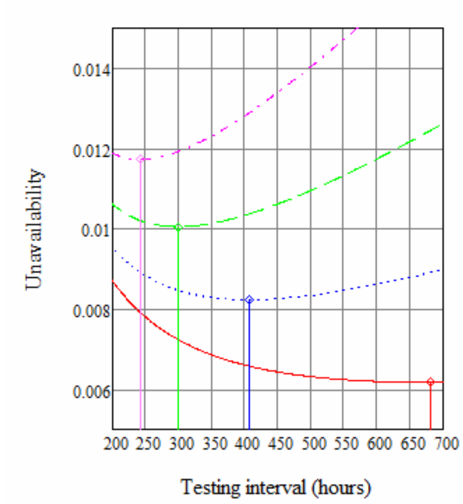
Aukščiau aptartuose modeliuose gedimų intensyvumas λ laikomas pastoviu. Tačiau realiomis sąlygomis, įrenginių savybės laikui bėgant keičiasi. Todėl darbe buvo patobulintas neparengtumo modelis, nagrinėjant patikimumo charakteristikų kitimą priklausomai nuo laiko. Darant prielaidą, kad senėjimo įtaka pastebima po 10 metų prietaiso veikimo, toliau buvo modeliuojama modelio charakteristikos λ dinamika kas dešimtmetį (1.3 pav.).

1.3.pav. Gedimų intensyvumo charakteristikos priklausomybė nuo laiko

Atsižvelgiant į parametrų kitimą dėl senėjimo, darbe plėtojama sistemos neparengtumo vertinimo metodika. Patikimumo charakteristikų senėjimo modeliavimui naudojamas Weibulo senėjimo modelis (1.3).

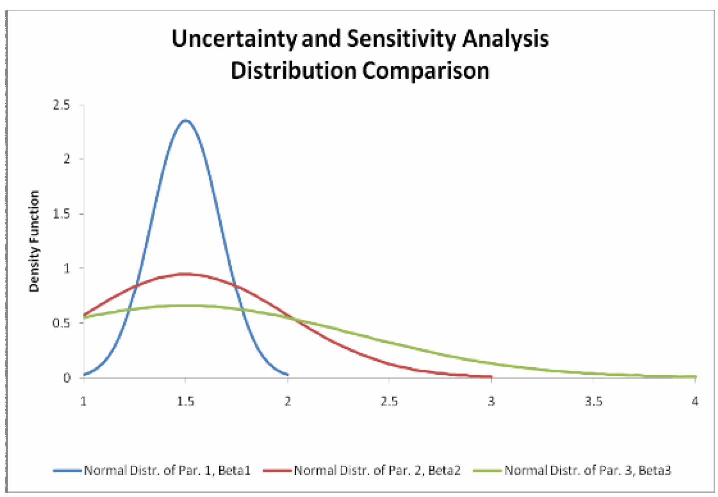
$$\lambda(t) = \lambda_0 t^{\beta} \ , \qquad (1.3)$$

Nustatyta, jog įrangai senėjant sistemos neparengtumas didėja, o minimalų neparengtumą atitinkantis intervalas tarp testavimų mažėja. Tai reiškia, jog įrangai senstant, testavimų dažnumas turi didėti.



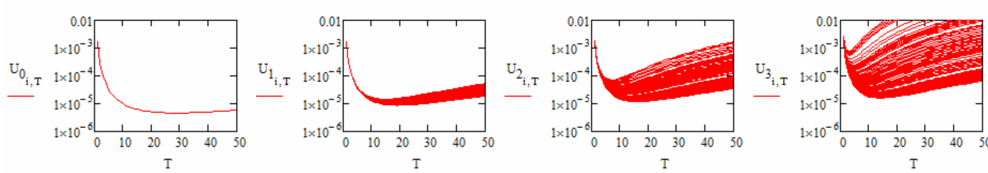
1.4.pav. Testavimo intervalo kitimas įrangai senėjant

Darbe taip pat nagrinėjama pradinio senėjimo parametro įverčio β neapibrėžtumo įtaka visos sistemos modelio rezultatams. Naudojantis statistinės analizės paketu SUSA buvo generuojamos parametro reikšmės, laikant, kad įrenginiui senstant, jų kitimo ribos plečiasi (1.5 pav.).



1.5.pav. Senėjimo parametro β neapibrėžtumas

Pastebėta, jog dėl degradacijos didėjant senėjimo parametro neapibrėžtumui, išauga ir visas modelio neapibrėžtumas (1.6 pav.).



1.6.pav. Sistemos neparengtumas esant skirtingoms charakteristikos λ reikšmėms

Taigi sistemai senstant, optimalaus testavimo intervalo parinkimo uždavinys tampa problematiškas arba visai neįmanomas.

Remiantis šiais rezultatais, siūlomos tolesnės studijos įtraukiant kitų charakteristikų senėjimą. Taip pat, atliekant jautrumo analizę, reikėtų nustatyti charakteristikų įtaka rezultatams skirtingais eksploatacijos periodais.

Magistrinio darbo tema parengtas straipsnis bus atspausdintas konferencijos „Matematika ir matematinis modeliavimas“ (KTU 2009, Kaunas) medžiagoje (žr. *Appendix 4* Paper to MIMM Conference).

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INTRODUCTION

In this work the reliability of the emergency systems is analysed. Some equipment in various chemical and industrial factories, power plants and similar corporations are ending their life. The possibility to extend it gives great importance to the reliability investigation. Since many of that type of systems is constantly in standby mode and runs only on demand, i.e. the emergence of certain conditions, the availability of the elements must be extremely high.

These devices are usually tested periodically. In order to prevent the occurrence of failure at an actual demand the latent and other faults are detected and eliminated on tests. On other side, too frequent testing may degrade the equipment and cause failures. Through a proper choice of testing interval, the negative and positive effects of testing can be balanced against each other.

Because of an ageing the failure rate rises and causes the changes of unavailability and testing period. In practice, the testing frequency is chosen mainly by engineering judgment, and according to general practices. Having the failure frequency data, the mathematical modelling can be used to support the decisions related to the testing interval.

The aim of the work is to investigate statistical models for system reliability control and the possibility to change the testing intervals of devices in such a way, that the safety level of whole system would not be decreased. The investigation is performed by modelling failure rate changes of system elements concerning ageing.

In this work the following objectives were set:

- to examine the system unavailability assessment probabilistic model;
- to develop methodology of the system reliability analysis concerning the change of the reliability parameters;
- to perform unavailability modelling and determine model parameters for the Ignalina nuclear power plant (NPP) diesel generators (DGs) system based on the Ignalina NPP DG statistics;
- to perform uncertainty analysis of the model;
- to develop recommendations for advanced models and the applications.

1. THEORETICAL PART

1.1. SOME DEFINITIONS FOR RELIABILITY AND AVAILABILITY ANALYSIS

• ***Success Criteria***: A statement of minimal equipment combination, operating environment, and mission time required to assure successful operation.

• ***Reliability***: Probability that a system will perform its function adequately (as intended), for period of time intended, and under intended conditions.

• ***Unreliability***: Complement of Reliability, quantified as: 1-Reliability

• ***Maintainability***: Probability that an item or a system, under stated conditions of use, will be retained in, or restored to, a state in which it can perform its required functions, when maintenance is performed under stated conditions and using prescribed procedures and resources.

• ***Availability***: Probability that an item or system, under the combined aspects of its reliability, maintainability, and maintenance support, will perform its required functions at a stated instant of time (instantaneous availability) or over a stated period of time (average availability).

• ***Unavailability***: Complement of Availability, quantified as: 1-Availability.

Reliability and **availability** analysis focus on different issues:

• ***Reliability*** analysis focuses on the ability of a system to continue performing its mission without interruptions or failures.

Example: A reactor shutdown system avoids spurious insertion of the control rods over an extended period of normal operation.

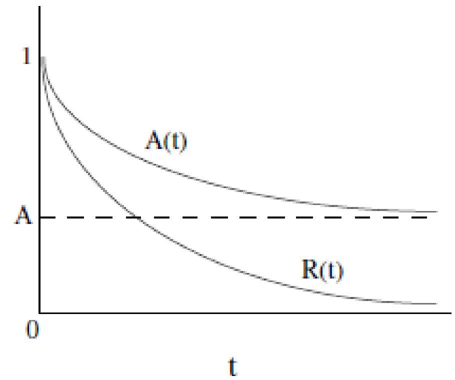
• ***Availability*** analysis focuses on ability to perform a mission at a particular period of time (considering issues such as local equipment failures, testing, maintenance, etc.)

Example: The same reactor shutdown system is capable at a particular moment in time of initiating an automatic shutdown should an emergency demand arise.

• A proper design is a *trade-off* between reliability in the mission of avoiding spurious trips and the availability in the mission of accomplishing shutdown when called upon.

Availability versus **Reliability**:

Availability $A(t)$ is the probability that a system is operating at time t while ***Reliability*** $R(t)$ is the probability that the system has been operating from time 0 to t. If we deal with a single unit with no repair capability, then, by definition: $R(t) = A(t)$. If repair is allowed, does not change but $A(t)$ becomes greater than $R(t)$.



1.1. Fig. Availability versus Reliability

1.2. UNAVAILABILITY MODEL

In general, the reliability of stand-by systems is related to unavailability mean, which is established by assessing the probability that system cannot perform designated functions in case of random demand. Periodic testing cannot affect reliability, but does affect availability and at same time unavailability. Unavailability is mostly influenced by the failure rate and their types. The failures generally are divided into two main types: monitored (observed) failures and latent failure, which are also called as hidden failures. In addition, according to the safety features, there are critical and non-critical failures (1.1 Table) [1], [2], [8].

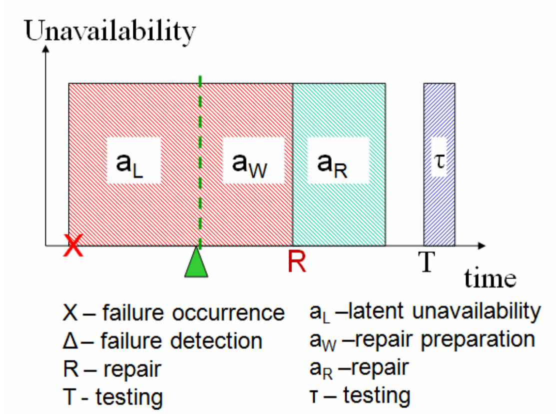
1.1 Table

Failure modes of stand-by component

Occurrence type	**Effect**	
	Prevents the operation	***Does not prevent the operation***
Monitored	Monitored Critical – MC	Monitored Non-critical – MN
Latent	Latent Critical – LC	Latent Non-critical – LN

1.2.1. Unavailability model of one device with different failure modes

Unavailability due to critical and non-critical failures unobserved during the maintenance is related to the maintenance time, while the latent critical failures influence the unavailability both due to their maintenance and undetected occurrence. When critical failure occurs, system cannot perform some of the designated functions until the time when this failure is found, i.e. until the testing.

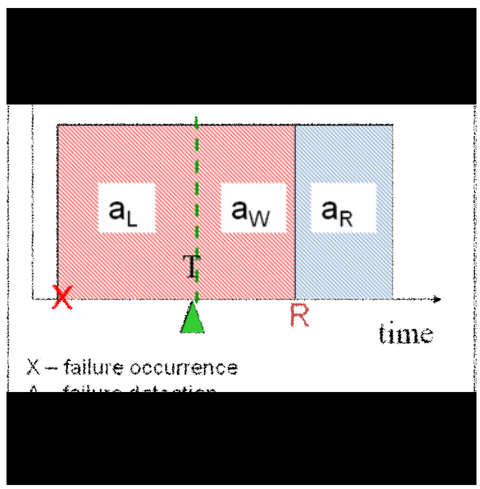


1.2. Fig. Component maintenance scheme

Total unavailability mean can be expressed by function, which depends on testing interval length T (period between tests). In general, it is a sum of three components, related to the impact of different type of failures, and one component, which defines testing time impact:

$$Q(T) = Q_{LC}(T) + Q_{MC} + Q_{NC} + Q_{TS}(T). \quad (1.1)$$

The latent critical faults contribute to expected unavailability during stand-by time, but the operator does not know their presence until the next test or demand (1.3 Fig.).



1.3. Fig. Latent critical failures caused unavailability

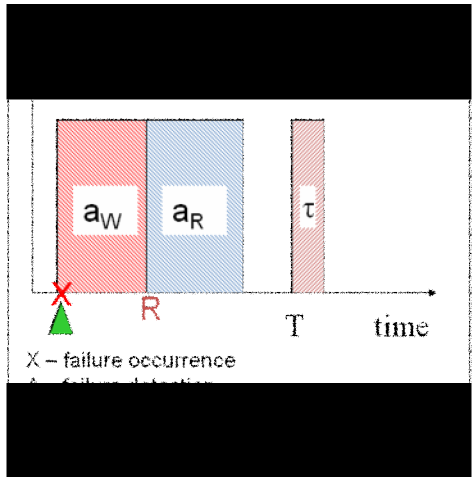
Total latent critical failures unavailability mean, taking into account due to maintenance formed average idle time a_{LC} impact, is expressed by formula:

$$Q_{LC} = \frac{1}{T}\int_0^T u(t)\,dt + \frac{u(T)\,a_{LC}}{T}. \quad (1.2)$$

Function $u(t)$ is instant latent critical failures unavailability. For system modelling it is assumed that all observed failures occur with constant rate λ_{MC}.

Observed critical failures unavailability average (1.4 Fig.), taking into account due to the maintenance formed average idle time a_{MC} impact, is expressed by formula:

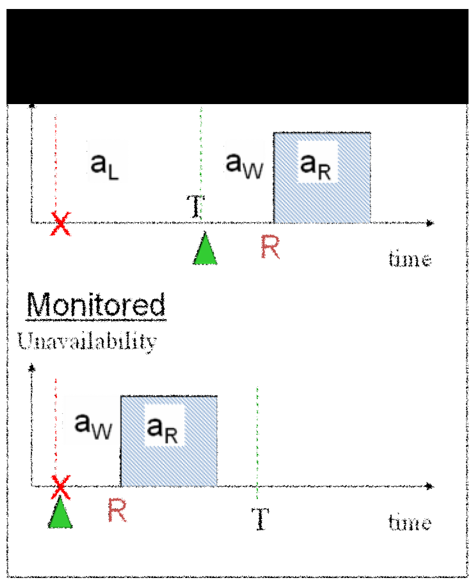
$$Q_{MC} = \lambda_{MC} \cdot a_{MC} \,. \tag{1.3}$$



1.4. Fig. Monitored critical failures caused unavailability

If non-critical failures (1.5 Fig.) occurrence rate is λ_{NC}, and for the maintenance the average idle time – a_{NC}, then the impact of these failures to the unavailability expression is:

$$Q_{NC} = \lambda_{NC} \cdot a_{NC} \,. \tag{1.4}$$

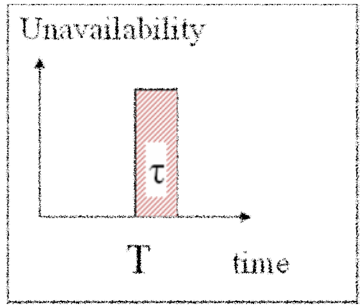


1.5. Fig. Non-critical failures caused unavailability

Testing duration impact to the unavailability (1.6 Fig.) is defined by formula:

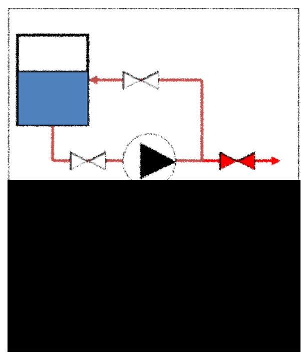
$$Q_{TS} = \frac{\tau}{T} E \,, \tag{1.5}$$

where τ is a testing duration, while E is an estimated probability that system functioning demand will not be fulfilled during the testing.



1.6. Fig. Testing duration caused unavailability

If during the testing system demand is found and it automatically is turned into the normal functioning mode, then testing duration's impact to the unavailability practically becomes insignificant ($E=0$). In other extreme case, when system during the testing was absolutely disconnected (1.7 Fig.), $E=1$ and impact of system testing duration is maximum.



1.7. Fig. System disconnection during testing

Seeking to optimize some device testing interval T mean unavailability has to be analyzed. Earlier analyzed mean unavailability function (1.1) is expressed as a sum of four terms, which describes the impact of different failures and testing duration (1.6):

$$Q(T)=\left(\frac{1}{T}\int_0^T u(t)\,dt+\frac{u(T)a_{LC}}{T}\right)+\left(\lambda_{MC}a_{MC}\right)+\left(\lambda_{NC}a_{NC}\right)+\left(\frac{\tau}{T}E\right). \tag{1.6}$$

One of the main parts influencing the unavailability variation, which depends on testing interval, is related to latent critical failures. The main feature of latent failures is that their existence is unknown until the system is in stand-by mode.

These failures usually are described by probability, called instant unavailability. Typically the simplified model is used for the calculation of instant unavailability $u(t)$:

$$u(t)=q+\lambda t, \tag{1.7}$$

where q – time independent unavailability term;

λ – failure rate (dependents on time);

t – time after the previous test or demand.

More precise model could be used, where the failure distribution itself is used but not it's linear approximation. In such a case the expression of instant unavailability is:

$$\mathrm{U}(t) = q + (1-q)\left(1-e^{-\lambda t}\right). \tag{1.8}$$

Time independent unavailability parameter q reflects the failures, which occur during the testing and they are not observed until the next testing or demand, and the failures, whose failure mechanism is related to the testing or system functioning and does not reveal itself in the stand-by mode.

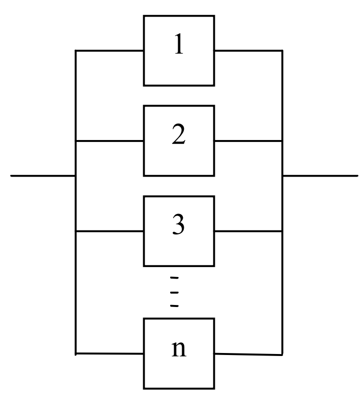
Unavailability part q_{LC}, which is influenced by latent critical failures, does not depend on time. This part is calculated by dividing the number of latent critical failures observed during the testing by the number of testing. Failure rate λ (part depends on time) for the corresponding failure types is obtained by calculating relation between the observed number of failures during the testing and the duration, when these failures occurred. Mean idle time a, which as a matter of fact occurs due to maintenance, is calculated by dividing total maintenance time by corresponding number of failures.

The minimum of testing interval for one diesel generator is obtained by solving such equation:

$$\frac{d}{dz}\left(\frac{1}{z}\int_0^z u(t)\,dt + \frac{u(z)\,a_{LC}}{z}\right) + \left(\lambda_{MC} a_{MC}\right) + \left(\lambda_{NC} a_{NC}\right) + \left(\frac{\tau}{z}E\right) = 0. \tag{1.9}$$

1.3. UNAVAILABILITY MODEL FOR THE SYSTEM OF DEVICES

Active on demand parallel system (1.8 Fig.) of n components designates a redundant system (a system with more units than absolutely necessary to function as required) in which all units are active on demand. At first, the considered system of this type is the system with all 100% parallel units:



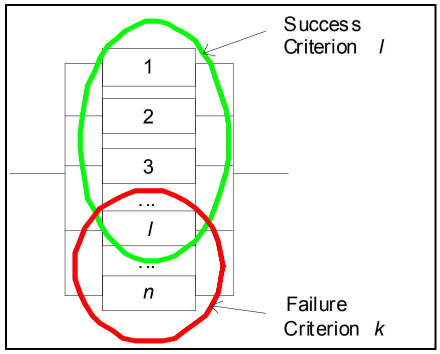
1.8. Fig. Active on demand parallel system

Redundant system assumes the individual elements are full (100%) capacity in accomplishing the design objective. So, since all elements must fail in order for the system to fail, the system unavailability:

$$\mathrm{U}(t)=\prod_{i=1}^{n} u_i(t); \tag{1.10}$$

where $u_i(t)$ is i element unavailability.

Analysing the success criteria of system operation (1.9 Fig.), this work considers the scheme, which consists of elements connected in parallel that perform system function.



1.9. Fig. Success and failure system operation criterions

In the redundant system it is assumed that separate elements can perform designated functions independently from the other elements. Analysing the system of n identical elements parallel interconnected, when for the system function performance only k elements are required, and when the instantaneous unavailability of separate elements is q, the total system unavailability is generally expressed by binomial distribution:

$$F_{k/n}(q)=\sum_{m=k}^{n}\frac{n!}{m!(n-m)!}q^m(1-q)^{n-m}. \tag{1.11}$$

Trying to assess the mean unavailability of the entire system one device mean unavailability model can be used. If one device mean unavailability is $Q(T)$, then entire system mean unavailability $U(T)$ in particular case can be expressed in analogy to the instant unavailability:

$$U_{k/n}(T)=\sum_{m=k}^{n}\frac{n!}{m!(n-m)!}Q(T)^m(1-Q(T))^{n-m}. \tag{1.12}$$

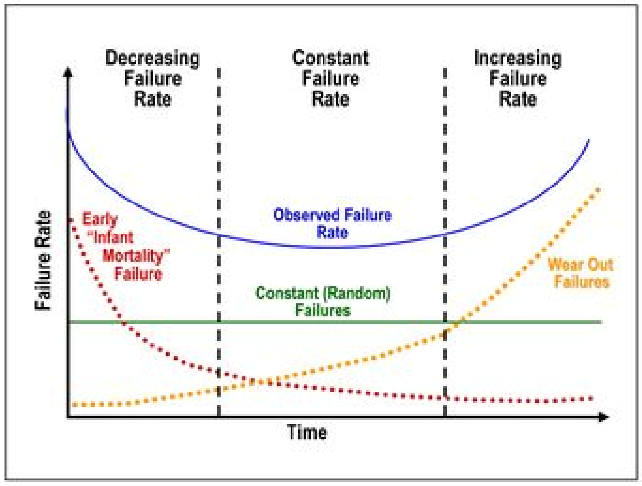
Then the minimum of mean unavailability can be obtained. The optimal testing interval is the solution of the following equation:

$$\frac{d}{dz}U(z)=0. \tag{1.13}$$

Values close to the system mean unavailability, such as in the case of one device unavailability, have sufficiently wide testing interval stripes.

1.4. MODELS OF AGEING

Reliability specialists often describe the lifetime of a typical electrical or mechanical device using a graphical representation called the Bathtub curve. The Bathtub curve consists of three periods: an early failure (burn in) or “infant mortality” period with a decreasing failure rate followed by a normal life period (also known as "useful life") with a low, relatively constant failure rate and concluding with a wear-out period that exhibits an increasing failure rate.



1.10. Fig. Failure rate dependence on component operating time

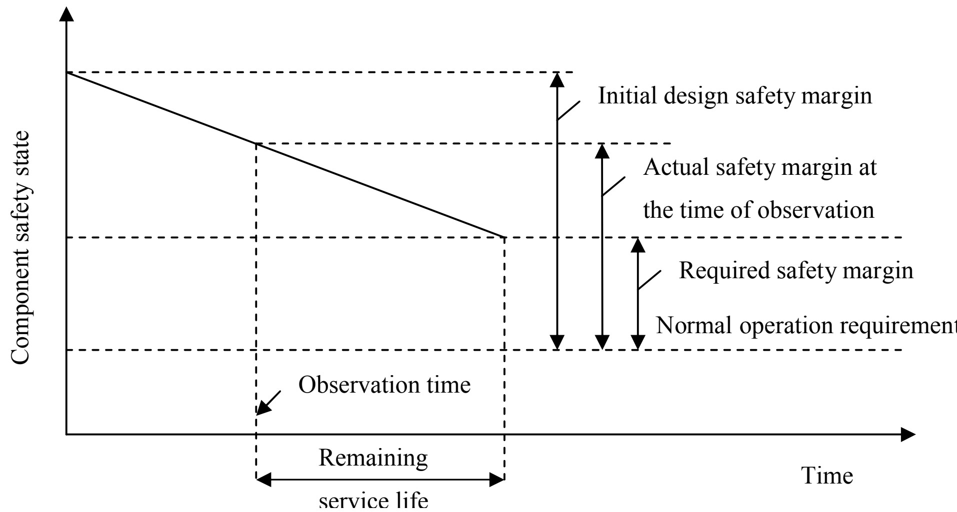
The period, where wear out failures occur is mostly caused by material degradation or ageing [12].

Ageing refers to the continuous time-dependent degradation of materials due to normal service conditions, which include normal operation and transient conditions, excluding postulated accident and post-accident conditions. [3]

Ageing affects all materials in nuclear power plants (NPPs) to some degree and therefore may lead to degradation of safety state /i.e. integrity and functional capability/ of plant components.

Ageing as cumulative degradation occurs with the passage of time. However, the amount of degradation within given period of time depends on the spectrum of degrading conditions present. These conditions are created by the operational environment, which includes the effects of operational procedures, policies and maintenance, etc.

Ageing related failures may significantly reduce system safety since they may impair one or more of the multiple levels of protection provided by the defence in depth concept. Ageing may lead to a large scale degradation of physical barriers and redundant components resulting in an increased probability of common cause failures. This could cause a reduction in component safety margins below limits provided in system design bases or in regulatory requirements and thus could cause impairment of safety systems.



1.11. Fig. Component safety state and safety margin as functions of time

Ageing phenomena are modelled differently, depending on the rate of the functional degradation of a component and the availability and quality of data (both failure and condition monitoring). /NEA(1995)

There are several methods for time dependant failure rate modelling [3], [4].

1.4.1. Linear ageing

The failure rate is of the form:

$$\lambda(t) = \lambda_0 + bt. \tag{1.14}$$

It is assumed that damage accumulates at a constant rate, and uses this to motivate linear degradation of λ. Here, λ_0 is the baseline rate and bt is the additional portion resulting from ageing. Formula can be rewritten as

$$\lambda(t) = \lambda_0(1 + \beta t), \tag{1.15}$$

with $\beta = b/\lambda_0$.

The reason for this change of notation is to make the analysis more comparable to analyses using other functional forms. To keep $\lambda(t)$ non-negative throughout the observed data period, β must satisfy the constraint: $\beta \geq -1/t_{max}$, where t_{max} is the maximum time in the observed data set.

Linear ageing is simple, an obvious natural way to give a first-order approximation to changes in the failure rate.

When two parameters are estimated from data, the estimators may be statistically correlated. In Equation (1.13), if β is overestimated then λ_0 will tend to be underestimated. To minimize this correlation, the data can be centred, that is, age can be measured not from 0 but around some value t_0 other than 0. Equation (1.15) then becomes:

$$\lambda(t) = \lambda_0\left[1 + \beta(t - t_0)\right]. \quad (1.16)$$

The constraints on β, to force $\lambda(t)$ to be non-negative, are:

$1/(t_{\max} - t_0) \leq \beta \leq 1/(t_0 - t_{\min})$, where $t_{\min}$ and $t_{\max}$ are the smallest and largest ages in the observed data set.

In this parameterization, λ_0 no longer represents the failure rate at age 0 but at age t_0. To minimize the correlation between the estimators of λ_0 and β, t_0 should be defined as the mean of all the component ages in the data. The intuitive idea is that it is relatively easy to estimate the failure rate in the middle of the data, λ_0.

Having done this, the linear trend line pivots around that middle value. The slope of the line determines β, and the estimators of the two parameters are statistically uncorrelated.

1.4.2. Exponential or log-linear ageing

Rather than assuming that λ increases linearly, assume that $\ln\lambda$ increases linearly:

$\ln\lambda(t) = a + \beta t$, or equivalently

$$\lambda(t) = \lambda_0 \exp(\beta t), \quad (1.17)$$

where $\lambda_0 = \exp(a)$.

This use of logarithms ensures that $\lambda(t)$ is always positive, regardless of the values of t and β, so the constraint on β is the trivial one: $-\infty < \beta < \infty$.

This model fits most neatly into the theory of generalized linear models. As a result, it is the default model for Poisson regression in statistical software packages.

In terms of practice, linear ageing and log-linear ageing are probably indistinguishable, except for unrealistically large data sets.

1.4.3. Power-law or Weibull ageing

Both terms, “power-law ageing” and “Weibull ageing”, are used in the literature. The failure rate is of the form:

$$\lambda(t) = \lambda_0 t^{\beta}, \quad (1.18)$$

with $\beta > -1$.

Equation (1.18) is very sensitive near $t = 0$. If β is positive (that is, increasing failure rate) then $\lambda(t) = 0$ at $t = 0$. If β equals 0 exactly (that is, constant failure rate) then $\lambda(t) = \lambda_0$ everywhere, including as $t \to \infty$. If β is negative then $\lambda(t) \to \infty$ as $t \to \infty$. If the sign of β is uncertain, then $\lambda(t)$ is extremely uncertain near $t = 0$. This fact means that one must be careful in defining the age that we call 0. Different results are obtained if age t is measured from the component's installation or, instead, from the start time of the data recording.

In the parameterization of Equation (1.18), λ_0 is the failure rate at age $t = 1$. This is dependent on the scale used. For example, if ageing takes place over years but age t is expressed in hours, λ_0 will be the failure rate at age one hour, a difficult quantity to measure. For this reason, and to reduce the statistical correlation of the estimators of λ_0 and β, it is recommended centring with t_0 chosen as in the previous subsections, using the formula:

$$\lambda(t) = \lambda_0 (t / t_0)^{\beta}, \tag{1.19}$$

with $\beta > -1$.

Then λ_0 is the failure rate at the age t_0.

1.4.4. Modified Weibull ageing

An additional base rate could be used, so that: $\lambda = \lambda_0 + at^{\beta}$.

However it is hard enough to estimate two parameters with the limited available data.

1.5. SAMPLING AND UNCERTAINTY MEASURES

The quantitative uncertainty analysis results can be expressed as percentiles (e.g. 5% and 95%) of the result distribution [11]. They could be obtained easily if result distribution is known. In practice these percentiles are estimated using parameters subjective probability distributions and Monte Carlo simulations. The quantitative uncertainties of model parameters can be expressed by the parameters distribution with mean and standard deviation values. Standard deviation in normal distribution case can be assumed as a value, which is three times less than the interval between maximum and minimum values. If distribution is untruncated, the probability that parameter value belongs to this interval is 0.866. Otherwise, if distribution is truncated, the probability is equal to one.

In addition, possible impact of the sampling error is considered. Usually this can be done by computing (u, v) statistical tolerance limits [15]. Where v is the confident level that maximum model result will not be exceeded with the probability u (or $u\%$ percentile, which reflects the amount of combined influence of all quantified uncertainties) of the corresponding output distribution, which is to be compared to the acceptance criterion. According to the classical statistical approach the confidence statement quantifies the possible influence of the fact that only a limited (frequently small) number of model runs have been performed. For example, according Wilks' formula [16], 93 runs are sufficient to have two sided (0.95, 0.95) statistical tolerance limits. The required number n_1 of runs for one-sided tolerance limits and correspondingly the number n_2 for two-sided statistical tolerance intervals can be expressed as following:

$$n_1 \geq \ln(1-v)/\ln(u)\ ;\ n_2 \geq (\ln(1-v) - \ln((n_2/u)+1-n_2))/\ln(u)\ , \qquad (1.20)$$

The minimum number of model runs needed for these limits is independent of the number of uncertain quantities taken into account and depends only on the two probabilities u and v given above. The amount of runs is a result from nonparametric statistics. Its advantage is that this amount is completely independent to the number of uncertainties taken into account and does not assume any particular type of underlying distribution. The distribution event does not need to be continuous [15].

2. RESEARCH AND TESTING PART

2.1. SYSTEM OF DIESEL GENERATORS

The research and testing part in this work is mostly based on unavailability and testing analysis of diesel generators system in Ignalina nuclear power plant.

Diesel generators are usually part of the emergency power supply system of power reactors. The diesel generators are the subsystems of the overall emergency power supply system. The boundary of diesel generator set defines the interfaces to the surrounding system. The set consists of:

- Diesel engine, generator, and generator output breaker;
- Switchgear equipment with overload protection;
- Control equipment, logic, and instrumentation;
- Service systems (fuel, compressed air, coolant water, lubricant).

The Diesel Generators System of the Ignalina NPP is one of the most redundant EDGS at any NPP in the world. However, the testing frequency is not considered in relation to EDGS redundancy, availability and system reliability data. One month testing interval for EDGS is used at present time in The Ignalina NPP [5]. Besides, the decision-making concerning the testing of EDGS is not based on actual statistical data of failures.

In order to prevent the occurrence of failure at an actual demand the latent and other faults are detected and eliminated on tests. On the other hand, too frequent testing may degrade the equipment and cause failures. Through a proper choice of testing interval, the negative and positive effects of testing are proposed to be balanced against each other.

2.2. SELECTION OF MODEL CHARACTERISTICS

Diesel generators unavailability model is described in section 1.2. Reliability parameters for this model are estimated from the statistical data, kept in Ignalina NPP Failures Journal [2].

Table. 2.1 The total time of considered period for each DG is 10 years (3650 days or 87600 hours).

2.1 Table

Statistical data and characteristics related to DG maintenance

Characteristic	Variable	1 DG	12 DG
Total lifetime, days (h)	T_T	*3650 (87600)*	*43800 (1051200)*
Operational time, days (h)	T_O	*6.76 (162.33)*	*81.17 (1948)*
Number of demands or tests	N_D	*125.25*	*1503*
Exceptional demand or tests	N_E	*16*	*192*
Number of LC faults on start	N_{LCS}	*2.58*	*31*
Total number of faults	N_F	*9.17*	*110*
Number of LC faults	N_{LC}	2.58	31
Number of MC faults	N_{MC}	2.92	35
Number of NC faults	N_{NC}	3.67	44
Total repair time, h	A_T	*308.75*	*3705*
LC faults repair time, h	A_{LC}	81.00	972
MC faults repair time, h	A_{MC}	159.50	1914
NC faults repair time, h	A_{NC}	68.25	819

It should be noted that the uncertainty intervals of the parameters are relatively large due to sparse data and inhomogeneities. Using Bayesian approach there is possibility to estimate the data uncertainty and to model the initiating event frequencies more precisely. There are rates for some failure modes, which usually is not available due to incomplete plant specific data base. In this case the general data (e.g. presented in T-Book) can be applied. Using Bayesian approach there is possibility to estimate the failure rate and express uncertainty using the confidence limits (e.g. 5% and 95%) for failure rate mean [1].

2.2 Table

Unavailability model estimated parameters

Unavailability mode	Parameter	Unit	Value
LC failures	q_{LC}	–	3.0E-3
	λ_{LC}	1/hour	4.38E-6
	a_{LC}	hour	4.44
MC failures	λ_{MC}	1/hour	6.4E-7
	a_{MC}	hour	6
NC failures	λ_{NC}	1/hour	2.43E-5
	a_{NC}	hour	7.13
Testing	τ	hour	1
	E	–	1

In practice usually there is available only conservative estimates of failure rate related to failure to start DG on demand. For Ignalina NPP case, there is conservatively assumed that failure to start is any failure revealed at demand day. The calculated failure to start rate is assumed equal to latent critical failure rate λ_{LC}. The summary of failure to start data of DGs is presented in following

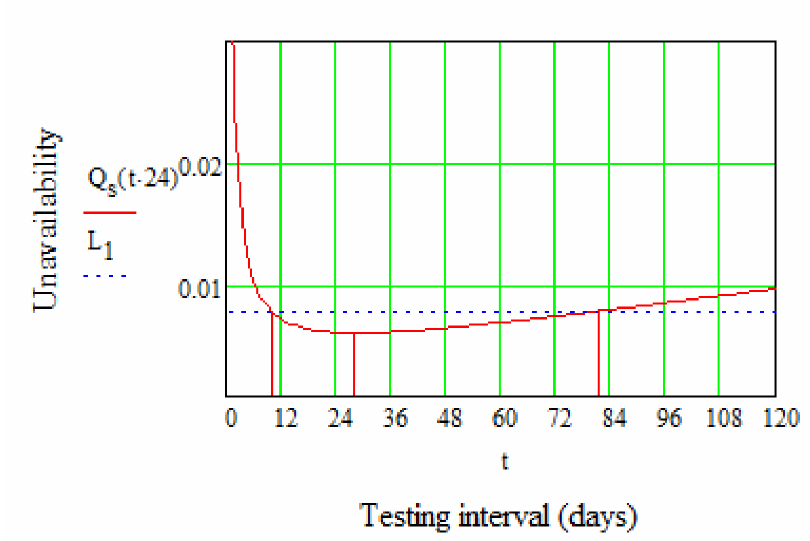
There is no criterion, which defines the allowable unavailability of EDGS in Ignalina NPP, however it is stated the design failure rate for one DG: $\lambda_D = 6{,}8 \cdot 10^{-3}$, from which the limiting unavailability of considered system can be assessed.

2.3. UNAVAILABILITY MODEL AND CHANGING OF TESTING INTERVAL

Referring to Wilks formula [15] and in section 1.5 described methodology of uncertainty analysis, 100 numerical simulations were performed.

Unavailability model for one DG (2.1) was calculated with the set of parameters from table 2.2 in (2.1 Fig.).

$$Q(T) = \left(\frac{1}{T} \int_0^T u(t)\,dt + \frac{u(T) \cdot 4.44}{T} \right) + \left(6.4 \cdot 10^{-7} \cdot 6 \right) + \left(2.43 \cdot 10^{-5} \cdot 7.13 \right) + \frac{1}{T}. \qquad (2.1)$$



2.1. Fig. Unavailability dependence on testing interval for one DG

The minimal unavailability value $6.177 \cdot 10^{-3}$ corresponds to the statistically most reliable 681.931 hours or about 29 days testing interval. However the limiting unavailability is $7.97 \cdot 10^{-3}$. Under this margin the unavailability does not exceed safety requirements. This means that in some cases the testing interval could be changed in the bounds of 11 and 82 days.

2.3 Table

Change of testing interval

	Best estimate	Minimal limit	Maximum limit
Testing interval (days)	28	11	82
Average unavailability	$6.177 \cdot 10^{-3}$	$7.97 \cdot 10^{-3}$	$7.97 \cdot 10^{-3}$

Again, it should be accented, that thought more frequent testing should eliminate the failures straight after their occurrence, however too often testing can raise failures because of ageing device.

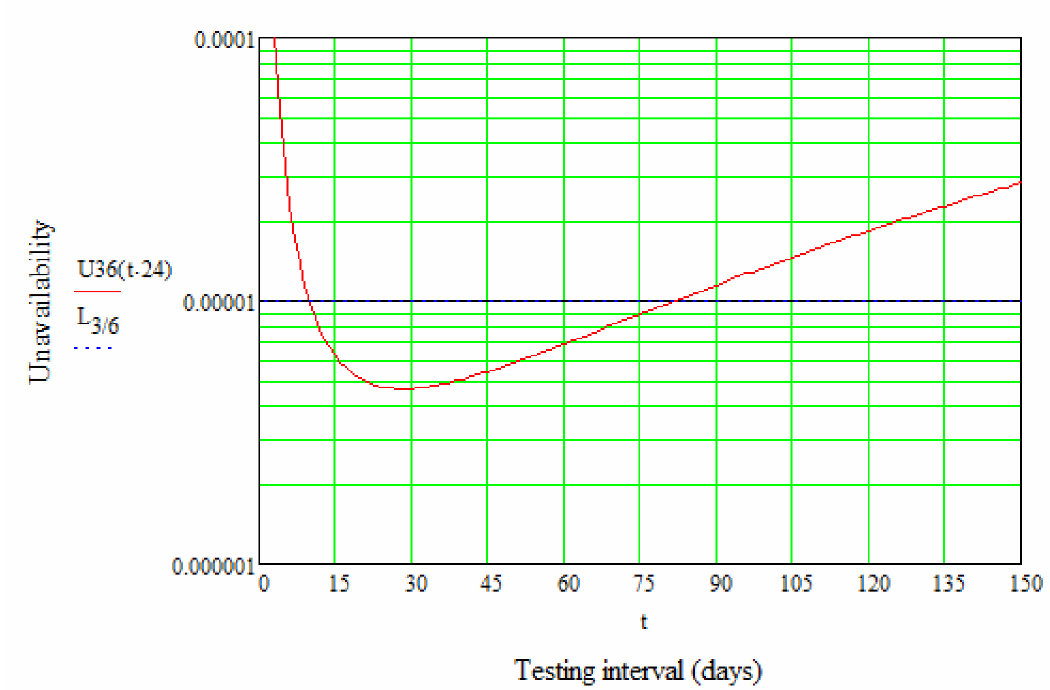
2.4. UNAVAILABILITY FOR SYSTEM OF GENERATORS

EDGS system "non-success criterion" for one Ignalina NPP unit with six DGs is the failure of four DGs, while the "success criterion" is three out of six DGs. In the case when four DGs would fail EDGS system cannot ensure function of safety system and it exceeds the limits of safe NPP operation.

Within one month 1 of 12 DGs cannot perform the designated functions because the annual preventive test is performed. Thus, for one unit only 5 of 6 DGs are available.

Considering EDGS "success criterion" the 3 out of 6 redundant EDGS unavailability level was analysed. (2.2) formula expresses the system unavailability model:

$$U_{3/6}(T)=\sum_{m=3}^{6}\frac{720}{m!(6-m)!}Q(T)^m\left(1-Q(T)\right)^{6-m}. \qquad (2.2)$$



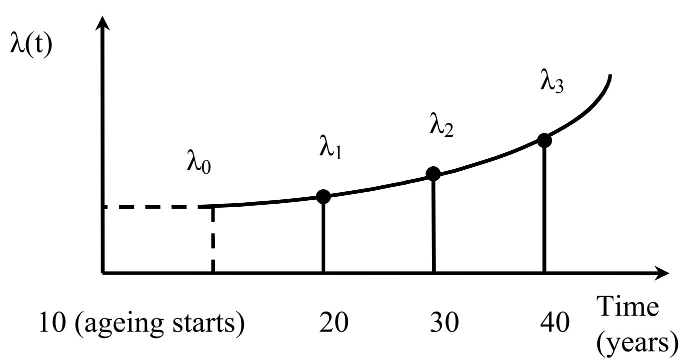
2.2. Fig. Unavailability of the system of DGs depending testing intervals

In this case the limiting unavailability was estimated as $9.9\cdot10^{-6}$.

2.5. AGEING OF UNAVAILABILITY MODEL CHARACTERISTICS

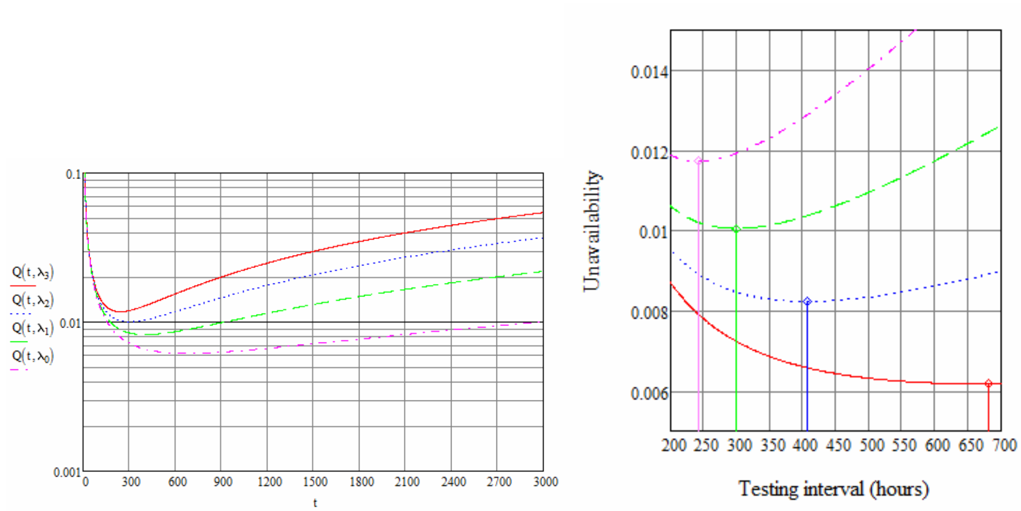
As it was explained in section 1.4, from some moment of time, unavailability increases because of so called "wear out" failures. The greatest impact on model results has unavailability characteristic λ, that is why in this work we model its changes depending on age of device.

The period of 10 years was chosen as the beginning of ageing process for Ignalina NPP DGs system. Model characteristic changes were investigated every 10 years (2.3 Fig.).



2.3. Fig. Failure rate dependence on operating time

With generated λ characteristic values we could evaluate the whole model results. It is notable, that with characteristic changes, the system unavailability grows up as shown in 2.4 Fig.



2.4. Fig. Device unavailability and testing interval change concerning ageing

Finally, the minimal unavailability corresponding interval between tests is getting shorter. This means that with system ageing the testing procedure must be initiated more often every year (2.4 Fig.) and 2.4 Table.

2.4 Table

Change of testing interval concerning ageing

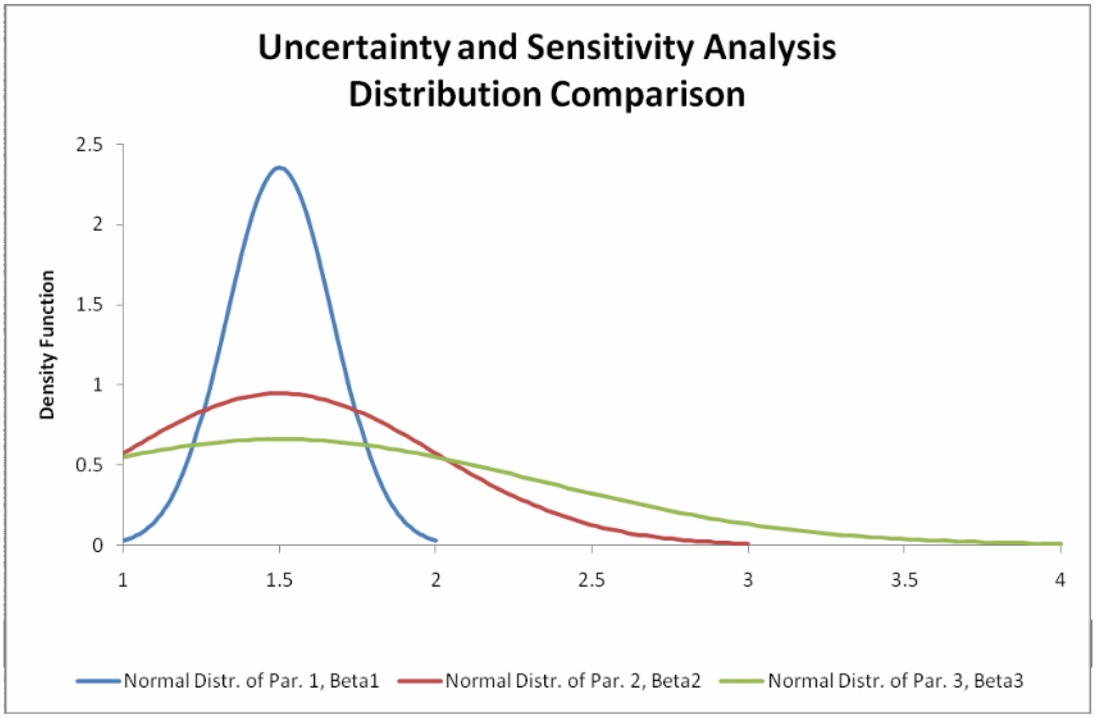
Time interval (years)	<10	(10; 20)	(20; 30)	(30; 40)
Minimal unavailability	$6.17 \cdot 10^{-3}$	$8.231 \cdot 10^{-3}$	0.01	0.012
Corresponding testing interval (hours)	682	406	300	242

2.6. UNCERTAINTY ANALYSIS

2.6.1. Uncertainty analysis for initial values

2.6.1.1. Ageing parameter β uncertainty

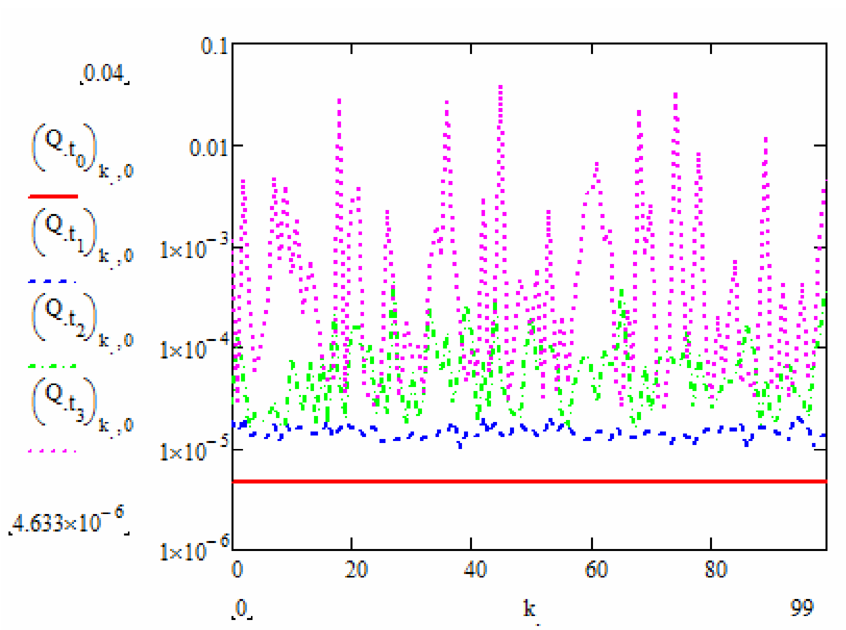
In order to show how the initial system parameter's uncertainty affects all the model result uncertainty, ageing parameter β was generated in SUSA using left side truncated distributions (read about in *Appendix 4* Truncated distributions). It was assumed that parameter β uncertainty is changing because of ageing. The initial value 1,5 as a mean and the minimal limit of 1 was taken for the distribution. The upper limit (maximum) was changed by 2, 3 and 4 respectively, considering the growing standard deviation.



2.5. Fig. Ageing parameter uncertainty

2.6.1.2. Failure rate λ as uncertainty model characteristic uncertainty

The change of ageing parameter β uncertainty concerning degradation generates different distributed failure rate λ values represented in 2.6 Fig.:



2.6. Fig. Model characteristic λ uncertainty changing depending ageing

The two-sided statistical tolerance limits (with given probability $u = 0.95$ and confidence $v = 0.95$) were used to express results uncertainty. The interval between these limits contains at least 95% of uncertain results at a classical statistical confidence level of at least 95%.

Two sided tolerance limits formed by sample extremes for different ageing stages are introduced in 2.5 table:

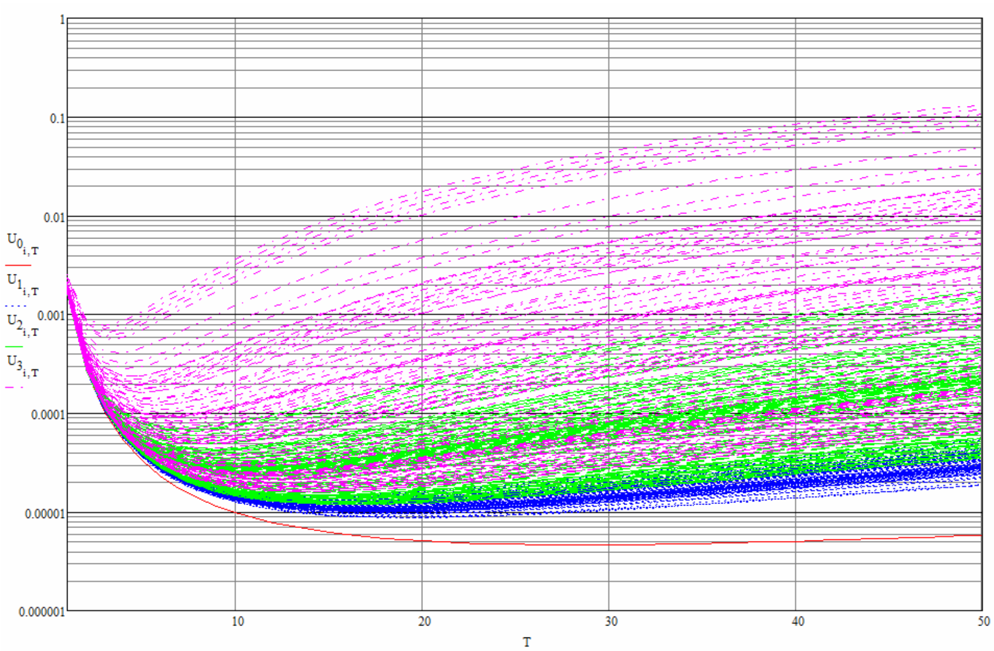
2.5 Table

Extreme values of characteristic λ for different ageing

Time interval (years)	<10	(10; 20)	(20; 30)	(30; 40)
Minimum	$4.38 \cdot 10^{-6}$	$9.66 \cdot 10^{-6}$	$1.35 \cdot 10^{-5}$	$1.84 \cdot 10^{-5}$
Maximum	$4.38 \cdot 10^{-6}$	$1.66 \cdot 10^{-5}$	$7.10 \cdot 10^{-5}$	$4.34 \cdot 10^{-4}$

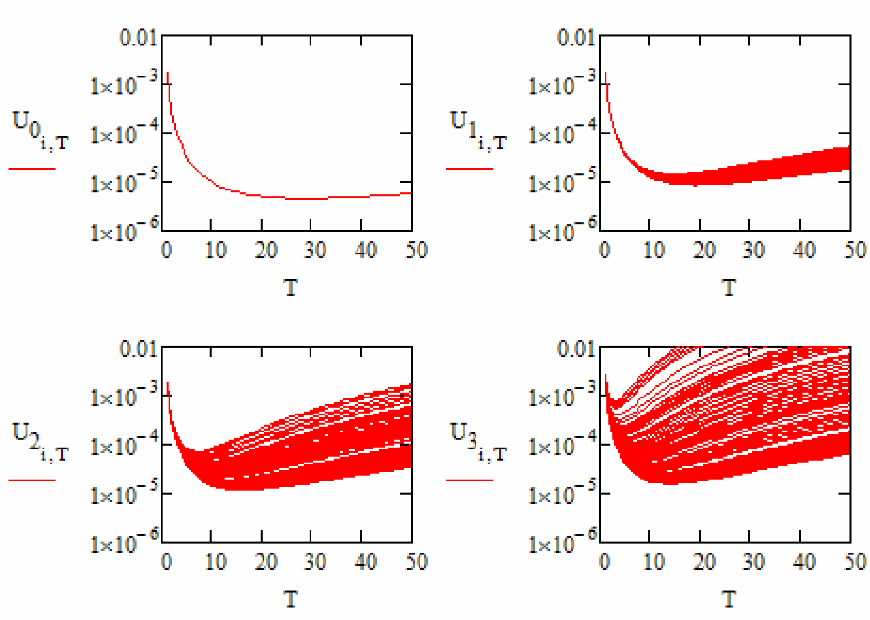
2.6.2. System uncertainty analysis

Followed by generated ageing parameter β values, the system unavailability characteristic λ and the whole model values were calculated. In 2.7 figure U_0 denotes the unavailability changes with constant λ value and U_1, U_2, U_3 – unavailability with growing λ after 10, 20 and 30 years in ageing respectively.



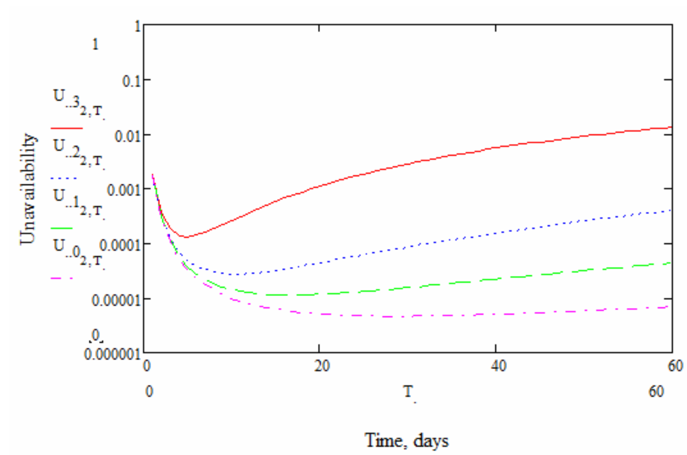
2.7. Fig. Uncertainty of system unavailability for changing ageing

In 2.8 Fig. we can see how system uncertainty changes every decade. Starting with small imprecision U_1 it rises up to the level, where the model evaluation becomes unreliable U_3.



2.8. Fig. Uncertainty dependence on age

In 2.9 Fig. mean values for unavailability model are represented every 10 years. It is significant that unavailability is growing up rapidly. This means that at the same testing interval level unavailability can exceed limiting unavailability. Therefore, corresponding to ageing effect, the testing interval, has to be shortened to keep unavailability under the reliable limit.



2.9. Fig. System uncertainty for each decade

When the ageing starts, the unavailability for testing interval of $T = 30$ days is little distributed. For later ageing, distribution is growing. The uncertainty limits, expressed by unavailability extremes, are represented in 2.6 table. Uncertainty grows with the ageing and the issue of testing interval determination is turning to be impossible.

2.6 Table

Extreme values of mean unavailability for different ageing, when testing interval $T = 30$ days

Time interval (years)	<10	(10; 20)	(20; 30)	(30; 40)
Minimum	$4.642 \cdot 10^{-6}$	$1.039 \cdot 10^{-5}$	$1.671 \cdot 10^{-5}$	$2.767 \cdot 10^{-5}$
Maximum	$4.642 \cdot 10^{-6}$	$2.331 \cdot 10^{-5}$	$5.019 \cdot 10^{-4}$	$4.5 \cdot 10^{-2}$

SUMMARY AND CONCLUSIONS

1. In this work system unavailability and reliability control methods were analysed. Analysis showed that unavailability Q of a device can be modelled concerning different failure critical levels and detection ways that make this modelling technique applicable for different mechanical and electronic devices. Also the whole system unavailability model $U_{3/6}$, which depends on system designed success and failure rates, was defined.
2. Model of testing interval T dependent unavailability $U(T)$ was analyzed with fixed (constant) reliability characteristics (e.g. failure rate λ). Using this model with certain limiting unavailability level L_C, which cannot be exceeded, enables to change testing interval T.
3. Reliability characteristics change concerning age of device was investigated. Depending on parameters change because of ageing, system unavailability estimation methodology was developed. For the reliability characteristics ageing simulation Weibull ageing model was used. Analysis showed that while the device is degrading, system unavailability is growing and the minimal unavailability corresponding interval T between tests is getting shorter. On the other side, keeping the same testing interval with the ageing impact, mean unavailability of the system is growing with potential chance of breaking limiting unavailability.
4. The impact of initial ageing parameter β uncertainty on whole system model results uncertainty was investigated. It was noticed that while parameter uncertainty is growing because of ageing, model uncertainty increases significant. Consequently the testing interval determination issue is getting impossible.

PADĖKOS

Norėčiau išreikšti didžiausią padėką savo magistrinio darbo vadovui dr. Robertui Alzbutui. Jo beribė energija ir mokslinis požiūris labai sudomino mane darbo tematika. Su jo pagalba aš suvokiau atliekamų skaičiavimų reikšmingumą ir naujumą šių dienų pasaulyje. Dėl R. Alzbuto išreikštų pastabų, patarimų ir sąsajų su konkrečiais realaus gyvenimo pavyzdžiais, magistrinio darbo rašymo procesas buvo įdomus ir dinamiškas.

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APPENDIX

APPENDIX 1 DIESEL GENERATOR DESCRIPTION:

Diesel generator

Each safety power supply train has its own independent power source - an automatic diesel generator mod. ASD-5600. Diesel generators are installed in building 111. They are independent on one another, as each diesel generator is installed in a separate compartment. The compartments are separated by walls and there is separate entrance into each one. There are no passages from one compartment into another.

Systems, individual for each diesel generator, are assembled in the compartments:

- batteries of start-up compressed air containers, which provide start- up without compressed air supply from outside;
- power distribution assembly for house loads of diesel generator with accumulating battery;
- fuel system with working tank;
- control cabinet for equipment control, control cabinet for diesel generator control, control cabinet for generator control;
- pumps and equipment of water, oil and fuel systems of diesel generator;
- heating and ventilation systems of compartments.

Outside the compartments for each generator there is:

- separate fuel reserve tank underground;
- individual procedure for diesel generator start- up in case of loss of power in 6kV bus of reliable supply.

The following is common for all diesel generators:

- two headers of technical water supply, which get power from technical water pumps of Units 2 and 1. 3 diesel generators at each Unit are connected to them;
- outside system of compressed air containers refilled from the plant's compressed air station;
- reserve power supply to RTZO assemblies, which supply power to ventilation and lightning of the compartments (it is used in case of maintenance of house operation section of diesel generator).

Diesel generator has the following technical characteristics:

- maximum power without restrictions: 5600 kW
- nominal rotational speed of the shaft: 1000 rpm
- three-phase AC
- nominal voltage: 6300 V

- nominal frequency: 50 Hz
- fuel consumption at full power: 228 g/kWh
- specified operating time without interruption before the first diesel generator maintenance outage: 1600 h.
- fuel reserve is 10 m^3 in the flow tank of every diesel;
- fuel reserve is 100 m^3 in the outer tank of every diesel.

Diesel-generator is started to provide power for the loads from the "duty" mode, with the air temperature in the room above zero and water and oil temperatures in the diesel systems minimum +20°C. The interval between the starting pulse is generated and the moment diesel is ready to pick up and carry the load is maximum 15 s, with the starting air pressure in pressure tanks in the range from 32 kgf/cm^2 to 25 kgf/cm^2.

The generator running at no-load provides startup of asynchronous motor with the power up to 30% N_{nom} of the diesel.

Under all conditions the generator can carry the following temporal current overloads under nominal voltage and frequency:

- 10%: during 2 hs
- 25%: during 30 min.
- 50%: during 5 min.

with coσφ of load = 0.6¸0.7.

After overloading the generator retains its capability to operate under nominal load and can survive further temporal overloads during the whole remaining lifetime. To supply power to DG house loads, a special 6/0.4 kV transformer (mod. TSZ-250 kV·A) is connected (via circuit breaker and cable) to the safety power supply bus, which is connected to the diesel generator. This transformer is sited in the same compartment as the DG and it supplies power to KTPSN-0.5. The latter is used to connect the following equipment via A3700 automatic equipment:

- cabinets for house loads (ShSN-1,2 type);
- assemblies mod. TZO-69, Sh-196, Sh-197;
- rectifier for re-charging accumulating battery of the diesel.

The RTZO-69 assemblies used to supply power to ventilation in rooms and provide lights in the compartments are provided with a backup supply from the 1LG11 assembly which is powered from 0.4 kV normal power supply bus 1CC07 at Unit 1.

Operating and standby pumps of the water, oil and fuel systems are connected to different house loads cabinets.

Diesel generators are maintained in a hot standby automatically. Control, protection and alarm circuits ASD-5600 are supplied with rectified ±24V DC from rectifier and accumulating battery of the 19NKG-10D type connected in parallel, with nominal capacity of 10 A·hours.

The DG control system provides automatic control and monitoring of all process operations during startup, on-load operation, normal and emergency shutdowns and under the "duty" mode. In addition to the automatic control, diesel can be controlled locally by operator from the equipment control cabinets.

The function of automatic and manual diesel control is performed by ***a complex control device of the KUAS-5600 typ***e. The latter ensures:

1. diesel generator availability for automatic startup at any moment;
2. routine startup in response to a short signal (min. 0.2 s and max 5 s) coming from remote control boards in MCR and RCR, with the startup command overriding normal disconnection command;
3. technological startup from the diesel control cabinet or from MCR or RCR during testing;
4. closing of the generator switch when the generator voltage reaches at least 95% of the nominal value;
5. automatic maintaining of the output generator voltage within the specified limits;
6. generator protection;
7. supply of 21-28 V DC. to the automatic control system;
8. continual re-charging of accumulating batteries;
9. alarms;
10. remote alarm in MCR and RCR indicating DG fault or unavailability;
11. normal and emergency shutdowns of the DG;
12. house power control;
13. startup of DG to operate in parallel with the grid by way of fine manual synchronization.

APPENDIX 2 SAFETY ANALYSIS REPORT 25.10.96

Ignalina NPP SAR Task 6

Emergency Power Supply - Diesel Generators Testing Program

INPP surveillance testing of the emergency diesel generators reflects the requirements of the Technological Regulations for Operation of Ignalina Nuclear Power Plant with RBMK-1500, Inventory No. 0-380 and the Regulations for Nuclear Safety of the Nuclear Power Plant Reactors (PNAE G-1-024-90).

INPP SAR Task 6 - Guidance for Inspection and Testing of Safety-Related Systems of Ignalina NPP Units with RBMK -1500 Reactors specifies, in Appendix VI – Guidance for Inspections and Tests of Safety Systems in the Department of Process Nitrogen and Oxygen Workshop, Section 1, Emergency Power Supply System, the requirements for Emergency Diesel Generator testing.

The INPP guidance specifies monitoring, checking and testing requirements for the Emergency Diesel Generators and their supporting systems, including the oil system, fuel system, internal cooling system, external cooling system (including the service water system), and the air starting system.

Similar to the pump and valve testing programs, the INPP guidelines for diesel generator surveillance testing are different from Western standards in that they include selected operational monitoring, checking and testing requirements normally performed by the shift operations personnel. These additional monitoring functions are listed on a per shift, daily or weekly basis and include normal operating parameters, instrumentation checks, alarm circuit checks, and monitoring of normal performance indicators. Actual surveillance testing requirements are listed as monthly, yearly or on a longer frequency basis.

The INPP guideline reviewed reflects a complete scope, schedule and type of test to be performed for each diesel generator and its supporting systems and components. The table of inspections and tests identifies the component to be tested, the design feature, attribute or parameter to be tested, test frequency, applicable implementing instructions, procedures and work programs, responsible test engineer and reporting/recording requirements. The table includes frequency requirements for shift work (continuous, once per shift, twice per shift, etc.), weekly, monthly, annually, every two, three, five years, etc.

The actual surveillance program specifies selected diesel generator operational performance indicators to be continuously monitored and supervised in the control room. In addition, the diesel generator and supporting systems (including the emergency battery and the 6kV and 0.4 kV transformers) are walked down on a per shift basis and local instrumentation of operational performance indicators is logged.

The surveillance testing program specifies several periodic diesel generator performance tests. Some tests are performed during power operations at one month and three month intervals. These tests are specified as follows:

- at least once a month each diesel generator is tested to check its operation in parallel with the 6 kV grid under 35% continuous overload for a minimum of 30 minutes; this test includes a trial diesel start-up from the diesel battery.
- at least once every 3 months uninterruptible power supply equipment is tested and maintenance performed online.
- at least once every 3 months a trial connection and disconnection of the main and auxiliary transformers is performed with the diesel generator normal and emergency power supply transformers.

More rigorous system functional testing and preventive maintenance is performed during planned outages. These include:

Once per year (Functional Tests):

- Perform routine preventive maintenance.
- Test the functioning of control relays to automatically start the diesel generators and perform a step-by-step connection of loads, simulating the loss of the 6 kV transformer.
- Test the functioning of control relays to automatically start the diesel generators due to an automatic bus transfer switch caused by one of the following:
- actuation of emergency protection
- low voltage in the 110V or 330 V bus
- trip of the only one operating turbine generator
- Test start 3 diesel generators from individual turbine generator power setback panels.
- Check that standby equipment powered from the normal 6 kV bus will automatically start or restart from the energized diesel generator buses.
- Check automatic start of standby equipment for diesel generator supporting systems, including DG transformer cooling.

Once per year (Performance Test):

Once a year and after each diesel maintenance a test is performed to check the diesel generator operation in parallel with the grid under full load during at least 30 minutes.

Once every 2 years:

- Once every 2 years test discharge the accumulating batteries.

Once every 6 years:

- Test the automatic switching feature of the 110 kV grid to the 6 kV safety sections.
- Test the performance of the uninterruptible power supply (UPS) under total loss of house power.

Based upon a review of the INPP Guidelines for Inspection and Tests of the Ignalina NPP Diesel Generators and other information provided in the referenced documents in this report, the INPP surveillance testing program for the emergency diesel generators and support systems appears to be an adequate testing program.

APPENDIX 4 TRUNCATED DISTRIBUTIONS

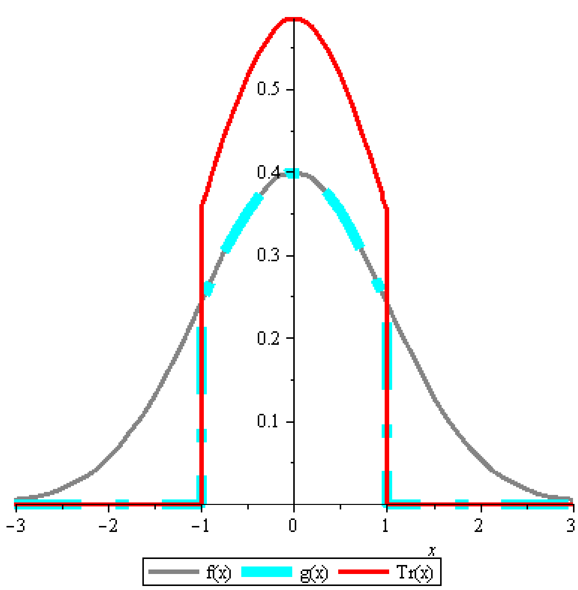
A truncated distribution (2.10) is a conditional distribution that is derived from some other probability distribution. Suppose we have a random variable X that is distributed according to some probability density function $f(x)$, with cumulative distribution function λ_0 both of which have infinite support. Suppose we wish to know the probability density of the random variable after restricting the support to be between two constants so that the support $y=(a,b]$. That is to say, suppose we wish to know how x is distributed given $a<x\leq b$.

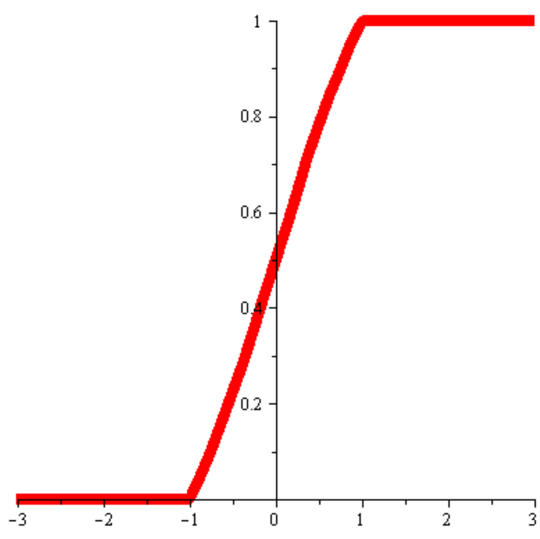
$$f(x|a<x\leq b)=\frac{g(x)}{F(b)-F(a)}=Tr(x)$$

where $g(x)=f(x)$ for all $a<x\leq b$ and $g(x)=0$ everywhere else. Notice that $Tr(x)$ has the same support as $g(x)$.

There is, unfortunately, an ambiguity about the term Truncated Distribution. When one refers to a truncated distribution they could be referring to $g(x)$ where one has removed the parts from the distribution $f(x)$ but not scaled up the distribution, or they could be referring to the $Tr(x)$. In general, $g(x)$ is not a probability density function since it does not integrate to one, where as $Tr(x)$ is a probability density function. In our case, a truncated distribution refers to $Tr(x)$.

In 2.10 Fig. the red line is a truncated standard normal distribution, truncated at -1 and 1





2.10. Fig. PDF and CDF for the truncated distribution

Notice that in fact $f(x|a<x\leq b)$ is a distribution:

$$\int_a^b f\left(x \middle| a < x \le b\right) dx = \frac{1}{F(b) - F(a)} \int_a^b g(x)\, dx = 1 .$$

Truncated distributions need not have parts removed from the top and bottom. A truncated distribution where just the bottom of the distribution has been removed is as follows:

$$f\left(x \middle| x > y\right) = \frac{g(x)}{1 - F(y)}$$

where $g(x) = f(x)$ for all $y < x$ and $g(x) = 0$ everywhere else, and $F(x)$ is the cumulative distribution function.

A truncated distribution where the top of the distribution has been removed is as follows:

$$f\left(x \middle| x \le y\right) = \frac{g(x)}{F(y)}$$

where $g(x) = f(x)$ for all $x \le y$ and $g(x) = 0$ everywhere else, and $F(x)$ is the cumulative distribution function

APPENDIX 4 PAPER TO MIMM CONFERENCE

ESTIMATION OF SYSTEM FAILURE RATE AND TESTING INTERVALS CHANGE CONSIDERING AGEING

Justinas Petkevičius, Robertas Alzbutas

Kauno technologijos universitetas

Introduction

Diesel generators (DGs) are part of the emergency power supply system of power reactors. Since these DGs are standby equipment and operate only during demand or during surveillance tests, their demand failure probability and operational unavailability should be very low. DGs are usually tested periodically. In order to prevent the occurrence of failure at an actual demand the latent and other faults are detected and eliminated on tests. On other side, too frequent testing may degrade the equipment and cause failures. Through a proper choice of testing interval, the negative and positive effects of testing can be balanced against each other. Because of an ageing the failure rate rises and causes the changes of unavailability and testing period. In practice, the testing frequency is chosen mainly by engineering judgment, and according to general practices. Having the failure frequency data, the mathematical modeling can be used to support the decisions related to the testing interval.

The objective of proposed paper is to review statistical models for system reliability control and to investigate the possibility to optimize or change the testing intervals of DGs in such a way, that the safety level of whole system would not be decreased. The investigation was performed by modeling failure rate changes of system elements and the DGs unavailability dependence on testing intervals.

Failure models

Availability $A(t)$ is the probability that a system is operating at time t while reliability $R(t)$ is the probability that the system has been operating from time t_0 to t. Unavailability is the complement of availability, i.e. the probability that an item does not function when required. Periodic testing cannot affect reliability, but does affect availability and at same time unavailability.

In general, the reliability of stand-by systems is related to unavailability mean, which is established by assessing the probability that system cannot perform designated functions in case of random demand. DGs unavailability is mostly influenced by the failure rate and their types. The failures generally are divided into two main types: monitored (observed) failures and latent failure, which are also called as hidden failures. In addition, according to the safety features, there are critical and non-critical failures (Table 1) [1], [2].

Table 1. Failure modes of stand-by component [1]

Occurrence type	**Effect**	
	Prevents the operation	**Does not prevent the operation**
Monitored	Monitored Critical – MC	Monitored Non-critical – MN
Latent	Latent Critical – LC	Latent Non-critical – LN

Unavailability due to critical and non-critical failures unobserved during the maintenance is related to the maintenance time, while the latent critical failures influence the unavailability both due to their maintenance and undetected occurrence. When critical failure occurs, system cannot perform some of the designated functions until the time when this failure is found, i.e. until the testing.

Total unavailability mean can be expressed by function, which depends on testing interval length T (period between tests). In general, it is a sum of three components, related to the impact of different type of failures, and one component, which defines testing time impact:

$$Q(T) = Q_{LC}(T) + Q_{MC} + Q_{NC} + Q_{TS}(T). \quad (1)$$

The latent critical faults contribute to expected unavailability during stand-by time, but the operator does not know their presence until the next test or demand. Total latent critical failures unavailability mean, taking into account due to maintenance formed average idle time a_{LC} impact, is expressed by formula:

$$Q_{LC} = \frac{1}{T}\int_0^T u(t)\,dt + \frac{u(T)\,a_{LC}}{T}. \quad (2)$$

Function $u(t)$ is instant latent critical failures unavailability. For system modeling it is assumed that all observed failures occur with constant rate λ_{MC}. Observed critical failures unavailability average, taking into account due to the maintenance formed average idle time a_{MC} impact, is expressed by formula:

$$Q_{MC} = \lambda_{MC} \cdot a_{MC}. \quad (3)$$

If non-critical failures occurrence rate is λ_{NC}, and for the maintenance an average idle time - a_{NC}, then of those failure impacting to the unavailability expression is:

$$Q_{NC} = \lambda_{NC} \cdot a_{NC}. \quad (4)$$

Testing duration impact to the unavailability is defined by formula:

$$Q_{TS} = \frac{\tau}{T}E, \quad (5)$$

where τ is a testing duration, while E is an estimated probability that system functioning demand will not be fulfilled during the testing.

If during the testing system demand is found and it automatically is turned into the normal functioning mode, then testing duration's impact to the unavailability practically becomes insignificant ($E = 0$). In other extreme case, when system during the testing was absolutely disconnected, $E = 1$ and impact of system testing duration is maximum.

Seeking to optimize DG testing interval T mean DG unavailability was analyzed. Earlier analyzed mean unavailability function is expressed as a sum of four terms, which describe the impact of different failures and testing duration.

One of the main parts influencing the unavailability variation, which depends on testing interval, is related to latent critical failures. The main feature of latent failures is that their existence is unknown until the system is in stand-by mode.

These failures usually are described by probability, called instant unavailability. Typically the simplified model is used for the calculation of instant unavailability $u(t)$:

$$u(t) = q + \lambda t, \tag{6}$$

where q - time independent unavailability term;

λ – failure rate (dependents on time);

t – time after the previous test or demand.

In considered application it was used more precise model, where the failure distribution itself was used but not it's linear approximation. In such a case the expression of instant unavailability is:

$$\mathrm{U}(t) = q + (1-q)\left(1 - e^{-\lambda t}\right). \tag{7}$$

Time independent unavailability parameter q reflects the failures, which occur during the testing and they are not observed until the next testing or demand, and the failures, whose failure mechanism is related to the testing or system functioning and does not reveal itself in the stand-by mode.

Unavailability part q_{LC}, which is influenced by latent critical failures, does not depend on time. This part is calculated by dividing the number of latent critical failures observed during the testing by the number of testing. Failure rate λ (part depends on time) for the corresponding failure types is obtained by calculating relation between the observed number of failures during the testing and the duration, when these failures occurred. Mean idle time a, which as a matter of fact occurs due to maintenance, is calculated by dividing total maintenance time by corresponding number of failures.

The minimum of testing interval for one diesel generator is obtained by solving such equation:

$$\frac{d}{dz}\left(\frac{1}{z}\int_0^z u(t)\,dt + \frac{u(z)\,a_{LC}}{z}\right) + \left(\lambda_{MC} a_{MC}\right) + \left(\lambda_{NC} a_{NC}\right) + \left(\frac{\tau}{z}E\right) = 0. \tag{8}$$

For calculation of $Q(T)$ the Ignalina nuclear power plant DGs statistical data and characteristics for 10 year period from 1990-01-01 up to 2000-01-01 was used (Fig. 1)

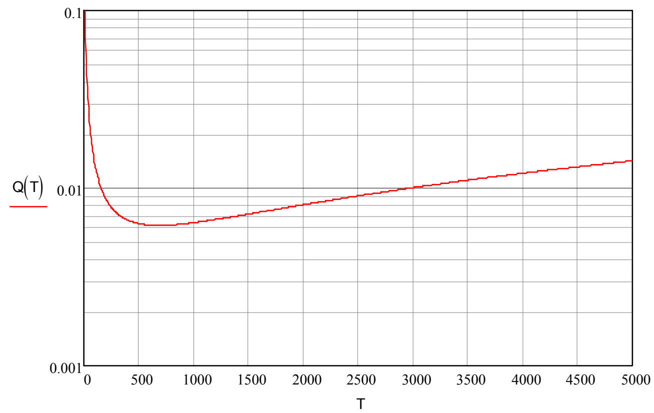


Fig. 1. Unavailability dependence on testing interval

Ageing

Ageing refers to the continuous time-dependent degradation of materials due to normal service conditions, which include normal operation and transient conditions, excluding postulated accident and post-accident conditions. [3]

Depending on devices age, their failure rate increases (Fig. 2)

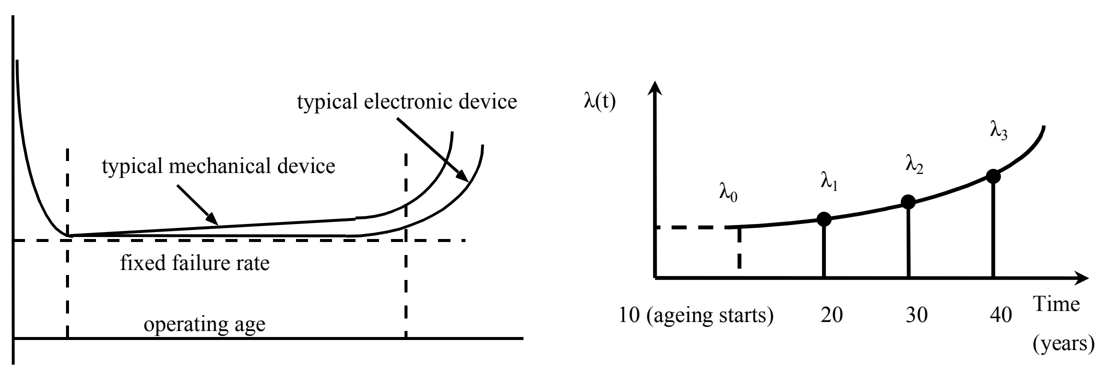


Fig. 2. Failure rate dependence on operating time

There are several methods for time dependant failure rate modeling [3], [4].

Linear ageing. The failure rate is of the form:

$$\lambda(t) = \lambda_0 + bt. \quad (9)$$

It is assumed that damage accumulates at a constant rate, and uses this to motivate linear degradation of λ. Here, λ_0 is the baseline rate and bt is the additional portion resulting from ageing. Formula can be rewritten as

$$\lambda(t) = \lambda_0(1 + \beta t), \text{ with } \beta = b/\lambda_0. \quad (10)$$

The reason for this change of notation is to make the analysis more comparable to analyses using other functional forms. To keep $\lambda(t)$ non-negative throughout the observed data period, β must satisfy the constraint: $\beta \geq -1/t_{\max}$, where $t_{\max}$ is the maximum time in the observed data set.

Linear ageing is simple, an obvious natural way to give a first-order approximation to changes in the failure rate.

When two parameters are estimated from data, the estimators may be statistically correlated. In Equation (10), if β is overestimated then λ_0 will tend to be underestimated. To minimize this correlation, the data can be centered, that is, age can be measured not from 0 but around some value t_0 other than 0. Equation (10) then becomes:

$$\lambda(t) = \lambda_0\left[1 + \beta(t - t_0)\right]. \qquad (10')$$

The constraints on β, to force $\lambda(t)$ to be non-negative, are:

$1/(t_{\max} - t_0) \leq \beta \leq 1/(t_0 - t_{\min})$, where $t_{\min}$ and $t_{\max}$ are the smallest and largest ages in the observed data set.

In this parameterization, λ_0 no longer represents the failure rate at age 0 but at age t_0. To minimize the correlation between the estimators of λ_0 and β, t_0 should be defined as the mean of all the component ages in the data. The intuitive idea is that it is relatively easy to estimate the failure rate in the middle of the data, λ_0.

Having done this, the linear trend line pivots around that middle value. The slope of the line determines β, and the estimators of the two parameters are statistically uncorrelated.

Exponential or log-linear ageing. Rather than assuming that λ increases linearly, assume that $\ln\lambda$ increases linearly:

$\ln\lambda(t) = a + \beta t$, or equivalently

$$\lambda(t) = \lambda_0 \exp(\beta t), \text{ where } \lambda_0 = \exp(a). \qquad (11)$$

This use of logarithms ensures that $\lambda(t)$ is always positive, regardless of the values of *t* and β, so the constraint on β is the trivial one: $-\infty < \beta < \infty$.

This model fits most neatly into the theory of generalized linear models. As a result, it is the default model for Poisson regression in statistical software packages.

In terms of practice, linear ageing and log-linear ageing are probably indistinguishable, except for unrealistically large data sets.

Power-law or Weibull ageing. Both terms, "power-law ageing" and "Weibull ageing", are used in the literature. The failure rate is of the form:

$$\lambda(t) = \lambda_0 t^{\beta}, \text{ with } \beta > -1. \qquad (12)$$

Equation (13) is very sensitive near t = 0. If β is positive (that is, increasing failure rate) then $\lambda(t) = 0$ at $t = 0$. If β equals 0 exactly (that is, constant failure rate) then $\lambda(t) = \lambda_0$ everywhere, including as $t \to \infty$. If β is negative then $\lambda(t) \to \infty$ as $t \to \infty$. If the sign of β is uncertain, then $\lambda(t)$ is extremely uncertain near t = 0. This fact means that one must be careful in defining the age that we call 0. Different results are obtained if age t is measured from the component's installation or, instead, from the start time of the data recording.

In the parameterization of Equation (12), λ_0 is the failure rate at age t = 1. This is dependent on the scale used. For example, if ageing takes place over years but age t is expressed in hours, λ_0 will be the failure rate at age one hour, a difficult quantity to measure. For this reason, and to reduce the statistical correlation of the estimators of λ_0 and β, it is recommended centering with t_0 chosen as in the previous subsections, using the formula:

$$\lambda(t) = \lambda_0 (t/t_0)^{\beta}, \text{ with } \beta > -1. \qquad (12')$$

Then λ_0 is the failure rate at the age t_0.

Modified Weibull ageing. **A**n additional base rate could be used, so that: $\lambda = \lambda_0 + at^{\beta}$.

However it is hard enough to estimate two parameters with the limited available data.

Time dependant failure rate

Time-dependant failure rate $\lambda(t)$ for $t = 10$, 20 and 30 years was calculated using power-law ageing model with β argument value 0.1. Then the unavailability is increasing consequently for $\lambda(10) = 4.69 \cdot 10^{-6}$, $\lambda(20) = 4.89 \cdot 10^{-6}$ and $\lambda(30) = 5.03 \cdot 10^{-6}$. Thus, in order to keep the lowest unavailability level, the testing interval T has to be shortened e.g. from initial 682 hours to 659, 646 and 637 respectively (Fig. 3)

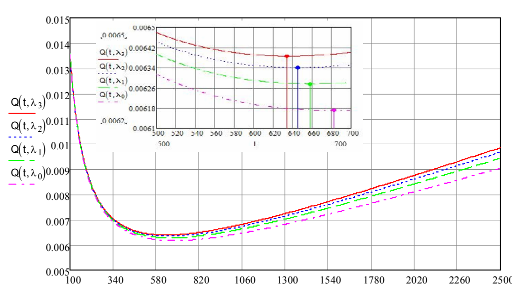


Fig. 3. Testing interval changes depending on ageing

Overview and Conclusions

The probabilistic model of diesel generator unavailability was analysed. Due to ageing effect the failure rate and the unavailability of this system is increasing. The different models of time-dependant failure rates were overviewed and power-law model was related with general unavailability model. Changing the testing interval it is possible to change the level of unavailability. The unavailability level is also changing depending on the change of failure rate due to the ageing effect. In order to keep the lowest unavailability level the testing should be more frequent, i.e. the testing interval should be shortened.

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SISTEMOS GEDIMO INTENSYVUMO BEI TESTAVIMŲ PERIODIŠKUMO KITIMO VERTINIMAS ATSIŽVELGIANT Į SENĖJIMĄ

Justinas Petkevičius, Robertas Alzbutas (*Kauno technologijos universitetas*)

Straipsnio tikslas yra pateikti tyrimą apie sistemos gedimo intensyvumo dinamiką bei sąryšį tarp neparengtumo ir testavimų periodiškumo atsižvelgiant į įrangos senėjimo efektą.

ESTIMATION OF SYSTEM FAILURE RATE AND TESTING INTERVALS CHANGE CONSIDERING AGEING

Justinas Petkevičius, Robertas Alzbutas (*Kaunas University of Technology*)

The objective of the paper is to present the investigation of system failure rate dynamics and unavailability relation with time interval between tests considering ageing effect