Ageing Effects Sensitivity Analysis

by Dynamic System Reliability Methods (GO-FLOW and ATRD)

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Abstract

The paper presents the dynamic system reliability approaches GO-FLOW and Analysis of Topological Reliability of Digraphs as extension of the fault tree methodology for NPP ageing effects sensitivity analysis. Alternative methodologies are proposed to investigate the sensitivity of increasing of failure, restore and repair rates of all component categories or changing the surveillance intervals of repairable components to take into account ageing processes in plant availability. The paper is divided into four sections: in the first one, classical methods used in sensitivity analysis are listed with their advantages and disadvantages, related to ageing; the second section describes the GO-FLOW and ATRD methods and discusses their applicability for sensitivity analysis; in the third section, a general methodology for unavailability sensitivity analysis to component ageing is presented and the fourth section gives examples of the ageing effects sensitivity analysis based on FT, GO-FLOW and ATRD equivalent models of a nuclear power plant safety system - the three-train residual heat removal and low pressure injection system of a Russian-design pressurized water reactor WWER-1000/V320.

1. Introduction

The Probabilistic Safety Assessment (PSA) methodology as the most integrated evaluation methodology of plant and process safety gives excellent opportunities for ageing safety and efficiency problems solving.

One of the tasks of Ageing Probabilistic Safety Analysis (APSA) is the incorporation of age-dependent reliability parameters and data of safety-related System, Structure and Component (SSC) into the PSA model and interpretation of its results.

The event tree (ET) and fault tree (FT) methods provide a global PSA model. They are computationally cheaper ageing-screening methods, which aim to identify the most important age-dependent SSCs of the PSA model from amongst a large number of ageing SSCs that may affect the safety, with the cost of not giving accurate information.

The ageing can affect the systems and structures only through their components. Consequently, the SSC availabilities may decrease due to the ageing of components. That is why the adjustment of the NPP PSA models on hand and its constant failure and repair rates (more precisely, failure and repair intensities) should not include the change of the models on the higher level than the component level, i.e. the system FTs are modified on the level of component ageing degradation by component basic events.

Component ageing degradation is defined as cumulative degradation that occurs during a component's lifetime and can lead to a loss or impairment of its function. The dynamic description of ageing component degradation could consist of many ageing states, multiple failure modes and transitions between these discrete basic events. All of these transitions are implemented in time, so they are age-dependent. That is why the dynamic aspects of ageing component and process management become increasingly notable and more advanced tools are needed for their analysis.

For complex PSA models of an NPP, it is helpful not only to screen the SSCs susceptible to ageing, but also to determine the reliability parameters that influence PSA model output, and values at which these parameters become influential. It could be denoted as an *ageing effects sensitivity analysis* (AESA) - hierarchical organization of the most influential input parameters on the output parameters. The AESA aims to quantify the relative importance of input of age-dependent reliability parameters and data with respect to the variability of the PSA model output. The possible issues associated with AESA are connected to:

1) Databases and failure, repair/restore models

An ageing analysis requires more data and more extended models than a standard PSA/reliability analysis. With regard to data, there is a general insufficiency of failure data records for components. Thus, ageing failure rates are estimated from raw and/or generic data and expert opinions, which generally have large associated uncertainties. The most thorough way of treating these uncertainties is to carry out sensitivity studies or uncertainties analyses using different ageing failure rates.

Different failure and repair/restore rate models can cause significant differences in the calculated results in ageing analysis. Sensitivity studies can help investigate these effects.

2) Test and maintenace model

There might be also a lack of information on detailed characteristics of specific tests and maintenances in controlling ageing to allow their precise modelling. In this case, approximate models may be used to approximate or bound the effects of the test and maintenance in controlling ageing. The sensitivity of risks/unavailability to ageing effects under given test and maintenance practices might be evaluated as well.

3) Results

The results of ageing analysis can be uncertain. Relative results and more qualitative results can be focused on to address this issue. Sensitivity and uncertainty analyses can also identify the meaningful conclusions and interpretations.

2. Sensitivity Analysis Approaches

Several approaches have been developed for performing sensitivity analyses [1]:

The deterministic method consists of carrying out a very restricted number of simulation for precise values of the parameters. Quick and simple to use, it provides, however, too little information.

The probabilistic methods consist of traversing a broad spectrum of parameters variation to have a global vision of the system behaviour, ranging from differential to Monte Carlo (MC) analysis, response surface methodology, and Sobol' indices, the Fourier Amplitude Sensitivity Test (FAST), the Morris method and extensions for non-linear and non-monotonic models. Typically, these approaches entail computing the model output several times for different input values sampled from appropriate ranges. The computation times required for numerical solution of the model often turn out to be prohibitively costly, so one has to resort to more simplified but fast models. To mitigate this problem, various methods (first-and-second-order reliability methods, response surface, directional.) can be used, which formally consist of locally studying part of the field of solution considered as criticism. These methods bring much more information that the deterministic ones, particularly because of the use of statistical tools on the variation of the output parameter, on hierarchical organization of the input parameters, etc.

A third alternative can be found in the *fuzzy logic,* which inclides replacing the probability distributions by membership functions. However, it requires a strong scientific preliminary investment, not so easy because of the physical complexity of ageing models, to set up an analytical model associated to the studied numerical model.

2.1. Monte Carlo method

The probabilistic method of Monte Carlo (MMC), sometimes called empirical method or stochastic method, is the most employed method for sensitivity analysis. Starting with the parameters whose level of knowledge is matched with an uncertainty interval, the method consists of performing a certain number of simulations (while varying parameters). So, a statistical analysis of the results obtained can be carried out, in order to determine the importance of various input parameters and their correlation.

The MMC advantages are:

- All the traditional tools of statistical analysis are used;
- The probability of an event related to an output parameter is obtained;
- The error estimate converges towards zero when the number of tests is increased;
- Tests can put forward various correlation (or non-correlation) between the parameters that could have escaped a preliminary analysis.

MMC disadvantages are:

- A great number of simulations are required;
- If any simulation is expensive in time, this default quickly becomes crippling;
- It is impossible to have complete security on the results from a qualitative point of view, the uncertainty of the parameters is determined by judgement and the output parameter is biased by this preliminary judgement;
- The probabilistic results can be sometimes difficult to interpret, and they are certainly not easy to present to a non-expert audience;
- The method requires the establishment of functions of distribution for various dubious parameters. It can sometimes be very difficult and vague.

2.2. First-and-second-order reliability methods

The first-and-second-order reliability methods (FORM and SORM) methods are used to determine the failure function. Beginning with an output parameter, which is associated to a breaking value or threshold that we wish not to exceed, these methods determine a function border or failure function (noted *H*), which determines the frontier between the output values to the lower part and upper part of the threshold. These methods are generally catalogued as probabilistic methods and can be used jointly with the methods of the Monte Carlo type. Indeed, they make it possible to identify the most influential areas on the probability of failure (for example, they allow to determine where to apply an importance sampling, to minimize the number of tests by maximizing the quality of the result).

FORM and SORM advantages are:

- One of the advantage of these methods is their lower cost. One can theoretically detrmine for which values of the input parameters the output can be found in a critical situation.
- These methods provide relevant indicators :
    - probability of failure
    - index of reliability,
    - importance factor
    - sensitivity factor (specific of the method)
- They allow to propose ways to improve the system reliability.

The FORM and SORM disadvantages are:

- The whole methodology is based and dependent on the determination of the design point *P*
    - This method can present limit, in particular, when there is no field of failure (for certain scenarios of safety) and when the surface of failure is discontinuous
    - to be sure of the validity of the point of design *P*, optimality tests must be set up and in certain cases it can be expensive
    - The sensitivity analysis is not global, but localized around the design point.
- It can be difficult to explain the method and results for a non-specialist audience.

2.3. Directional method

The directional method, like the FORM and SORM methods, is based on the determination of a failure surface, noted *H* . The principal difference is that we do not seek to represent *H*, but to determine the probability of exceeding this border, by traversing a broad panel of directions.

The advantages are:

- The directional method is robust, whatever the form and the position of the surface of failure.

- This method is more effective when the surface of failure is almost hyperspheric in standard space.

The disadvantage are:

- The principal problem of the directional method is that it is really effective when you know areas where the probability of failure is concentrated, which is seldom the case.

2.4. Response surfaces method

The method of response surfaces consists of obtaining a function which simulates the phenomenon behavior in the field of variation of the influential parameters. This function will be obtained by a certain number of tests (the term of experiment plan is used). Various types of response surfaces can be built: polynomials 1^{st} degree, polyharmonic splines, neurons networks, generalized linear models, partial least squares (PLS) regression.

The advantages are:

- These methods allow to "replace" (to approach) the numerical code by an analytical function.
- The advantage of these methods is their lower cost compared to probabilistic methods. This cost is however not negligible.
- These methods provide a surface solution of the problem, which makes it possible to carry out uncertainty and sensitivity analysis without carrying out new simulations.
- The step and the type of result obtained are rather simple to present for a neophyte public.
- The error can be formally estimated.

The disadvantages are:

- These methods require to take into account only a restricted number of uncertain parameters. Each uncertain parameter adds a dimension to the response surface.
- It is necessary to know preliminarily the influential parameters. The choice of the number of parameter can become a problem in the sense that this number is limited in a lower position by the necessary precision for good approximation of the solution and upper by the growing of simulation number necessary and the complexity of the model.
- The valid surface of answer is made locally, and it is difficult to estimate and to quantify the global approximation

2.5. Fuzzy logic

The theory of the fuzzy subsets consists of reasoning not in term of probability but in term of membership function. The methodology of operation is as follows: First, one has to carry out an analysis of the physical problem by breaking up the equations into a whole of representative processes of the elementary phenomena. Then each phenomenon is represented in a simplified way by an analytical function. By sensitivity studies, the parameters whose uncertainties are most influential are selected, and their uncertainties are determined. One can then carry out fuzzy calculation, independently to the numerical code to determine the uncertainty on the final result.

Fuzzy Logic advantages are:

- This method has lower cost. You can determine theoretically for which values of the input parameters you are in a critical situation.

- When the method is gauged and checked, it is possible to obtain a multitude of information without additional simulation.

- It allows to propose some improvents of the system reliability.

Fuzzy Logic disadvantages are:

- This method requires a preliminary and thorough study of equations system. This system is sometimes relatively complicated (coupling of various models, nonlinearity), and we precisely request to the method more information.

- It implies creation and use of an analytical model. It cannot be used directly on the complex numerical model.

- Sensitivity study must be made in a preliminary way by traditional probabilistic methods.

- It seems rather difficult to explain the method for a non–specialist audience.

3. Methodology for Unavailability Sensitivity Analysis to Component Ageing

3.1. Age-dependent models and reliability parameters

The prefereble way for taking into account the SSCs susceptible to ageing is the external physics-based reliability model embedded directly into PSA software and updated the component reliability database of already calculated PSA models. The system FTs are modified to account for components' ageing mechanisms and these hybrid deterministic-probabilistic models are linked to FT segment of components susceptible to ageing. This "plug-in" concept allows easy integration of external calculation [2] and FTs extension by alternative dynamic systems and processes reliability models.

The first simple way to describe the age-related degradation and strength reduction of unrepairable components is by different functions growing in time.The simplest model is the linear function:

$$\lambda(w) = \lambda_0 + aw,\ \lambda(t-\tau) = \lambda_0 + a(t-\tau) \tag{1}$$

where $w=(t-\tau)$ is the age, t is the global time, λ_0 is preageing constant failure rate – charctersitic of a new component, τ is the threshold time at which ageing starts and a is a rate of ageing degradation/strength reduction process.

The results for some ageing failure probability do not agree with linear ageing model, e.g. flow accelerated corrosion [2]. That is why in the most of ageing component cases the three-parameter Weibull ageing model is chosen:

$$\lambda(w) = \lambda_0 + \alpha(\beta+1)(w)^{\beta}, \tag{2}$$

where α is a scale parameter, β is a shape parameter and τ is a location parameter.

The linear and Weibull ageing models could be easily used for repairable components by insertion *t'* as a local time at which last repair/restoration was completed. The basic parameters for description of a repaired/restored object are availability $A(t)$ and unavaliability $U(t)=1-A(t)$. The failure intensities for above models are given by

$$\lambda(w) = \lambda_0 + a(w - t'), \tag{3}$$

$$\lambda(w) = \lambda_0 + \alpha(\beta+1)(w - t')^{\beta}, \tag{4}$$

The second simple way to take into account incompleteness of restoration or repair is based on the use of degradation factor $\gamma(w)$ ($0<\gamma<1$) or equivalent one-parameter Weibull ageing model [3]. As a result of incomplete restoration/repairing the operating time ξ_i of restored object is γ times less (on probability) compared to the previous operation stage $\xi_{i-1}=\xi_i/\gamma(w)$. For exponential law the formula of constant failure rate for the *i* period after repair/restoration is:

$$\lambda_i = \lambda_0 / \gamma^{i-1}(w), \tag{5}$$

3.2. Component categories with multiple ageing states and failure modes

The plant availability and safety may decrease due to the ageing of unrepairable and repairable components. The resulting increase in the overall plant unavailability and risk could be reduced by different maintenance measures: replacements and upgrading of renewable (repairable and restorable) components during repairs, changing of surveillance intervals of renewable components or setting the trend of the degradation factor to unit ($\gamma \rightarrow 1$).

The following categories of ageing components could be identified [4]:

Category 1: Unrepairable or irreplaceable components

1.1 unrepairable (non-restorable irreplaceable components),

1.2 restorable-irreplaceable components.

Category 2: Hard-to-replace (replaceable but costly) components

2.1 non-restorable hard-to-replace component,

2.2 restorable hard-to-replace components.

Category 3: Replaceable on a routine basis

3.1 non-restorable replaceable components,

3.2 restorable replaceable components.

The state transition diagram of gradually ageing component with multiple ageing normal and failure states (modes) is shown on Figure 1.

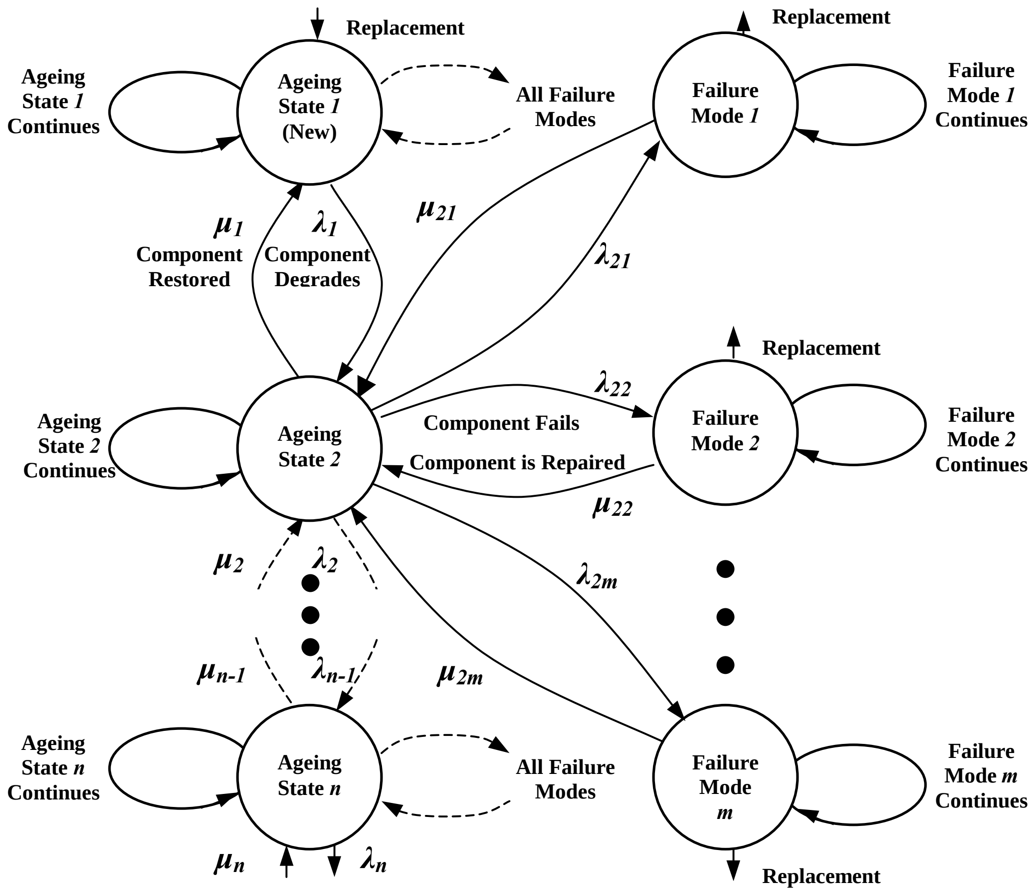


Figure 1. State transition diagram of gradually ageing component with multiple failure modes

Constant-failure (λ), constant-repair or constant-restore (μ) rates greatly simplify systems analysis and they could be treated even analitically by Laplace transforms or Markov analyses. The analytical formulas, obtained by these analyses, for dynamic system behaviour for constant rate model are given by equations (6) and (7)

For unrepairable component *Unreliability* is
$$F(w) = Q(w) = 1 - \exp[-\lambda(w+\tau)], \qquad (6)$$

For renewable component *Unavailability* is
$$Q(w) = 1 - A(w) = \frac{\lambda}{\lambda+\mu}\left[1 - e^{-(\lambda+\mu)(w+\tau)}\right], \qquad (7)$$

The assumptions of the constant rates are feasible when the following conditions are fulfilled [4]:

1. the component is in its prime of life;
2. the component is large with many subcomponents having different rates or ages;
3. the data are so limited that elaborate mathematical treatments are unjustified.

It is necessary to extend the PSA techniques for modelling of ageing components and systems in such a way that rate processes are treated with pseudo-constant rates (the first-order approximation of the rate/intensity is a constant rate/intensity). Anyway, the above matrices and vectors could be simplified for each sub-category of components by equations (1)÷(5), age discretization and flexible formulation of boundary conditions (initial states and transition properties).

In FTs, when the basic event has more than one failure mode, it can be developed through OR gates to more basic events, each of which refers to a single component failure mode. Thus, it is assumed that each basic event has associated with only one failure mode, although a component itself may suffer from multiple failure modes. Suppose that a basic event is a single-failure mode and by lumping the normal state and all other failure modes in nonexistence of the basic event it is possible to reduce the multiple state model to the two-state model (two-state transition diagram). The two-state models are quite applicable for the FT technique and no other modifications are necessary for quantification and calculations. But these calculations are just approximative because the multiple state component is modelled by a two-state transition diagram. If the approximation errors of these calculations are not negligible, then the Markov transition diagrams must be constructed and solved, as shown on Figure 1. However, a Markov analysis cannot handle the age-varying rates beacause the conditional intensities are age-varying unknowns. It is too complicated to solve analytically the multiple state component model with many ageing states and failure modes that could be dependent and compatible. Additionally, a NPP is a complex structure with many systems, subsystems, regimes, components, dependent and common cause failure modes. Therefore, the models of dynamic system reliability methods could be useful extensions to the existing PSA models. Such alterternative methods may give more flexibility, convenience and applicability for incorporation of age-dependent effects and dynamics of physical processes.

3.3. Adapted Methodology for Determining Sensitivity to SSC Ageing

It should be noted that the concept of ageing is related to age but not to time. The difference between age and time is that age generally incorporates the effect of the surveillance, maintenance, and replacement of the subcomponent or whole component, while the time does not. The age of the component does not proceed at the same speed as that of actual time.

When the whole component is replaced, the age of component starts over again from a value of zero but time does not. In the case of the replacement of specific subcomponents, the age of the component takes a partially restored value, however time remains unchanged. Preventive maintenance actions, such as lubricating bearings, will not change the age of the component since subcomponents are not replaced, but will slow the ageing process of the component. Therefore, the component failure rate versus time does not show an ageing effect while the failure rate versus the component age can show it.

It as important to understand these differences since the confusion of age and time can result in statements that components are not ageing when indeed they are. This confusion can furthermore result in incorrect data analysis. That is why the IAEA methodology for determining risk sensitivity to SSC ageing for unrenewal (dependent on time) and renewal (dependent on age) components is described and adapted below [5].

The SSC ageing could have impact on safety (risk) and efficiency (economics) of NPP. In both cases the component and/or system reliability (availability) requirements should be established. That is why an adapted methodology for determining reliability sensitivity to component ageing is proposed by IAEA.

In order to characterize the unavailability/reliability impact of component ageing effects, it is necessary to characterize the age (time) dependent nature of the change in system unavailability/reliability. That is

$$I_A = \frac{\partial Q}{\partial w}, I_A = \frac{\partial Q}{\partial t} \tag{8,8'}$$

where $\boldsymbol{I_A}$ is a unavailability impact of ageing, and $\boldsymbol{Q}$ is the system unavailability.

The system unavailability is a function of the component failure rate λ; For the study of ageing, the failure rate is a function of age *w*. By the chain rule, changes in system unavailability are expressed as:

$$\frac{\partial Q}{\partial w} = \frac{\partial Q}{\partial q_i}.\frac{\partial q_i}{\partial \lambda_i}.\frac{\partial \lambda_i}{\partial w}, \frac{\partial Q}{\partial t} = \frac{\partial Q}{\partial q_i}.\frac{\partial q_i}{\partial \lambda_i}.\frac{\partial \lambda_i}{\partial t} \tag{9,9'}$$

The unavailability impact due to ageing can now be separated into two distinct parts:

- The effects of changes in the component failure rate (the first two terms of the right hand side of Eq. 9);
- Time dependent effects of ageing on the component failure rate (the third term of the right hand side of Eq.9).

We define the unavailability ageing sensitivity to failure rate as

$$g_i = \frac{\partial Q}{\partial \lambda_i} = \frac{\partial Q}{\partial q_i}.\frac{\partial q_i}{\partial \lambda_i}, \tag{10}$$

The first term of the equation, the partial derivative of system unavailability with respect to component unavailability, is equal to the Birnbaum measure. This is a measure of the component failure impact on system unavailability and it can be computed by changing the unavailability of the component in the system unavailability equation to unity and determining the change in system unavailability.

3.3.1. Comprehensive approach for determining unavailability sensitivity to component ageing

The unavailability sensitivity to ageing is determined more comprehensively from equation for the rate of unavailability change in terms of the component unavailability changes:

$$\frac{dQ}{dw} = \sum_i \frac{dQ}{dq_i}\frac{dq_i}{dw}, \frac{dQ}{dt} = \sum_i \frac{dQ}{dq_i}\frac{dq_i}{dt} \tag{11,11'}$$

where

$\frac{dq_i}{dw}$ = the rate of change with age of component unavailability q_i (12)

$\frac{dq_i}{dt}$ = the rate of change with time of component unavailability q_i (12')

In this case, appropriate equations must be substituted for q into Eq. 11.

To distinguish unavailability sensitivity to ageing-caused time dependencies, we will express the component unavailability q_i as:

$$q_i = q_{0,i} + (q_i - q_{0,i}) \tag{13'}$$

where $q_{0,i}$ is the component unavailability with the ageing contribution not included.

Substituting Eq. (13') into Eq. (11) yields:

$$\frac{dQ}{dt} = \sum_i \frac{dQ}{dq_i}\frac{dq_{0,i}}{dt} + \sum_i \frac{dQ}{dq_i}\frac{d(q_i - q_{0,i})}{dt} \tag{14'}$$

The first term on the right hand side of Eq. 14' is the unavailability change from the normal time dependence in the component unavailability that is not due to ageing. The second term on the right hand side of Eq.14' is the contribution from the additional change due to ageing, and by associating the expression with the rate of unavailability change due to ageing we obtain the basic equation for ageing unavailability sensitivity:

$$\left(\frac{dQ}{dt}\right)_A = \sum_i \frac{dQ}{dq_i}\frac{d(q_i - q_{0,i})}{dt} \tag{15'}$$

If there is no ageing $q_i = q_{0,i}$ and Eq.15' gives:

$$\left(\frac{dQ}{dt}\right)_A = 0, \text{(no ageing)} \tag{16'}$$

Each term in the sum on the right hand side of Eq.11/15' gives the contribution of the ageing of each specific component to the unavailability change. The component ageing unavailability sensitivity contribution is denoted by θ:

$$\theta = \frac{dQ}{dq}\frac{dq}{dw}, \theta = \frac{dQ}{dq}\frac{d(q - q_0)}{dt} \tag{17,17'}$$

The component ageing system unavailability sensitivity contribution is equal to the importance of the component, multiplied by the extra rate of change of the component unavailability due to ageing.

The total rate of unavailability increase due to ageing given by Eq. 11/15' is then simply the sum of the component ageing system unavailability sensitivity contributions:

$$\frac{dQ}{dw} = \sum_i \theta_i \,, \left(\frac{dQ}{dt}\right)_A = \sum_i \theta_i \qquad (18,18')$$

In general, the system unavailability of the component *dQ/dq* is also age dependent and is changing with time and age.

3.3.2. Specific formulas for the component ageing system unavailability sensitivity

Category 1

In case the component is ***unrepairable***

$$q = 1 - \exp[-\int_0^{w+\tau} \lambda(w')dw'] \,, q = 1 - \exp[-\int_0^{t} \lambda(t')dt'] \qquad (19,19')$$

and

$$q_0 = 1 - \exp[-\lambda_0 (w + \tau)] \,, q_0 = 1 - \exp(-\lambda_0 t) \qquad (20,20')$$

where $\lambda(w)$ $\{\lambda(t)\}$ is the age {time} dependent component failure rate with ageing and λ_0 is the constant failure rate assuming no ageing.

$$\frac{d(q - q_0)}{dw} = \lambda(w+\tau)\exp[-\int_0^{w+\tau} \lambda(w')dw'] - \lambda_0 \exp[-\lambda_0 (w+\tau)], \quad (21)$$

$$\frac{d(q - q_0)}{dt} = \lambda(t)\exp[-\int_0^{t} \lambda(t')dt'] - \lambda_0 \exp(-\lambda_0 t), \qquad (21')$$

For many applications the quantities $\int\lambda(t')dt'$ and $\lambda_0 t$ will be small, which corresponds to the unavailabilities q and q_0 being less than 0.1 and exponentials are approximately unity. Hence,

$$\theta \approx \frac{dQ}{dq}[\lambda(w+\tau) - \lambda_0], (q, q_0 < 0.1), \qquad (22)$$

$$\theta \approx \frac{dQ}{dq}[\lambda(t) - \lambda_0], (q, q_0 < 0.1), \qquad (22')$$

This means that for $q, q_0 < 0.1$, to the first order, the unreliability sensitivity θ to an ageing component that is unrepairable is simply the unreliability importance of the component *dQ/dq*.

The unreliability sensitivity *to an ageing unrepairable component is equal to the unreliability importance of the component multiplied by the increase in failure rate due to ageing.*

In the extreme ageing cases where for large t, q is near 1 (i.e., $q>0.1$), but where q_0 is still less than 0.1, we have:

$$\frac{dq}{dw} = \lambda(w+\tau)\exp[-\int_0^{w+\tau}\lambda(w')dw'] - \lambda_0 \le \lambda(w+\tau) - \lambda_0 \,, \qquad (23)$$

$$\frac{d(q-q_0)}{dt} = \lambda(t)\exp[-\int_0^{t}\lambda(t')dt'] - \lambda_0 \le \lambda(t) - \lambda_0 \,, \qquad (23')$$

Hence, the appropriate expression for the component unreliability sensitivity given by Eq.(22,22') serves not only as an accurate approximation for small to moderate ageing effects but also serves as a conservative bound for extreme ageing effects.

Category 2 (restorable) and Category 3 (repairable)

If failures are detectable by test and maintenance, the degree to which the failures are repaired must be considered.

The component may simply be restored to an operational status without replacing the degradaded sub-components. In this case the component may be modelled as being restored to "as good as old".

If the component is replaced at the test or maintenance, it can be modelled as being restored to "as good as new".

If the ageing mechanism affects various sub-components and some are simply restored to an operational status and others are replaced, then each sub-component should be considered as a separate component.

The component ageing unavailability sensitivity θ will be evaluated for the case, where the component was last checked at t_c and was last restored at τ, where $t_c>\tau$. For a test at t_c and a renewal at τ, where $t_c>\tau$, the unavailability q_0 is:

$$q_0 = 1-\exp[-\lambda_0(w+\tau-t_c)]\,, q_0 = 1-\exp[-\lambda_0(t-t_c)] \qquad (24,24')$$

$$q_0 = \frac{\lambda_0}{\lambda_0+\mu_0}[1-e^{-(\lambda_0+\mu_0)(w+\tau-t_c)}]\,,\; q_0 = \frac{\lambda_0}{\lambda_0+\mu_0}[1-e^{-(\lambda_0+\mu_0)(t-t_c)}] \qquad (25,25')$$

The ageing unavailability q is given by:

$$q = 1-\exp[-\int_{t_c-\tau}^{w}\lambda(w')dw']\,,\; q = 1-\exp[-\int_{t_c-\tau}^{t-\tau}\lambda(t')dt'] \qquad (26,26')$$

$$q(w)=\frac{\lambda}{\lambda+\mu}\exp[-\int_{t_c-\tau}^{w}(\lambda+\mu)(w'+\tau-t_c)dw',\ q(t)=\frac{\lambda}{\lambda+\mu}\exp[-\int_{t_c-\tau}^{t-\tau}(\lambda+\mu)(t'-t_c)dt' \qquad (27,27')$$

where $t_c > \tau$

Hence, the component ageing unavailability sensitivity θ is :

$$\theta=\frac{dQ}{dq}\left(\frac{dq}{dw}-\frac{dq_0}{dw}\right)=\frac{dQ}{dq}[\lambda(w)\exp(-\int_{t_c-\tau}^{w}\lambda(w')dw')-\lambda_0\exp[-\lambda_0(w+\tau-t_c)] \qquad (28)$$

$$\theta=\frac{dQ}{dq}\left(\frac{dq}{dt}-\frac{dq_0}{dt}\right)=\frac{dQ}{dq}[\lambda(t-\tau)\exp(-\int_{t_c-\tau}^{t-\tau}\lambda(t')dt')-\lambda_0\exp[-\lambda_0(t-t_c)] \qquad (28')$$

For many applications, the ageing and non-ageing unavailabilities are less than approximately 0.1, and we have:

$$\frac{dq}{dw}-\frac{dq_0}{dw}\approx\lambda(w)-\lambda_0\,,\ \frac{dq}{dt}-\frac{dq_0}{dt}\approx\lambda(t-\tau)-\lambda_0 \qquad (29,29')$$

and the system unavailability sensitivity is then approximately:

$$\theta=\frac{dQ}{dq}[\lambda(w)-\lambda_0]\,,\ \theta=\frac{dQ}{dq}[\lambda(t-\tau)-\lambda_0] \qquad (30,30')$$

Thus, the first-order component ageing unavailability sensitivity depends only on the restoration time τ and does not depend on any other test time t_c which does not renew the component, so the results obtained are interpretable for general test and maintenance situations.

For application, specific ageing models for *λ(t)* should be used in the equations for the unavailability sensitivities (equations 22, 22’, 30, 30’ and 30’) to obtain specific numerical results that can be used to rank the influence of specific components ageing on the system unavailability and plant risk.

A variety of time dependent component failure rate models can be used for treating potential ageing effects (Weibull distribution, the gamma distribution and truncated normal distribution).

4. Description of Applied Dynamic System Reliability Methods

An important characteristic of natural and engineering systems and processes is that they behave dynamically. System and process dynamics evolves over time:

1.1 components interaction with each other and with the environment.

1.2 components response to initial perturbations and changes of process variables.

1.3 configuration changes depending on the required task or component failure occurrence.

1.4 component characteristics depending on their condition, standby or operation.The conventional ET-FT methodology for reliability and risk assessment is designed to describe static relationships between logical variables and does not explicitly treat time, physical process variables, ageing or human behavior. The overcoming of quasi-static tree models limitations needs essential extensions or alternative methodologies for due assessment of reliability and risk. Dynamic aspects of hardware-software-liveware systems and processes require more advanced tools for analysis.

The alternative methodologies should include extensions of the ET-FT approach, rather than revising the methodology itself. However, alternative methods could be intended also to supplant the ET-FT approach in certain situations. The applicability of these dynamic system and process reliability methods for incorporation of age-dependent reliability parameters and data into the PSA model is discussed.

4.1. Applicability, spectrum and features of dynamic system reliability methodologies

The applicability of the alternative methodology for dynamic reliability and risk modelling depends on analysis level, qualitative and adequate database, available knowledge of structural, physical and functional system relationships and the opportunity to compare, validate and verify the methodology results. The spectrum of some applicable dynamic system reliability methodologies for incorporation of ageing effect could be classified as [3]:

- *ET-FT extensions* - expanded ETs, GO-FLOW, digraph-based FT construction;

- *Explicit state-transition methods* - event sequence diagrams, explicit Markov chains models;*Implicit state-transition methods* - continuous ETs (semi-Markov chains), dynamic logical analysis methodology (DYLAM), dynamic ETs (DETAM), discrete/analogue event (Monte Carlo) simulation;

- *"Cell-to-cell" approach* - Analysis of Topological Reliability of Digraphs (ATRD).

4.2. GO-FLOW methodology

It is a success-oriented system reliability analysis methodology. The GO-FLOW chart is constructed with standardized operators and signal lines and deals with limited extent changes in model structure over time. The analysis is performed by one GO-FLOW chart and one computer run with supported system. The method was developed by Matsuoka & Kobayashi from the NMRI, Japan in 1988. The conceptual image of the GO-FLOW analysis procedure is shown on Figure 2.

GO-FLOW does not trace each event sequence. It performs numerical calculation as early as possible in the process of analysis. On Figure 2, C_n indicates a component, and a failure of a specific component produces a particular system state. For example, a failure of C_1 produces state i. During a small time interval Δt, a failure of component C_1 or C_2 or C_3 increases the occurrence probability of state i. A failure of C_4 decreases the occurrence probability; that is, a transition from state i to j occurs in this case. At the end of each time interval, the numerical values of the occurrence probability of system states are calculated. In the GO-FLOW methodology, it is not considered when a transition from state i to j has occurred.

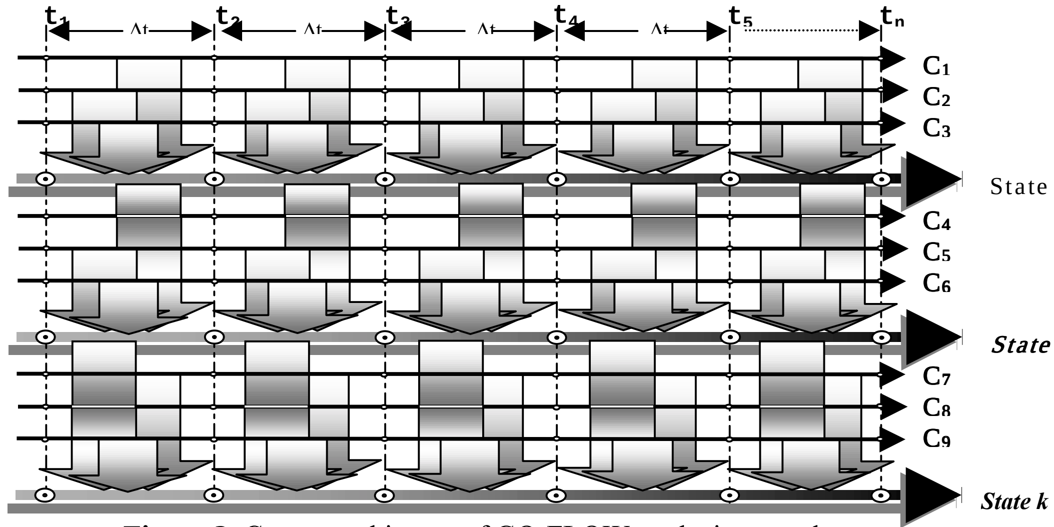


Figure 2. Conceptual image of GO-FLOW analysis procedure

4.3. Analysis of Topological Reliability of Digraphs methodology

The ATRD method uses inductive logic, where every physical and logical connection should be expressed in an explicit form. The ATRD system model is a digraph of system functioning. Reliability networks are presented as stochastically independent or dependent graphs. The multiple network with control or physical processes links or places (Petri Nets elements) can discretely, hierarchically and dynamically change the state of the system components. The ATRD method could be used to overcome the static models of the ET and FT methodology. The ATRD method was developed by G. Petkov, Moscow Power Engineering Institute, Russia in 1992.

The cell-to-cell methodology is a way out of the limitations of the explicit methodology (Markov model). It provides a physics-based context for component ageing states and failure modes by some implicit methodology elements. An ATRD cell-to-cell procedure, called ‘matreshka’, is used to transform the complex dynamic component/system into a component/system of modules. Each module represents 3-component dynamic system with 4 states (cube). The ATRD method traces each event sequence in cubes. The conceptual image of the ATRD cell-to-cell analysis procedure is shown on Figure 3.

4.4. Applicability of dynamic system and process reliability methods

Approaches to sensitivity analysis such as those based on variance decomposition are very useful when the systems or processes modeled are strongly influenced by the interactions of various parameters and factors. The study of the effects that such interactions may have on the model output is of great importance to gain a deep physical understanding of the model, to control the output uncertainty, to identify the dominant parameters. When the model is complex, multivariate and possibly nonlinear, the computations required by such sensitivity methods may be burdensome. Thus, one has to resort to simplified models or empirical interpolators capable of providing quick computations.

A possible alternative for such computations is the dynamic system and process reliability methods, like GO-FLOW and Analysis of Topological Reliability of Digraphs (ATRD). They could be used to confirm the ET-FT ageing-screening analysis but first and foremost to give additional information about ageing effects on local SSC models and SSC importance on the PSA model. Variance based on the GO-FLOW and ATRD techniques for AESA is intended to estimate the fractions of the output variability due to each of the input ageing effects, both separately and in combination.

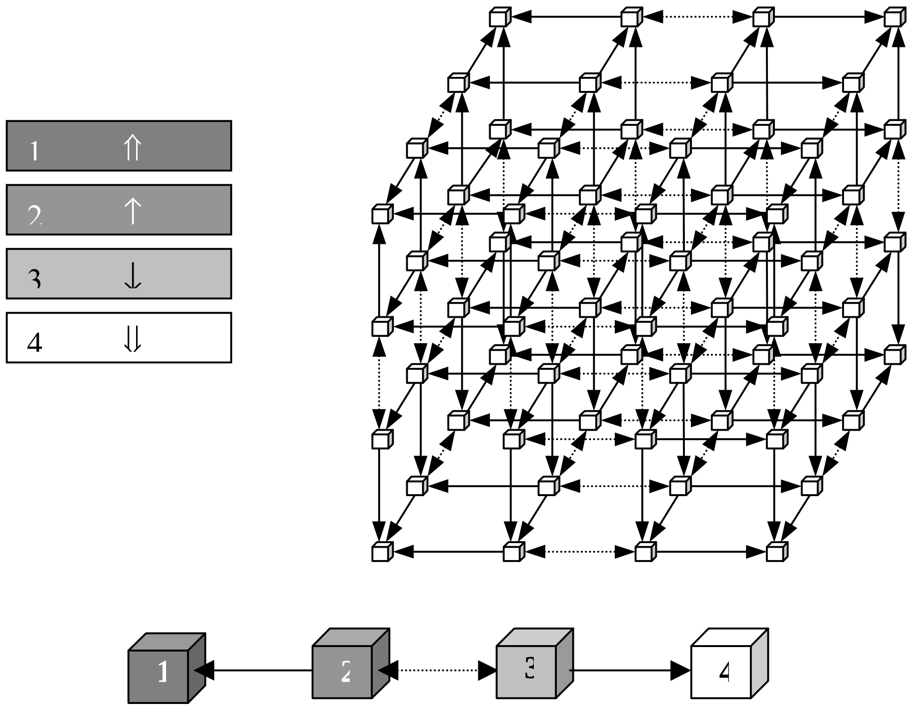


Figure 3. Conceptual image of ATRD cell-to-cell analysis procedure

A widely accepted approach for performing global sensitivity analysis is the one based on the MC analysis. Within MC a rich range of model parameter combinations is investigated and model failure is more easily identified. An MC approach also allows different correlation structures among factors to be tested in an iterative procedure. But unacceptably high deviations can be tracked back to unrealistic input value ranges by the dynamic system method simulation, which allows models and data to be verified by ‘point by point’ comparison of the FT, GO-FLOW and ATRD models. However, MC verifications are usually more robust than the ‘point by point’ comparison between individual model predictions and observations.

The purpose of AESA by dynamic system reliability methods could be manifold. AESA is an important element of judgment for the corroboration or falsification of the hypotheses embedded into a hybrid deterministic-probabilistic model. This is especially crucial when the physics-based reliability model inputs and the available component reliability database are affected by uncertainties. Furthermore, AESA could be an effective tool for mechanism identification and mechanism reduction. It may be used to direct research priorities by focusing on the ageing effects that mostly determine the uncertainty in the model. Finally, AESA methods offer an element of model quality control by confirming that the model does not exhibit strong dependence on supposedly non-influential ageing parameters.

5. Case Study: AESA of the WWER-1000 Residual Heat Removal System”

The case study investigates the feasibility of dynamic system reliability methods (GO-FLOW and ATRD), to model the unavailability of ageing components and the three-train residual heat removal system (RHRS) of a Russian-design pressurized water reactor WWER-1000/V320. Both methods are used for preparation of comparable ageing process component and system models. The possible extensions of these methods are compared with the equivalent RHRS FT model in which a static component unavailability calculated forms are used.

The case study is implemented in three steps:

1) Identify the components to be assessed.

Parameters typically taken into account for identification are component importances and component/system unavailabilities.

2) Analyse the ageing time-dependent effects and calculate their failure and repair rates.

The analysis consist in examining, calculation and plotting the ageing effects of increasing component failure rates on system unavailability and reliability. Linear or Weibull distributions are usually used.

3) Ageing effects sensitivity analysis

Based on the information collected from the preceding two steps and RHRS reliability models by the ATRD and GO-FLOW methods, conclusions about the relative importance of input of age-dependent reliability parameters and data with respect to the variability reliability models output are derived.

The reviews of operational and environmental stresses on the components and/or systems and plant Kozloduy NPP maintenance schedule have not been carried out. Only assumptions about possible impacts on the RHRS were made. That is why the derived and used ageing reliability data should be considered as an example but not as typical for the WWER-1000.

5.1. Description of the RHRS of WWER-1000

The RHRS has to perform two functions/regimes:

1) low pressure injection in case of large break LOCA – *regime ‘I’*;

2) emergency and planned core cooling – *regime ‘P’*.

The RHRS consists of three trains with electrically driven pump, 3x100%, supplied from normal and emergency power supply systems; a heat exchanger, valves, check valves and a common tank for all three chanels. A diagram of the RHRS is given in Figure 4.

Alternative methods have been applied for feasibility studies of changing of failure, restore and repair rates of all component categories or reducing the surveillance intervals of repairable components to take into account ageing processes in plant availability.

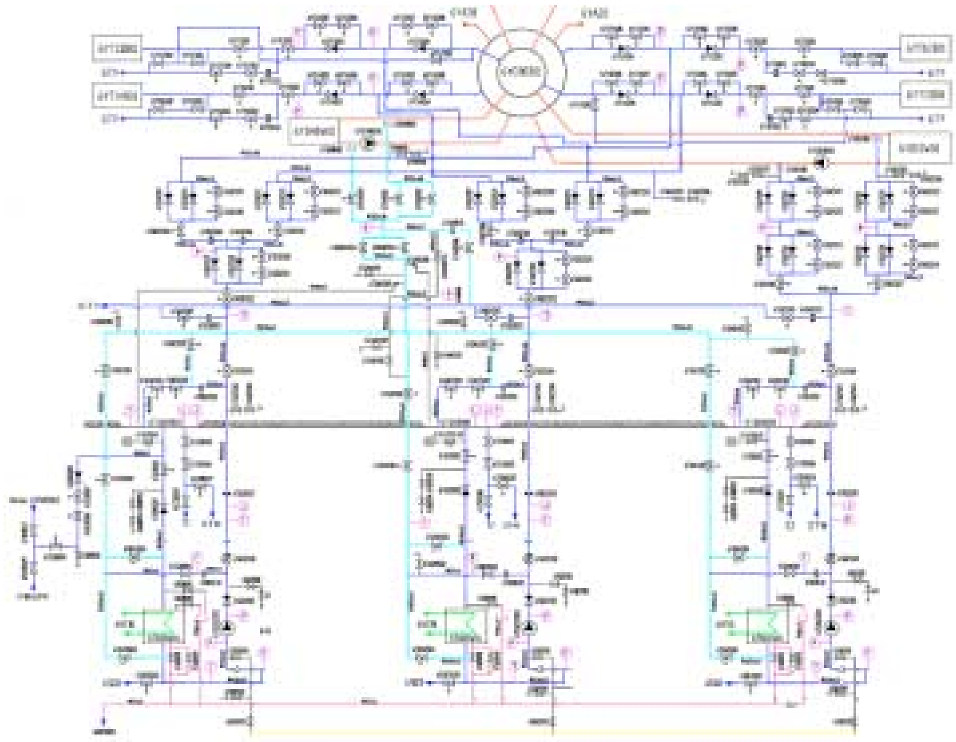


Figure 4. The WWER-1000 Residual Heat Removal System Diagram, Unit 6, Kozloduy NPP

The dynamic system reliability methods could be used to allocate the ageing reliability data for basic events and ageing failure mode and effect analysis (FMEA). The case study comprises three categories of ageing components:

- *restorable replaceable* – valves, pumps;
- *non-restorable replaceable* – check valves and pipes;
- *restorable hard-to-replace* – tanks and heat exchangers.

5.2 RHRS fault tree analysis

The RHRS FT was modelled with SAPHIRE software. The failure probabilities calculated by first order approximation for the top events “RHRS fails to low pressure injection in case of large break LOCA” – *regime 'I'* and “RHRS fails to emergency and planned core cooling” – *regime 'P'* are shown on Figure 3. The criterion is 1 of 3 trains to fulfill the function but the results for criteria 2-of-3 trains and 3-of-3 trains are calculated and shown as well. The evaluation was done with the probability cutoff 1.0E-15 and hence resulted accordingly: 1) for 1 of 3 trains - 47638 MCSs, 30182 of which are 3-component, 16663 of which are 4-component and the rest are 5-component (793); 2) for 2 of 3 trains - 6324 MCSs, 3392 of which are double-component, 2668 of which are 3-component and the rest are 4-component (264); 3) for 3 of 3 trains - 167 MCSs, 101 of which are single-component, 50 of which are double-component and the rest are triple-component (16). The FTs are composed of 295 basic events whose probabilities were mainly assigned from the following SAPHIRE reliability models: a) constant probability (value obtained from Basic Events database); b) periodic test (required parameters are standby failure rate and test interval); c) mission (required parameters are operating failure rate and mission time).

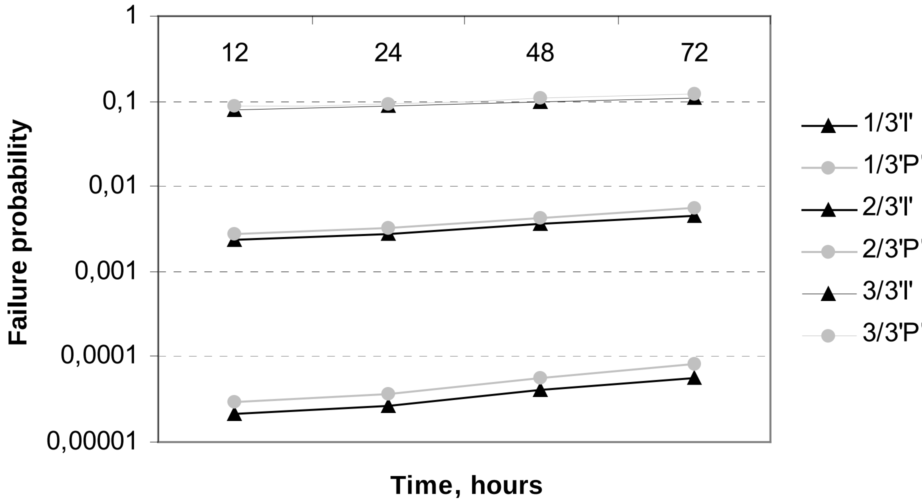


Figure 5. The WWER-1000 RHRS FT Analysis Results for Different Failure Criteria

5.3 Selection of basic events for ageing analysis

The FT was converted into the GO-FLOW and ATRD softwares using the same settings and equivalent reliability models. The validation acceptance has been considered based on the similarity of results - similar probabilities of the basic event (BE).

The selection criterion of BEs for ageing analysis relies on the probabilities and importance measures (Fussel-Vesely – F-V), the diversity of component types and limitations of case study. The main focus was on typical mechanical equipment (active components - valves, pumps and passive components – tanks and heat exchangers). Thus, there are envisaged particularly for this FT the next main mechanical component types: 1) check valves; 2) motorized valves (electrical valves); 3) pumps (starting and running); 4) heat-exchangers; 5) tanks.

The scope of selected BEs includes the primary failures for all above component types. Therefore the basic events ranked by importance and selected for further ageing analysis are presented in Table 1. The basic event identification (BE ID) is given in a transformed SAPHIRE format.

Table 1. "I" & "P" Regimes BE Reliability Data for AESA based on Fussel-Vesely Importance.

N	BE ID	Failure Mode	Probab.	FV Injection	FV Cooling	λ, 1/y (1/d)	*I*/**M**
1	TQ12D01_PS	Fails to Start	2.04E-02	5.425E-01	5.030E-01	(3E-3)	*1m*
2	TQ22D01_PS	Fails to Start	2.04E-02	5.030E-01	4.687E-01	(3E-3)	*1m*
3	TQ32D01_PS	Fails to Start	2.04E-02	5.030E-01	4.687E-01	(3E-3)	*1m*
4	TQ12D01_PR	Fails Running	2.40E-03	6.336E-02	5.873E-02	8.76E-1	*1m*/24h
5	TQ22D01_PR	Fails Running	2.40E-03	5.874E-02	5.473E-02	8.76E-1	*1m*/24h
6	TQ32D01_PR	Fails Running	2.40E-03	5.874E-02	5.473E-02	8.76E-1	*1m*/24h
7	TQ10S01_EV	Fails Closed	2.87E-03	7.561E-02		8.76E-2	*1m*
8	TQ12S02_EV	Fails Open	2.87E-03	7.561E-02	7.010E-02	8.76E-2	*1m*
9	TQ12S03_EV	Fails Open	2.87E-03	7.561E-02	7.010E-02	8.76E-2	*1m*
10	TQ12S04_EV	Fails Closed	2.87E-03	7.561E-02	7.010E-02	8.76E-2	*1m*
11	TQ12S30_EV	Fails Closed	2.87E-03	7.561E-02	7.010E-02	8.76E-2	*1m*
12	TQ41S01_EV	Fails Closed	2.87E-03		7.010E-02	8.76E-2	*1m*
13	TQ41S02_EV	Fails Closed	2.87E-03		7.010E-02	8.76E-2	*1m*

N	BE ID	Failure Mode	Probab.	F-V Injection	F-V Cooling	λ, 1/y (1/d)	*I*/**M**
14	TQ42S02_EV	Fails Closed	2.87E-03		6.532E-02	8.76E-2	*1m*
15	TQ43S02_EV	Fails Closed	2.87E-03		6.532E-02	8.76E-2	*1m*
16	TQ42S01_EV	Fails Closed	2.87E-03		6.532E-02	8.76E-2	*1m*
17	TQ43S01_EV	Fails Closed	2.87E-03		6.532E-02	8.76E-2	*1m*
18	TQ22S30_EV	Fails Closed	2.87E-03	7.011E-02	6.532E-02	8.76E-2	*1m*
19	TQ32S30_EV	Fails Closed	2.87E-03	7.011E-02	6.532E-02	8.76E-2	*1m*
20	TQ22S22_EV	Fails Closed	2.87E-03	7.011E-02	6.532E-02	8.76E-2	*1m*
21	TQ32S22_EV	Fails Closed	2.87E-03	7.011E-02	6.532E-02	8.76E-2	*1m*
22	TQ22S04_EV	Fails Closed	2.87E-03	7.011E-02	6.532E-02	8.76E-2	*1m*
23	TQ32S04_EV	Fails Closed	2.87E-03	7.011E-02	6.532E-02	8.76E-2	*1m*
24	TQ22S03_EV	Fails Closed	2.87E-03	7.011E-02	6.532E-02	8.76E-2	*1m*
25	TQ32S03_EV	Fails Closed	2.87E-03	7.011E-02	6.532E-02	8.76E-2	*1m*
26	TQ22S02_EV	Fails Closed	2.87E-03	7.011E-02	6.532E-02	8.76E-2	*1m*
27	TQ32S02_EV	Fails Closed	2.87E-03	7.011E-02	6.532E-02	8.76E-2	*1m*
28	TQ20S01_EV	Fails Closed	2.87E-03	7.011E-02		8.76E-2	*1m*
29	TQ30S01_EV	Fails Closed	2.87E-03	7.011E-02		8.76E-2	*1m*
30	TQ42S03_EV	Fails Closed	2.87E-03		1.870E-04	8.76E-2	*1m*
31	TQ43S03_EV	Fails Closed	2.87E-03		1.870E-04	8.76E-2	*1m*
32	TQ42S04_EV	Fails Closed	2.87E-03		1.870E-04	8.76E-2	*1m*
33	TQ43S04_EV	Fails Closed	2.87E-03		1.870E-04	8.76E-2	*1m*
34	TQ40S03_EV	Fails Closed	2.87E-03		1.870E-04	8.76E-2	*1m*
35	TQ40S04_EV	Fails Closed	2.87E-03		1.870E-04	8.76E-2	*1m*
36	TQ41S03_EV	Fails Closed	2.87E-03		1.377E-04	8.76E-2	*1m*
37	TQ41S04_EV	Fails Closed	2.87E-03		1.377E-04	8.76E-2	*1m*
38	TQ12S06_EV	Fails Closed	2.87E-03	2.165E-04	1.377E-04	8.76E-2	*1m*
39	TQ12S07_EV	Fails Closed	2.87E-03	2.165E-04	1.377E-04	8.76E-2	*1m*
40	TQ22S06_EV	Fails Closed	2.87E-03	2.007E-04	1.873E-04	8.76E-2	*1m*
41	TQ32S06_EV	Fails Closed	2.87E-03	2.007E-04	1.873E-04	8.76E-2	*1m*
42	TQ22S10_EV	Fails Closed	2.87E-03	2.007E-04	1.870E-04	8.76E-2	*1m*
43	TQ32S10_EV	Fails Closed	2.87E-03	2.007E-04	1.870E-04	8.76E-2	*1m*
44	TQ10W01_H	Leakage	5.48E-06	1.443E-04	3.835E-07	3.00E-7	*12m*
45	TQ20W01_H	Leakage	5.48E-06	1.338E-04	3.574E-07	3.00E-7	*12m*
46	TQ30W01_H	Leakage	5.48E-06	1.338E-04	3.574E-07	3.00E-7	*12m*
47	TQ10S02_CV	Fails Closed	3.00E-06	7.901E-05		1.752E-3	*1m*
48	TQ12S01_CV	Fails Closed	3.00E-06	7.901E-05	7.324E-05	1.752E-3	*1m*
49	TQ22S01_CV	Fails Closed	3.00E-06	7.325E-05	6.825E-05	1.752E-3	*1m*
50	TQ32S01_CV	Fails Closed	3.00E-06	7.325E-05	6.825E-05	1.752E-3	*1m*
51	TQ20S02_CV	Fails Closed	3.00E-06	7.325E-05		1.752E-3	*1m*
52	TQ30S02_CV	Fails Closed	3.00E-06	7.325E-05		1.752E-3	*1m*
53	TQ10B01_T	Reserve water	2.70E-08	7.110E-07		1.80E-9	*12m*
54	TQ20B01_T	Reserve water	2.70E-08	6.913E-07		1.80E-9	*12m*
55	TQ30B01_T	Reserve water	2.70E-08	6.913E-07		1.80E-9	*12m*
56	TQ40S01_EV	Fails Closed	2.87E-03		5.350E-07	8.76E-2	*1m*
57	TQ40S02_EV	Fails Closed	2.87E-03		5.350E-07	8.76E-2	*1m*
58	TQ40S05_EV	Fails Closed	2.87E-03		5.350E-07	8.76E-2	*1m*
59	TQ22S18_CV	Fails Closed	3.00E-06	2.198E-10	2.048E-10	1.752E-3	*1m*
60	TQ32S18_CV	Fails Closed	3.00E-06	2.198E-10	2.048E-10	1.752E-3	*1m*
61	TQ22S19_CV	Fails Closed	3.00E-06	2.198E-10	2.048E-10	1.752E-3	*1m*
62	TQ32S19_CV	Fails Closed	3.00E-06	2.198E-10	2.048E-10	1.752E-3	*1m*
63	TQ12S08_CV	Fails Closed	3.00E-06	6.707E-13	6.207E-13	1.752E-3	*1m*
64	TQ12S09_CV	Fails Closed	3.00E-06	6.707E-13	6.207E-13	1.752E-3	*1m*
65	TQ12S10_CV	Fails Closed	3.00E-06	6.707E-13	6.207E-13	1.752E-3	*1m*
66	TQ12S11_CV	Fails Closed	3.00E-06	6.707E-13	6.207E-13	1.752E-3	*1m*
67	TQ12S16_CV	Fails Closed	3.00E-06	6.707E-13	6.207E-13	1.752E-3	*1m*
68	TQ12S18_CV	Fails Closed	3.00E-06	6.707E-13	6.207E-13	1.752E-3	*1m*
69	TQ12S20_CV	Fails Closed	3.00E-06	6.707E-13	6.207E-13	1.752E-3	*1m*
70	TQ12S22_CV	Fails Closed	3.00E-06	6.707E-13	6.207E-13	1.752E-3	*1m*
71	TQ22S11_CV	Fails Closed	3.00E-06	6.208E-13	5.775E-13	1.752E-3	*1m*

N	BE ID	Failure Mode	Probab.	F-V Injection	F-V Cooling	λ, 1/y	*I*/**M**
72	TQ32S11_CV	Fails Closed	3.00E-06	6.208E-13	5.775E-13	1.752E-3	*1m*
73	TQ22S14_CV	Fails Closed	3.00E-06	6.208E-13	5.775E-13	1.752E-3	*1m*
74	TQ32S14_CV	Fails Closed	3.00E-06	6.208E-13	5.775E-13	1.752E-3	*1m*
75	TQ22S15_CV	Fails Closed	3.00E-06	6.208E-13	5.775E-13	1.752E-3	*1m*
76	TQ32S15_CV	Fails Closed	3.00E-06	6.208E-13	5.775E-13	1.752E-3	*1m*
77	TQ22S07_CV	Fails Closed	3.00E-06	6.208E-13	5.775E-13	1.752E-3	*1m*
78	TQ32S07_CV	Fails Closed	3.00E-06	6.208E-13	5.775E-13	1.752E-3	*1m*

5.4 Reliability models by FT, ATRD and GO-FLOW of the RHRS Segment 2

Since the reliability models of 3-train RHRS of the WWER-1000 are too large , it is decomposed to allow the illustration of feasibility of the dynamic system reliability methods. The RHRS diagram, FT, ATRD and GO-FLOW models of Segment 2 “RHRS pump re-cerculation” are shown on Figures 6, 7 and 8.

In the GO-FLOW model four types of operators are used: Type 25 – signal generator (noted as 1, 2 and 3); Type 26 an 27 – normally open and closed contacts (with input signal 2); Type 35 – failure during operation (with input signal 3).

The ATRD RHRS model is also static and consist of trival arcs and vertices. It is intended just to repeat assumptions and results of the FT RHRS model.

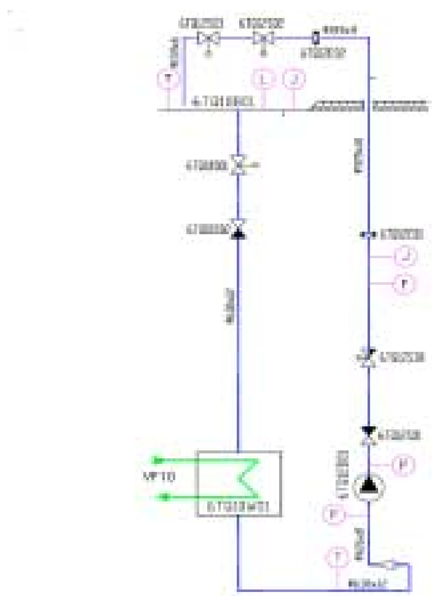


Figure 6. Diagram and FT Model of Segment 2 “RHRS pump re-circulation”

5.5 RHRS reliability and sensitivity analysis by the GO-FLOW and ATRD methods

The results fo RHRS Segment 2 unavailability by the GO-FLOW and ATRD methods are shown on Figure 9. The non-coinsidence of the outcome results (<7%) is based on their different precision - 1.1E-7 for the GO-FLOW and 1E-3 for the ATRD. The ATRD model is solved by the MS Excel to obtain conservative results that are equal to the FT results obtained by the SAPHIRE 7.0 (β version).

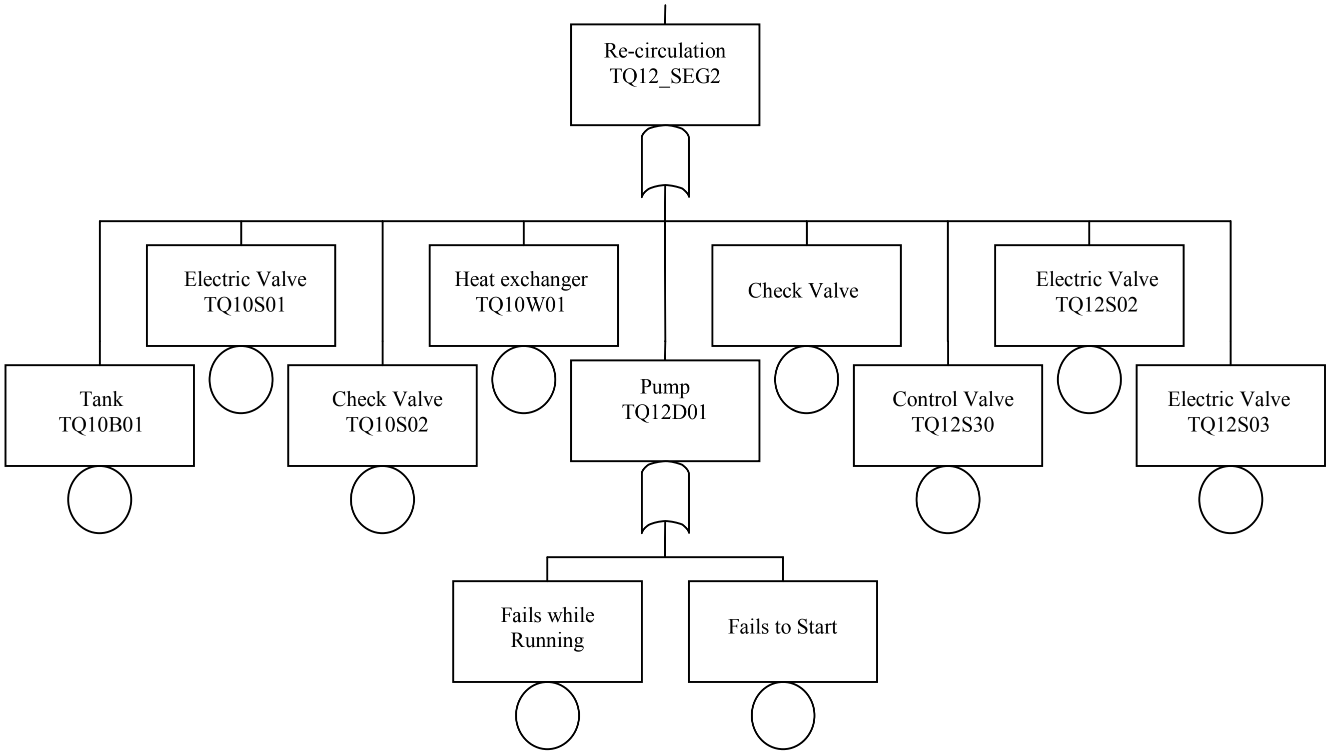
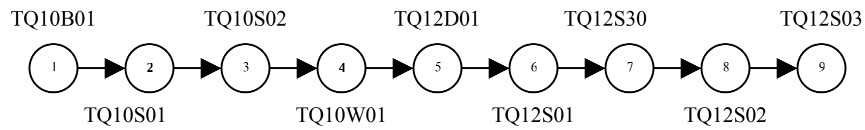
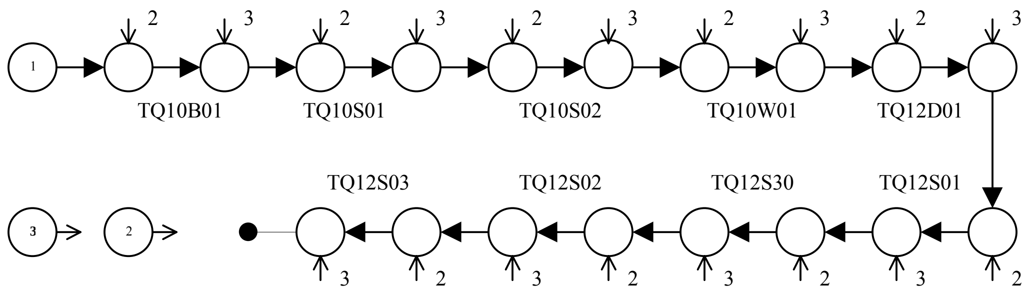


Figure 7. Fault Tree Model of the Segment 2: "RHRS Pump Re-circulation"



a. ATRD Mode1



b. GO-FLOW Mode1

Figure 8. ATRD (a) and GO-FLOW (b) Models of the Segment 2: “RHRS Pump Re-circulation”

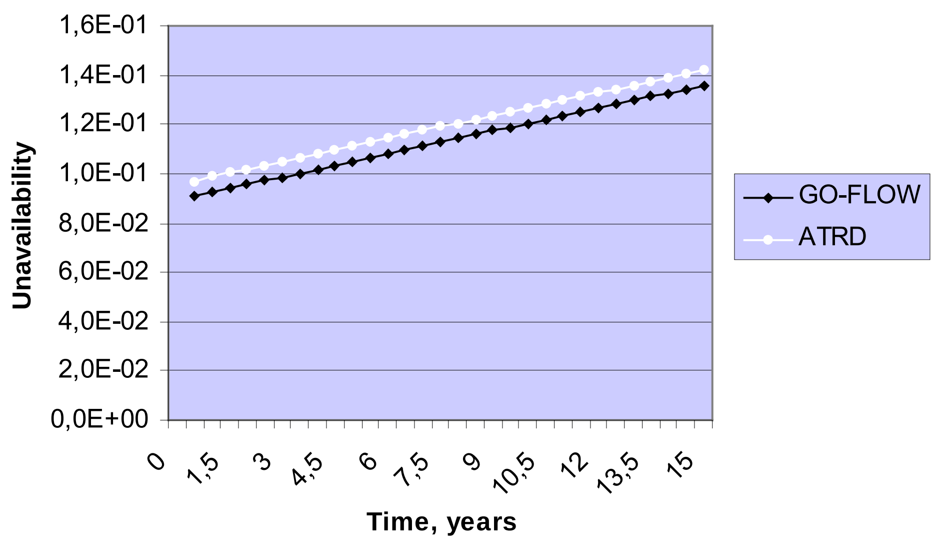


Figure 9. Unavailability of WWER-1000 RHRS Segment 2 by GO-FLOW and ATRD methods

The results of the ageing effects sensitivity analysis based on the ATRD model are shown on figures 10 and 11. The linear ageing models for *unrepairable* (check valve) and *repairable* (pump) equipment are used, see equations (1), (22’) and {30):

- **check valve**: $\lambda_0^{CV}=1,75.10^{-3}\ y^{-1}$, $a^{CV}=2,63.10^{-8}\ y^{-2}$, $\tau_{CV}=0$,

$$\lambda^{CV}(t-\tau)=\lambda_0^{CV}+a^{CV}(t-\tau_{CV}),\ \theta_{\_CV}\approx\frac{dQ_{RHRS\#2}}{dq_{CV}}[\lambda^{CV}(t)-\lambda_0^{CV}]$$

- **pump**: $\lambda_0^{P}=8,76.10^{-1}\ y^{-1}$, $a_\lambda^{P}=7,88.10^{-6}\ y^{-2}$, $\mu_0^{P}=12\ y^{-1}$, $a_\mu^{P}=7,88.10^{-5}\ y^{-2}$, $\tau_P=10$, where

$$\lambda^P(w) = \lambda_0{}^P + a_\lambda^P w \,,\; \theta_{\_P} = \theta_{\_P\_l} = \frac{dQ_{RHRS\ \#2}}{dq_P}[\lambda^P(w) - \lambda_0{}^P]$$

$$\mu^P(w) = \mu_0{}^P + a_\mu^P w \,,\; \theta_{\_P\_m} = \frac{dQ_{RHRS\ \#2}}{dq_P}[\mu^P(w) - \mu_0{}^P]$$

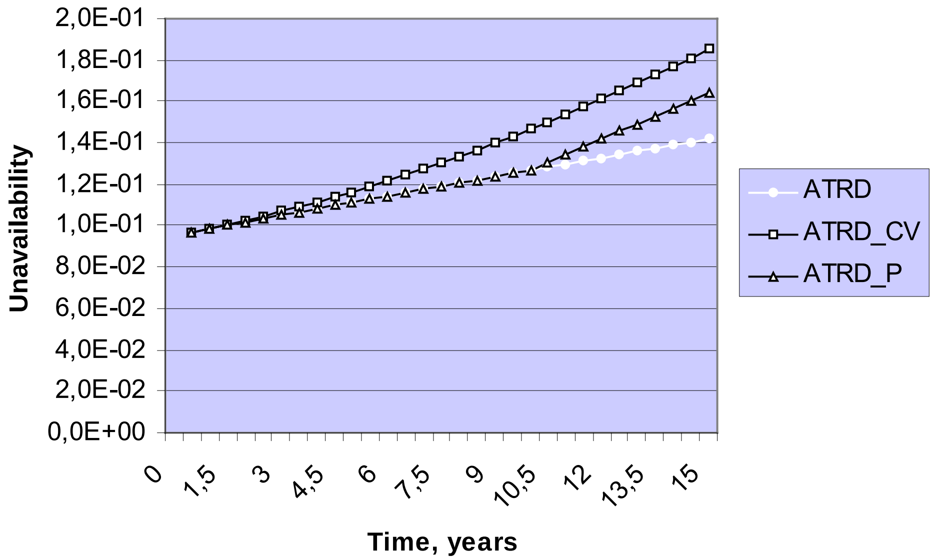


Figure 10. Unavailability comparison of a non-ageing RHRS to an RHRS with ageing check valve (CV) and pump (P)

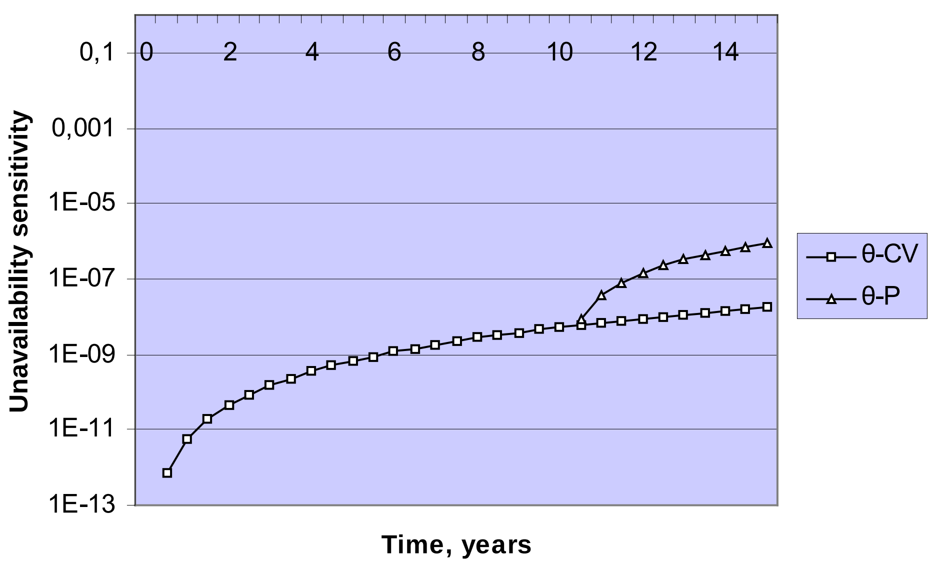


Figure 11. Unavailability sensitivity comparison of a non-repairable check valve (CV) and a repairable pump (P)

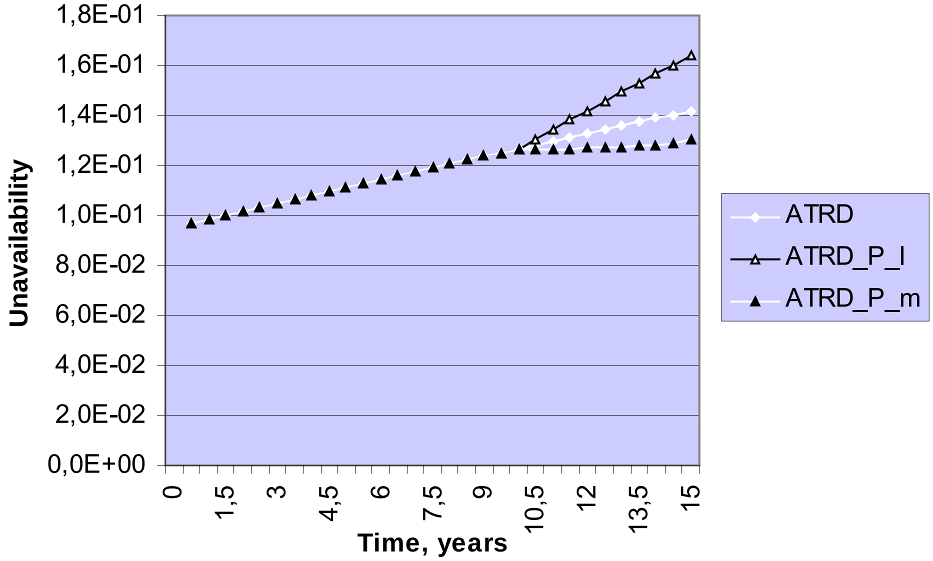


Figure 12. Unavailability sensitivity comparison of a non-repairable check valve (CV) to a repairable pump (P)

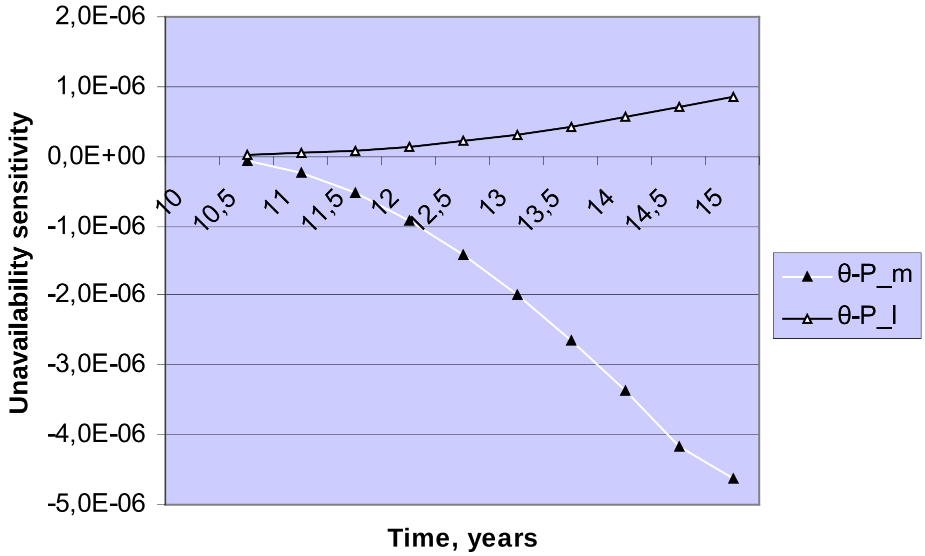


Figure 13. Ageing unavailability sensitivity comparison of ageing and non-ageing repairable pump with changed surveillance interval

The ageing rates values are chosen for better visualisation. The ageing of the check valve starts at the time and age zero ($t=0$ and $w=0$) and the ageing of the pump starts at the time=10 years ($w=10-\tau=0$).

6. Summary and Conclusions

The process of incorporating ageing effects into reliability models has been demonstrated using two different dynamic system reliability approaches – GO-FLOW and ATRD. The dynamic system reliability methods could be applied to allocate the ageing reliability data for basic events and ageing failure mode and effect sensitivity analysis.

These methods were applied to two typical mechanical components – repairable pump and non-repairable check valve, in a segment of the WWER-1000 safety system fault tree in order to evaluate the ageing impact on the RHRS unavailability and unavailability sensitivity to a given component. The RHRS FT has been converted from Saphire 7.0 to the GO-FLOW and ATRD models and they were validated based on identity of results. Therefore, using the same settings and equivalent reliability models/data were used and no major outcome differences can occur. The result of the analysis give evidence that the ageing contributors should be treated distinctive on the basis of system unavailability and importance mesures (Fussel-Vesely). The ageing degradation and restoration are modeled by linear functions, however there are no obstacles to apply one-, two or three Weibull distributions.

The GO-FLOW and ATRD methods could be used for calculation and synchronization of the ageing impact to the safety system component unavailabilities. The methods have also more sophisticated features (the GO-FLOW combination of operators or the ATRD Petri-nets elements such as delays, marking, local clocks and time transitions) that could be used for more detailed sensitivity simulations, e.g. to simulate only part of component failure modes or process that is suspected of ageing. They may extrapolate and predict the component unavailability curves up to stationary values in different time intervals and to the end of the plant lifetime.

All dynamic system reliability methods could be used to propose the optimal periodical test and preventive maintenance intervals for components based on risk or system unavailability by decomposition and determination options and criteria. The investigation demonstrates that unavailability sensitivity studies give opportunities to determine ageing rates limits concerning degradation and restoration. The quantification of age-related effects must be sensitive to a component's function. A practicable approach seems to be the use of different individual ageing process, component degradation and restoration factors. The shortening of surveillance intervals for renewable components that is applied as an ageing compensation measure would be more explicitly modelled and treated in PSA.

7. References

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