Application of Methods and Discussion of the Results about the Ageing in Probabilistic Safety Assessment

Čepin Marko
"Jožef Stefan" Institute
Jamova 39, SI-1000 Ljubljana, Slovenia
marko.cepin@ijs.si

ABSTRACT

Probabilistic safety assessment is a standardised tool for assessment of safety of nuclear power plants. It is more and more included in the risk-informed decision-making. The objective of the paper is to analyze theoretical models of ageing and to provide examples of their application, which would represent the standpoint for an upgrade of current probabilistic safety assessment with the direct inclusion of ageing. The paper presents theoretical models of ageing and practical examples, which show, how the current models can be upgraded in sense to directly include the effects of ageing into the models of probabilistic safety assessment. The most important problem is the lack of data about the effects of ageing, which would suit to the well developed and detailed models of ageing. In addition to theoretical models of ageing and to practical examples of their application in the probabilistic safety assessment, this paper brings forward findings and judgments, which does not support a direct inclusion of ageing into the existing probabilistic safety assessment. Namely, ageing has already been included in the models, when the constant failure rate is assumed. It only isn't separated from other causes of components and systems faults. Another fact is that the effects of ageing may contribute to the models and results of probabilistic safety assessment less than other important features, which are candidates for improvement of the existing probabilistic safety assessment. From this, it can be concluded, that it is reasonable, that the models and the results of probabilistic safety assessment are firstly improved considering the suggested features and then the inclusion of ageing is considered.

1 INTRODUCTION

Ageing is a process, where the properties of systems and processes may degrade through the time and age.

Probabilistic safety assessment is a standardised tool for assessment of safety of nuclear power plants, references from [1] to [29]. It is more and more included in the risk-informed decision-making.

The objective of the paper is to analyze theoretical models of ageing and to provide examples of their application, which would represent the standpoint for an upgrade of current probabilistic safety assessment with the direct inclusion of ageing.

2 STATE –OF-THE-ART

Many activities are connected with consideration of ageing and lifetime of the equipment. Models and analysis include a wide variety of applications, which are included in references from [30] to[69].

Consideration of ageing in probabilistic safety assessment is dealt with in the references from [70] to [100]. The most important problem is the lack of data about effects of ageing, which would suit to the well developed and detailed models of ageing.

Selected studies have shown the risk and reliability implications of aging [95], [96], [97]. Same authors believe that the contribution of aging to the risk measures may be assessed as very small or almost negligible considering the uncertainty of models, data and analysis results [98], [100]. Others indicate, that aging of passive components may be necessary for assessment of safety [77].

3 METHODS

Many mathematical methods for consideration of ageing exist. They include mathematical formulations of parameters, for which it is very difficult to get appropriate data, which could make the methods widely applicable.

Selected methods for consideration of ageing are presented in the following sections.

3.1 Basic methods for modelling of ageing

Weibull method, linear method and exponential method are presented.

3.1.1 Weibull method

This method represents the failure rate of equipment with a function, where the failure rate is changed with age of equipment from constant failure rate before the threshold age to the Weibull increasing failure rate after the threshold age.

The basic mathematical formulation of the method is presented in the equation below.

$$\lambda(w) = \lambda_0 \qquad \forall \qquad w \le w_0$$

$$\lambda(w) = \lambda_0 \left[\frac{w}{w_0}\right]^b \qquad \forall \qquad w > w_0 \qquad \textbf{eq. 1}$$

λ_0 … initial constant failure rate

b … Weibull shape parameter

w_0 … threshold age after which the failure rate increases

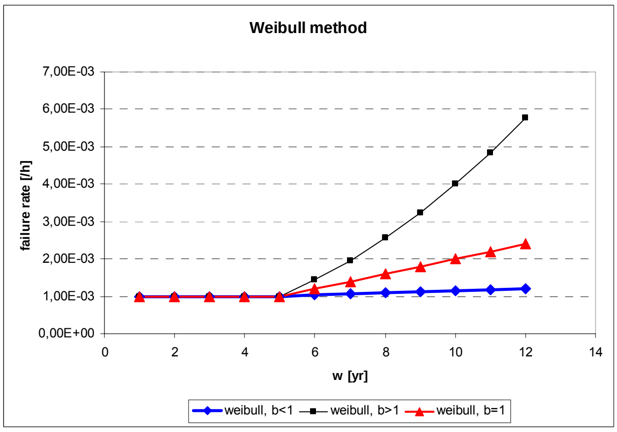

Figure 1: Weibull method for modelling of ageing

Similarly, the evaluation can be done for other probability parameters than failure rate, such as failure probability.

3.1.2 Linear method

This method represents the failure rate of equipment with a function, where the failure rate is changed with age of equipment from constant failure rate before the threshold age to linear increasing failure rate after the threshold age.

Threshold can be incorporated in the mathematical formulation to represent the beginning of ageing at some nonzero age w_0. The basic mathematical formulation of the method is presented in the equation below.

$$\lambda(w) = \lambda_0 \qquad \forall \qquad w \le w_0$$
$$\lambda(w) = \lambda_0 + \alpha(w - w_0) \qquad \forall \qquad w > w_0 \qquad \textbf{eq. 2}$$

λ_0 … initial constant failure rate

α … linear aging rate

w_0 … threshold age after which the failure rate increases

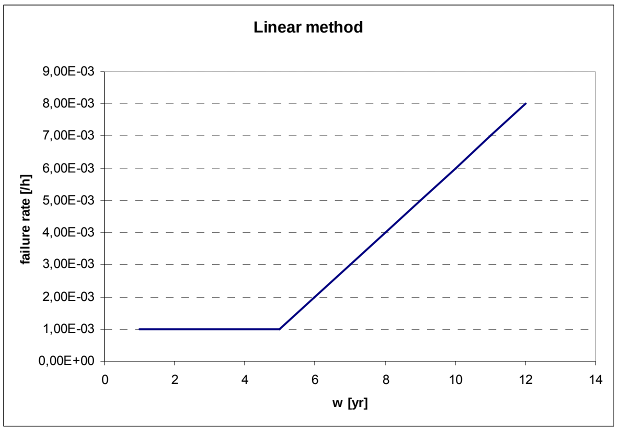

Figure 2: Linear method for modelling of ageing

Similarly, the evaluation can be done for other probability parameters than failure rate, such as failure probability.

3.1.3 Exponential method

This method represents the failure rate of equipment with a function, where the failure rate is changed with age of equipment from constant failure rate before the threshold age to exponentially increasing failure rate after the threshold age.

The basic mathematical formulation of the method is presented in the equation below.

$$\lambda(w) = \lambda_0 \qquad \forall \qquad w \le w_0$$
$$\lambda(w) = \lambda_0 \cdot \exp(c(w - w_0)) \qquad \forall \qquad w > w_0 \qquad \textbf{eq. 3}$$

λ_0 … initial constant failure rate

c … exponential scale parameter

w_0 … threshold age after which the failure rate increases

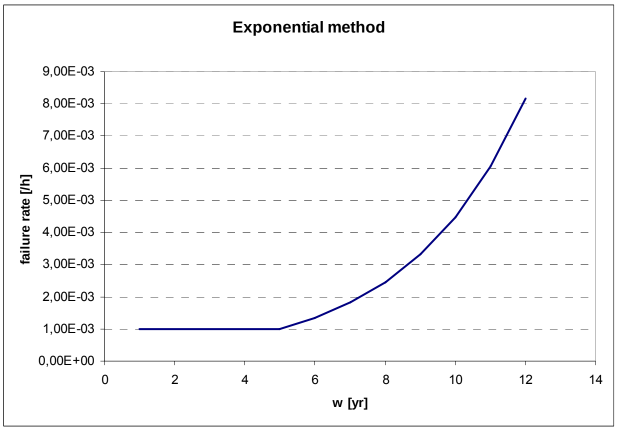

Figure 3: Exponential method for modelling of ageing

Similarly, the evaluation can be done for other probability parameters than failure rate, such as failure probability.

3.2 Detailed methods for modelling of ageing

More detailed methods for modelling of ageing are developed. Their use is more theoretical than practical due to lack of real data for the support of the parameters in mathematical formulations. Examples are presented in the references from [82] to [93].

3.3 Basic methods for consideration of ageing in probabilistic safety assessment

3.3.1 Method of stepwise constant failure rates

The development of a method for consideration of aging in probabilistic safety assessment follows the initiation of activities on the field of modelling and analysis of aging effects.

The standpoint for the development of this method lays in a fact that a detailed probabilistic safety assessment of a nuclear power plant exist, which does not directly include consideration of aging in its probabilistic models. In this sense, it seemed that the extension of the existing probabilistic safety assessment models with addition of aging as an independent contribution would be the easiest solution. The deficiency of such approach would be the fact that contribution of aging may not be independent from existing contribution.

Figure 4 shows the difference in modelling, if aging is considered or not.

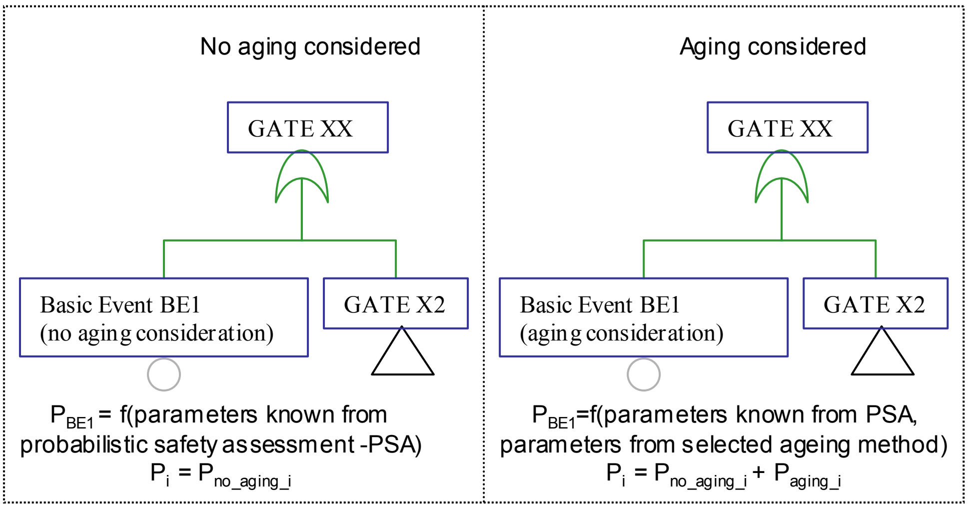

Figure 4: Schematic modelling for consideration of aging

Stepwise constant failure rate method assumes the constant failure rates or constant failure probabilities of equipment in the determined time intervals {t_i, t_{i+1}], and hence this failure rates or failure probabilities are determined as their average through the time of the time interval. The change of failure rates or failure probabilities changes through the selected time intervals according to the selected method for evaluation of failure rates or failure probabilities due to ageing.

At each selected time interval the average failure rates or failure probabilities are calculated for the equipment under investigation and the evaluation of the probabilistic safety assessment is performed.

An advantage of this method is that it can be used in standard probabilistic safety assessment by standard tools for performing probabilistic safety assessment. Figure 2 shows the basic principle of method.

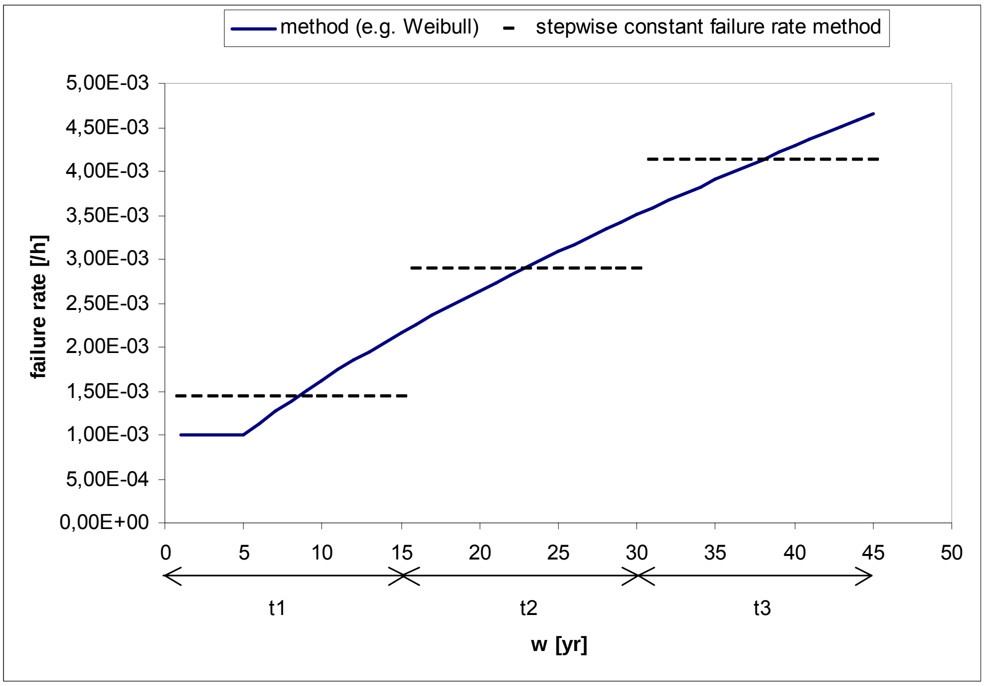

Figure 5: Method of stepwise constant failure rates

3.3.2 Method of prioritization of ageing from results of probabilistic safety assessment

The method of assessment of ageing from results of probabilistic safety assessment is presented in reference [88], while the data are analysed also in reference [87].

The mathematical formulation bases on the data base about components ageing rates – TIRGALEX data base, which is presented in Table 1.

Table 1: TIRGALEX data base for ageing rates of equipment

Component	Ageing rate [per hour per year]
AC bus	1.0E-09
Air operated valve	4.0E-07
Battery	3.0E-07
Check valve	4.0E-09
Circuit breaker	2.0E-08
DC bus	1.0E-09
Diesel generator	3.6E-06
Motor driven pump	2.0E-07
Motor operated valve	3.6E-06
Relay	3.0E-07
Safety/relief valve	7.0E-07
Transformer	2.0E-09
Turbine driven pump	3.0E-06
Solenoid operated valve	6.7E-07

The mathematical formulation of the method is the following.

$$\Delta\lambda_i = \lambda_i - \lambda_{i0} \qquad \textbf{eq. 4}$$

λ_{i0} … failure rate of equipment i (no ageing considered)

λ_i … failure rate of equipment i with ageing considered

$\Delta\lambda_i$ … the increase of failure rate of equipment i due to ageing

$$\Delta q_i = q_i - q_{i0} \qquad \textbf{eq. 5}$$

q_{i0} … unavailability of equipment i (no ageing considered)

q_i … unavailability of equipment i with ageing considered

Δq_i … the increase of unavailability of equipment i due to ageing

For tested equipment:

$$\Delta q_i = \frac{1}{4} a_i \left(\frac{1}{\lambda_{i0}} - T_i\right) T_i + \frac{1}{6} a_i T_i^2 \qquad \textbf{eq. 6}$$

a_i ... ageing rate of equipment i

T_i ... test interval of equipment i

For equipment, which is not tested:

$$\Delta q_i = \frac{1}{2} a_i t_0^2 \qquad \textbf{eq. 7}$$

t_o … facility lifetime

$$\Delta CDF = \sum_i S_i \Delta q_i + \sum_{i>j} S_{ij} \Delta q_i \Delta q_j + \sum_{i>j>k} S_{ijk} \Delta q_i \Delta q_j \Delta q_k + \ldots + S_{12..n} \Delta q_1 \Delta q_2 \ldots \Delta q_n \qquad \textbf{eq. 8}$$

ΔCDF … change in core damage frequency due to ageing

S_i …importance of equipment i

4 UPDATE OF PROBABILISTIC SAFETY ASSESSMENT MODEL FOR CONSIDERATION OF AGEING

Update of probabilistic safety assessment model for consideration of ageing can be done in two directions:

- addition of components to the models and
- changes made to existing models, changes of the probabilistic data.

4.1 Addition of components to the models

In the current probabilistic safety assessment it is possible that:

- the failures of certain structures or passive components or other equipment are not considered, because their failure probability is negligibly low, or
- the failures of certain passive components are indirectly considered within the existing models and data connected with the corresponding active components.

In other words, probabilistic safety assessment models generally does not directly include passive components, which may be susceptible to the ageing issues more than active and tested components. Therefore the models may be updated with inclusion of the passive components.

The method for selection of passive components may consider the importance results of existing probabilistic safety assessment. The equipment with higher risk importance factors may be investigated in sense if the consideration of additional passive components improves the model.

The criteria for selection of equipment, for which a consideration about the neighbouring passive components is performed, are presented in Table 2.

Table 2: Risk criteria for determining important equipment

Risk importance measures	Criteria
RRW- Risk Reduction Worth system level component level	 >1.05 >1.005
FV- Fussell -Vesely Importance system level component level	 >0.005 >0.005
RAW- Risk Achievement Worth	>2

For the identified equipment with high risk factors the method of stepwise constant failure rate or failure probability or unavailability can be used considering linear increase of failure rate or failure probability or unavailability.

$$q_i(w) = k_i(w)q_{i0} \qquad \textbf{eq. 9}$$

$q_i(w)$ ... unavailability of equipment i due to ageing

q_{i0} ... unavailability of equipment i (no ageing considered)

$k_i(w)$ ... factor of ageing of the respective equipment i (e.g. pipelines)

4.2 Changes made to existing models

Frequencies of initiating events such as large, medium or small loss of coolant accident, steam generator turbine rupture and steam line break depends on the history of experience with the pipes. The frequencies of newer pipelines may be lower than the frequencies of older ones.

Method of stepwise constant initiating event frequency can be used considering linear increase of initiating event frequency.

$$f_{IE}(w) = k_i(w)\, f_{IE0} \qquad \textbf{eq. 10}$$

$f_{IE}(w)$ … initiating event IE frequency due to ageing

f_{IE0} … initiating event IE frequency as it is in current probabilistic safety assessment

k_i (w) … factor of ageing of the respective equipment i (e.g. pipelines)

5 RESULTS OF SELECTED EXAMPLES

5.1 Ageing consideration for existing models - containment spray system example

The containment spray system is selected as an example. Its fault tree consists of 11 gates and 22 basic events represented by 11 parameters.

Table 3 shows data for parameters of containment spray system considering ageing contribution. Parameters of ageing connected with of common cause failures are the same as the parameters of ageing connected with the respective basic events modelling respective primary failures.

Figure 6 shows calculated basic event unavailabilities due to ageing, which depend on timely independent unavailability and ageing parameters, such as Weibull parameter b and threshold age. Unavailability of basic events connected to test and maintenance is constant through the age.

Figure 7 shows the system unavailability due to ageing, which is obtained through the fault tree evaluations specified for time intervals of 1 year. Results show the increase of system unavailability of one order of magnitude for the considered period of 15 years.

Table 3: Data for parameters of containment spray system considering ageing contribution

Identification	Weibull Parameter b	Threshold Age [y]
BE-PAR-01	1,00E+00	5,00E+00
BE-PAR-02 (CCF)	1,30E+00	7,00E+00
BE-PAR-03	3,00E+00	4,00E+00
BE-PAR-04	1,00E+00	6,00E+00
BE-PAR-05	4,00E+00	5,00E+00
BE-PAR-06	1,30E+00	7,00E+00
BE-PAR-07 (T&M)	1,00E+00	2,00E+01
BE-PAR-08	7,00E-01	4,00E+00
BE-PAR-09	4,00E+00	5,00E+00
BE-PAR-10	2,00E-01	5,00E+00
BE-PAR-11	1,70E+01	1,00E+01

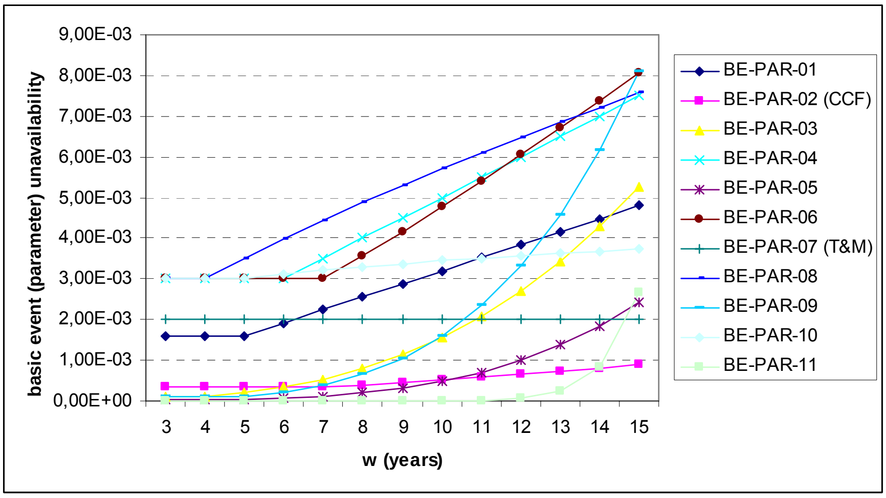

Figure 6: Basic event unavailability due to ageing

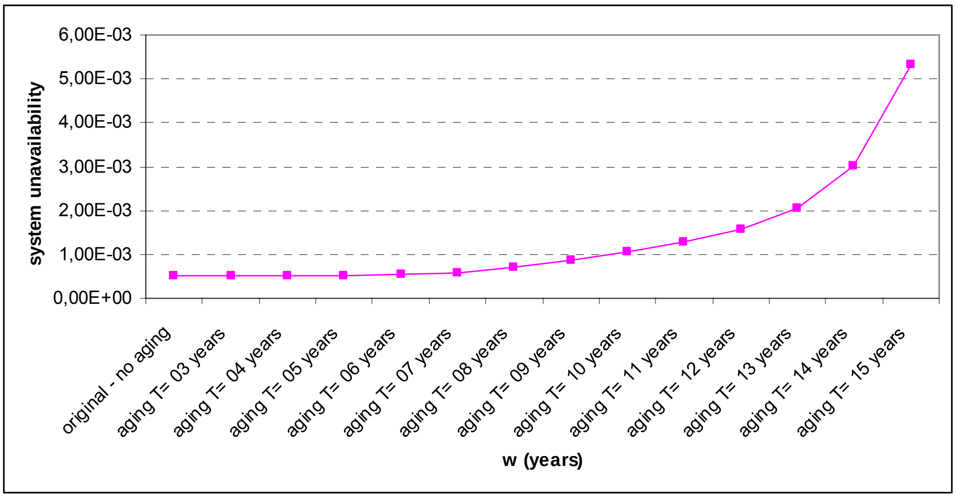

Figure 7: System unavailability due to ageing

Figure 8 and Figure 9 show Fussel-Vesely importance measure for the selected basic events of the fault tree representing selected components of the system. Results show that some equipment can be non-important, if no ageing is considered, and very important if ageing is considered and vice versa.

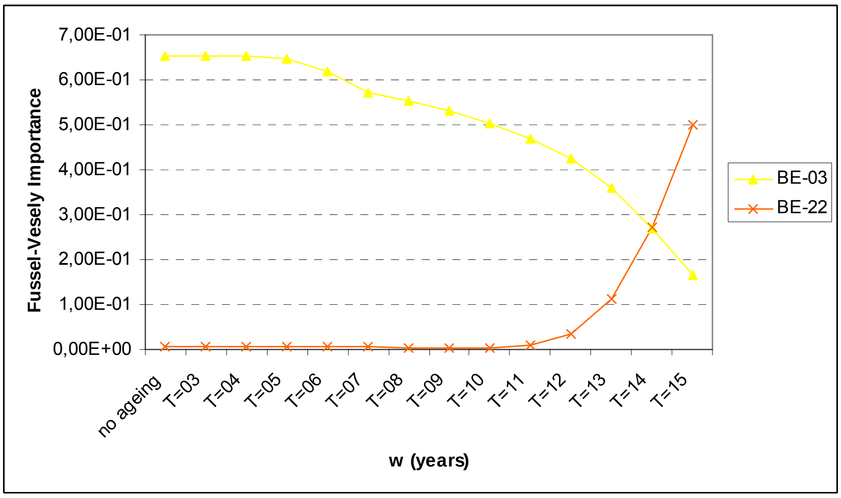

Figure 8: Fussel-Vesely Importance due to ageing

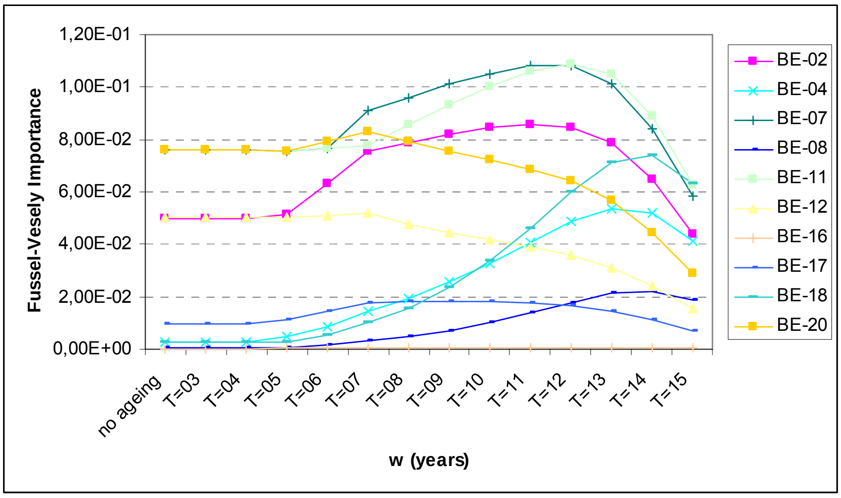

Figure 9: Fussel-Vesely Importance due to ageing (part 2)

Figure 10 and Figure 11 show the risk decrease factor due to ageing.

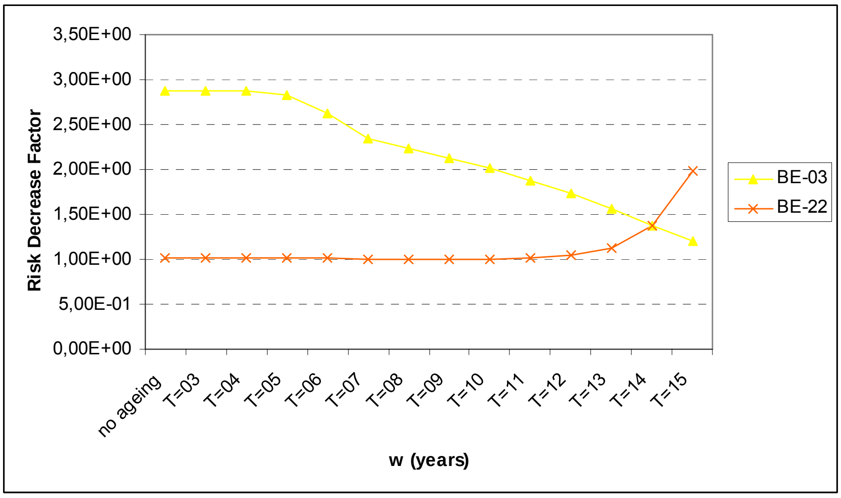

Figure 10: Risk Decrease Factor due to ageing

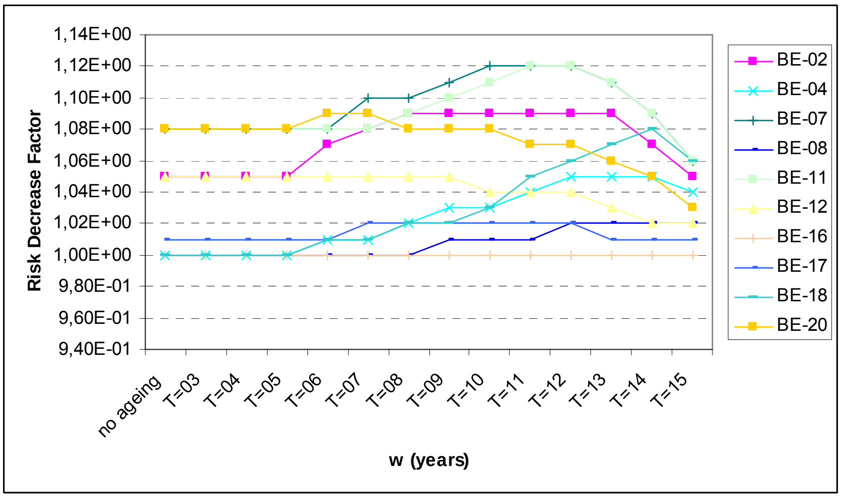

Figure 11: Risk Decrease Factor due to ageing (part 2)

Figure 12 shows the risk increase factor due to ageing. Results show that risk factors may considerably vary depending on ageing. If the other than linear method for consideration of ageing would be selected, the differences in risk importance measures are expected to be even higher.

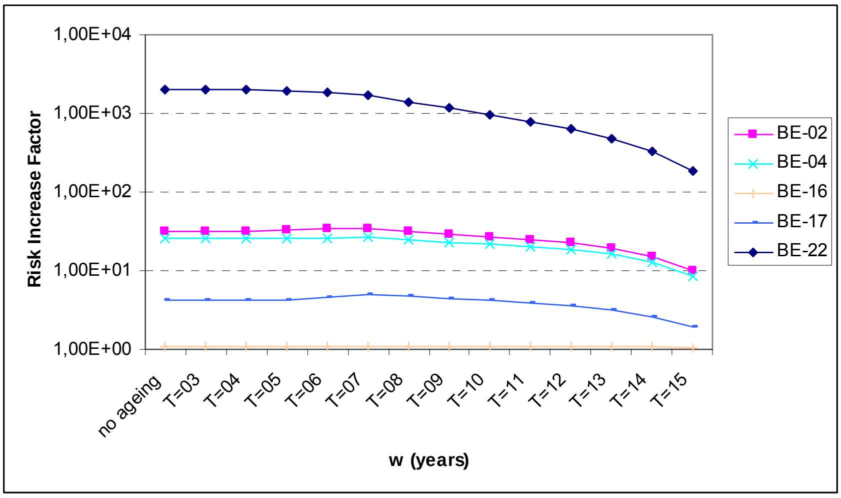

Figure 12: Risk Increase Factor due to ageing

5.2 Ageing consideration for passive components in probabilistic safety assessment - containment spray system example

The containment spray system is selected as an example. Its fault tree has been changed. Two basic events representing the piping failures were added to their respective places with small piping failure probability assessed based on piping length, number of elbows and number of welds ($Q_{piping0} = Q_{piping0\_pipelenght} + Q_{piping0\_no\_elbow} + Q_{piping0\_no\_welds} = 1E\text{-}6$). Factor of ageing is assessed as linear function $k_{piping}(w)=K_a*w$ and K_a=8,76e-6/year is assumed and 15 years of operating time is considered.

The results show that system unavailability slightly changed from 5,059E-4 to 5,092E-4, which can be assumed as neglected. The risk measures connected with piping give no indication of piping importance, except of the risk increase factor (RIF_{piping}=26), when ageing is 15 years.

Experience shows that the most important issue for consideration of piping is that the models of piping are performed on train bases or on appropriate segments basis. If all piping of one system is simplified and considered as one component, the model is not suitable and as such not needed.

5.3 Ageing consideration - complete probabilistic safety assessment example

Complete probabilistic safety assessment of a nuclear power plant is selected as another example. The probabilistic safety assessment model is a detailed model with thousandths of gates, thousandths of basic events, hundredths of fault trees and 16 event trees with 16 initiating events.

5.3.1 Adding passive components

Systems and subsystems, which models are changed with added basic events about piping failure probability are the following: auxiliary feedwater system motor driven pump 1, pump 2, turbine driven pump, chemical volume and control system, component cooling system train A, train B, instrument air train A, train B, residual heat removal train A, train B, safety injection to cold leg 1, cold leg 2, safety injection pump 1, pump 2, containment spray injection pump 1, pump 2, service water system train A and train B.

Added basic events about piping failure probability do not change the core damage frequency and do not impact significantly other probabilistic safety assessment results ($Q_{piping\_i\_0}$=1E-6).

If the ageing of piping is considered, the core damage frequency changes: $Q_{piping\_i\_0}$ = 1,31E-4 for the period between 10 and 20 years of plant operation; $k_{piping}(w)=K_a*w$ is assumed; K_a=8,76e-6/year; 15 years of ageing is assumed as the average for the period between 10 and 20 years of plant operation. The core damage frequency changes negligibly: from 2,81E-55/ry to 2,88E-5/ry, but the risk increase factor of the parameter piping becomes significant (RIF_{piping}=1,74E+4). Significant RIF_{piping} means that the core damage frequency and thus risk may increase significantly with the increase of piping failure probability.

Figure 13 shows sensitivity of core damage frequency due to changes of the piping failure probabilities due to ageing.

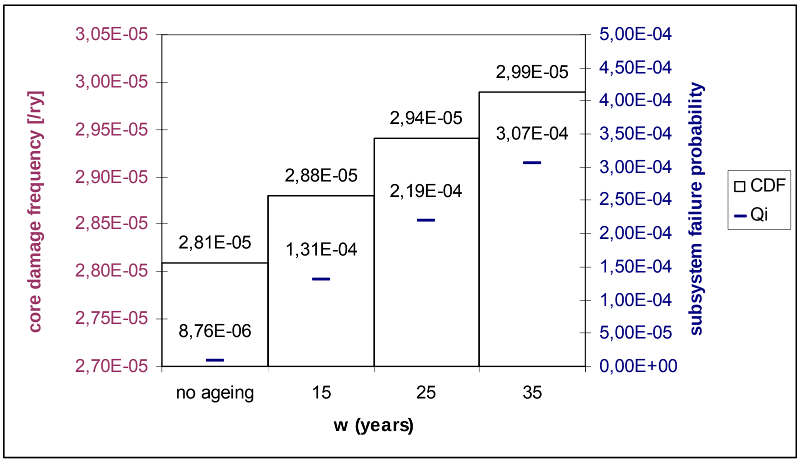

Figure 13: Sensitivity of core damage frequency due to changes of the piping failure probabilities due to ageing

5.3.2 Changing existing models – initiating events only

Initiating events frequencies were changed for two groups of initiating events. The first group include initiating events: large loss of coolant accident, medium loss of coolant accident, small loss of coolant accident, steam line break and steam generator tube rupture. The second group include initiating events: interfacing system loss of coolant accident, loss of essential service water, loss of component cooling water and loss of instrument air. For the initiating events from the first group, the initiating events frequency is changed according to linear method of consideration of ageing. For the initiating events from the second group, only the assessed part of the initiating event frequency due to piping is changed according to linear method of consideration of ageing. For the initiating events from the second group, this means that the impact of ageing is negligible, because a small increase of small part of the initiating event frequency may be lower than the round up.

The resulted core damage frequency increases with increasing initiating event frequencies depending on the percentage contribution of respective initiating events to the core damage frequency.

Table 4 shows sensitivity of core damage frequency due to changes of the initiating events frequency due to ageing. Results show that the core damage frequency increases for less than 8 percents, because the contribution of selected basic events to the initial core damage frequency (without consideration of ageing) is approximately only 21%.

Table 4: Sensitivity of core damage frequency due to changes of the initiating events frequency due to ageing

	f_{IE0} [/ry]	f_{IE}(15y) [/ry]	f_{IE}(25y) [/ry]	f_{IE}(35y) [/ry]
Large LOCA	5,00E-06	5,50E-06	6,05E-06	6,66E-06
Medium LOCA	1,38E-03	1,52E-03	1,67E-03	1,84E-03
Small LOCA	2,70E-03	2,97E-03	3,27E-03	3,59E-03
SLB	1,30E-02	1,43E-02	1,57E-02	1,73E-02
SGTR	1,82E-03	2,00E-03	2,20E-03	2,42E-03
CDF [/ry]	2,81E-05	2,88E-05	2,94E-05	3,02E-05
IE frequency increases for K i.e. for 10% per ten years.				
LOCA ... Loss of Coolant Accident; SLB ... Steam Line Break SGTR ... Steam Generator Tube Rupture; CDF ... Core Damage Frequency				

5.3.3 Adding passive components and changing existing models

Both separate considerations from previous sections are joined together and the results are obtained.

Results on Figure 14 show that core damage frequency changes up to 14%. Results show that importance measures change more than core damage frequency (Fussel-Vesely importance measure may change for more than 30%). Figure 15 shows ussel-Vesely importance measure for selected four important components.

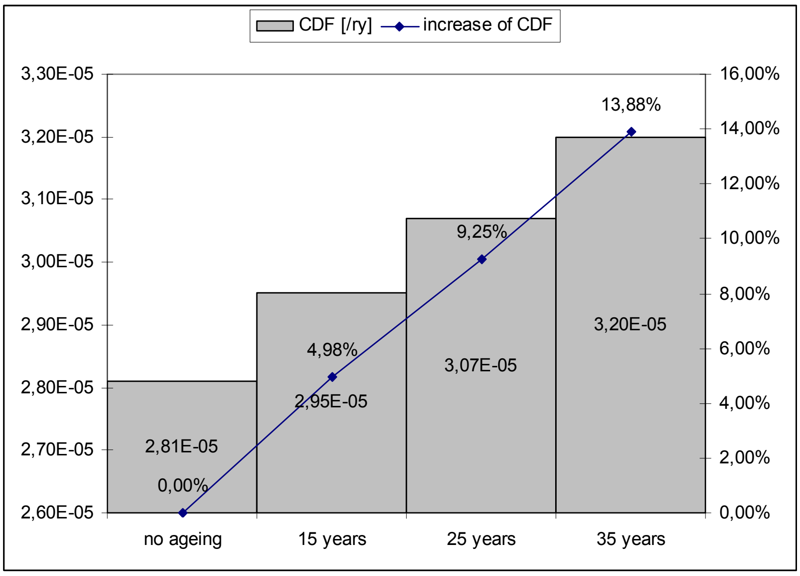

Figure 14: Sensitivity of core damage frequency due to ageing

The contribution of ageing of tenths of percents of the core damage frequency is smaller than the experienced change of the core damage frequency due to modifications of probabilistic safety assessment model due to plant modifications and due to procedure changes.

Figure 16 shows an example of history of probabilistic safety assessment model, which shows much larger decrease of core damage frequency, which is shown by the increase of core damage frequency due to ageing.

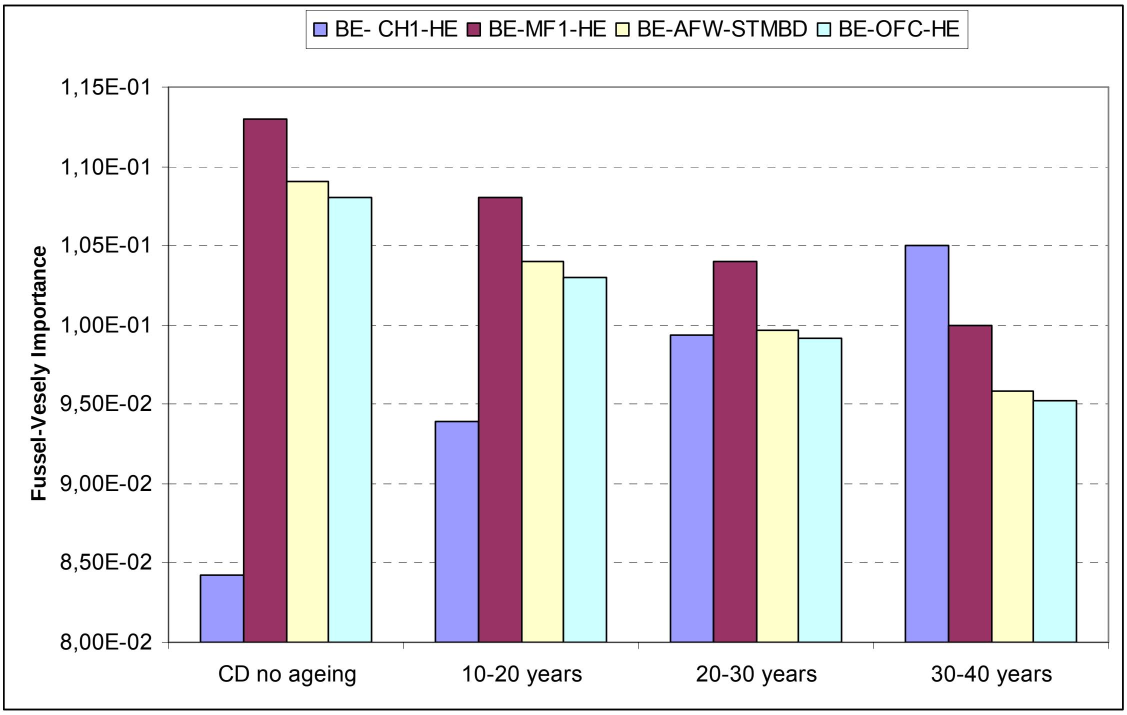

Figure 15: Fussel-Vesely importance measure for selected basic events

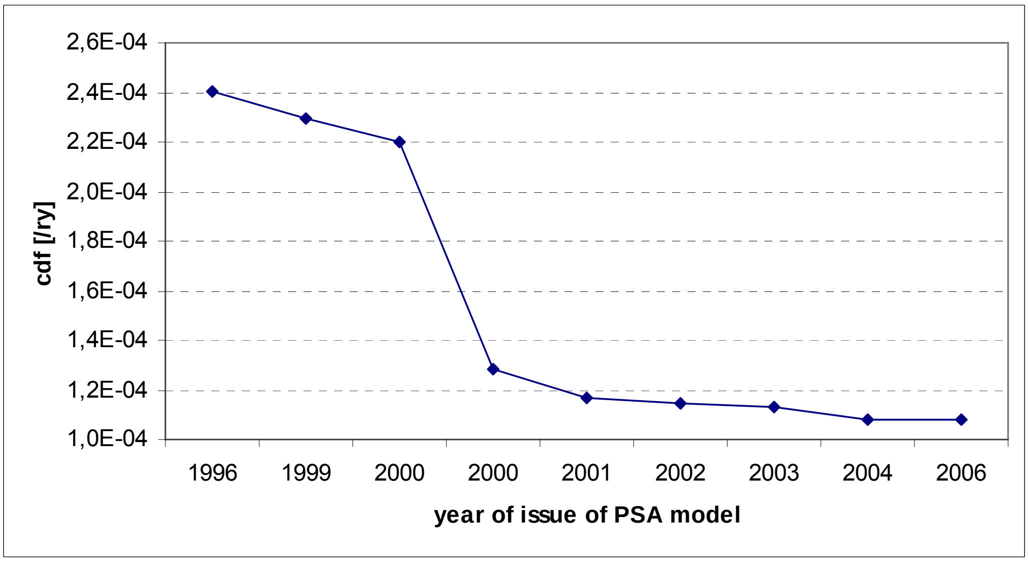

Figure 16: The history of CDF of PSA model due to changes (plant modifications and procedure changes)

Consideration of ageing does not consider changes of human reliability, which is an important issue in probabilistic safety assessments contributing to the core damage frequency in the order of tenths of percents. Neglecting the changes of human reliability due to simulator experience and due to operators experience about the plant itself may be a larger portion than the contribution of ageing is.

Uncertainties in probabilistic safety assessment are large and through the years they were reduced by intensive data collection and analysis. Insertion of ageing issues may again largely increase the uncertainties.

6 PROBLEMS CONNECTED WITH INCLUSION OF AGEING IN PROBABILISTIC SAFETY ASSESSMENT

Experience shows that the contribution of ageing into the probabilistic safety assessment is a difficult issue at the current stage of developed models and availability of data. Some facts still prevent inclusion of ageing into the probabilistic safety assessment.

- Uncertainty of data is large in probabilistic safety assessment; with inclusion of ageing the uncertainty would increase significantly.
- Conservatism of models and analyses in probabilistic safety assessment may be much larger as the contribution of ageing.
- It is very difficult to distinguish between failures due to other reasons and failures due to ageing.
- Ageing components are mostly made of many subcomponents and possibly the problems with subcomponents may cause failures of components.
- Consideration of ageing may require significant efforts and largely more complex models, and the effects to the results may not justify the invested efforts.
- Finally, one can always argue that the consideration of ageing has already been included in the existing models with assumed constant failure rates, because the constant failure rates are determined as the average values, where all failure history is taken into account, no matter if the failures are in the beginning or at the end of the component life time.

7 CONCLUSIONS

The objective of the paper is to analyze theoretical models of ageing and to provide examples of their application, which represent the standpoint for an upgrade of current probabilistic safety assessment with the direct inclusion of ageing.

The paper presents theoretical models of ageing and practical examples, which show, how the current models can be upgraded in sense to directly include the effects of ageing into the models of probabilistic safety assessment.

The most important problem is the lack of data about the effects of ageing, which would suit to the well developed and detailed models of ageing.

One may argue that ageing is already included in the models. It only isn’t separated from other causes of components and systems faults.

The effects of ageing may contribute to the models and results of probabilistic safety assessment less than other important features, which are candidates for improvement of the existing probabilistic safety assessment. From this, it can be concluded, that it is reasonable, that the models and the results of probabilistic safety assessment are firstly improved considering the suggested features and then the inclusion of ageing is considered.

8 ACKNOWLEDGEMENT

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