# APPLICATION OF DYNAMIC SYSTEM RELIABILITY METHODS FOR INCORPORATION OF AGE-DEPENDANT RELIABILITY PARAMETERS AND DATA INTO THE PSA MODEL

G. Petkov
Technical University of Sofia, Bulgaria

*Email address of main author: gip@tu-sofia.bg*

**Abstract**

The simplest way to quantify reliability models consists in using the hypothesis that SSC failure and repair rates are constant. However, failures and repaires are implemented in time and consequently they are age-dependent. That is why the dynamic aspects of aging and decision-making in NPP lifetime management become increasingly notable and more advanced tools are needed for their analysis. The paper presents the dynamic system reliability approaches - GO-FLOW and ATRD - to extend the FT methodology for NPP aging systems. Alternative methodologies to investigate the feasibility of increasing of failure, restore and repair rates of all component categories or reducing the surveillance intervals of repairable components to take into account aging processes in plant availability. Both approaches are used for preparation of comparable aging process component and system models of the three-train residual heat removal and low pressure injection system of a Russian-design pressurized water reactor WWER-1000/V320. The possible extensions of these methodologies are compared with the equivalent FT models of this system.

## 1. Introduction

Twenty years ago the aging problem and lifetime management of Nuclear Power Plant (NPP) equipment were theoretical issues of relatively small importance for successful operation and they were easily neglected. However, approaching the end-of-design-life and safety margins, the lifetime management becomes not only an immediate technical task but an essential political, economical and social requirement as well. Because of decision-making complexity of this problem nowadays it is one of the greatest concerns of engineers and scientists of industry and also a topic of national and international discussions. These discussions give a new meaning to economical and political reality. The questions of free competitiveness, rights and obligations following social and environmental risk of NPP have been brought out.

Bulgaria operates nuclear power plants since 1974. First four units of Kozloduy NPP with reactors WWER-440/V230 were already decommissioned because of external political reasons and economical factors. The ‘old’ units’ safety and aging (technical and ‘moral’) problems were of primary importance for modernization and reconstraction measures implementation. Approximately 400 millions euros were invested for these purposes. However, these measures were not helpful to convince the public opinion and some our partners in EU to percept the risk from these units without prejudices.
At present Kozloduy NPP successfully operates two units with WWER-1000/V320 (fifth unit was commissioned in 1987 and the sixth one in 1992). The broad-scale modernization program of these units has been recently completed. The two units with WWER-1000/V466 has started to be build in the new Belene NPP.

Most Bulgarians recognize that the modernized and new nuclear power units should be operated for extended periods of time (at least more than their design lifetime) and that efficient plant lifetime management (PLiM) is very important issue. It is important not only for maintaining and increasing NPP safety and efficiency but also for persuasion of international society and politics that nuclear power for peaceful purposes is prosperity and success for all people. That is why for Bulgaria an investigation of the impact of aging on NPP safety and aging effects duly modelling and accounting into safety policy, regulation, new design and modernization programmes is becoming a major concern. Last but not least is the proof, spreading and popularization of NPP risk-reduction measures in the framework of international (IAEA), European (EC), regional and national organisations and societies.

## 2. Age-dependent reliability models for the PSAM methodology

The Probabilistic Safety Assessment and Management (PSAM) methodology as the most integrated evaluation methodology of plant and process safety gives excellent opportunities for aging safety and efficiency problems solving. One of the tasks of Aging Probabilistic Safety Analysis (APSA) is an incorporation of age-dependent reliability parameters and data of certain safety-related System, Structure and Component (SSC) in to the PSA model and interpretation of its results. The aging process could take place as a gradual degradation or improvement of characteristics of materials. Usually the improvement of one characteristic is accompanied by degradation of other characteristics. Sometimes a forced aging of materials is applied for improvement and stabilization of certain characteristics.

### 2.1. Aging physics models for incorporation into SSC reliability parameters

The simplest way to quantify reliability models consists in using the hypothesis that SSC failure and repair rates are constant. However, failures and repairs are occured in time and consequently they are age-dependent. That is why the dynamic aspects of aging and decision-making in NPP lifetime management become increasingly notable and more advanced tools are needed for their analysis.

The aging can affect the systems and structures only through their components. Consequently the SSC availabilities may decrease due to the aging 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 rapair 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 basic events.

The prefereble way for taking into account the SSC susceptible to aging is the external physics-based reliability models 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' aging mechanisms and these hybrid deterministic-probabilistic models are linked to FT segment of components susceptible to aging [1]. 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 [3].The simplest model is the linear function: $\lambda(t) = \lambda_0 + a(t)(t - \tau)$, (1) where t is the global time, $\lambda_0$ is preaging constant failure rate – charctersitic of a new component, $\tau$ is the threshold time at which aging starts and a(t) is a rate of degradation/strength reduction process.

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

$$\lambda(t) = \lambda_0 + \alpha(\beta+1)(t-\tau)^{\beta}, \qquad (2)$$

where $\alpha$ is a scale parameter, $\beta$ is a shape parameter and $\tau$ is a location parameter.
The linear and Weibull aging 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

$$\lambda(t) = \lambda_0 + a(t)(t - t' - \tau), \qquad (3)$$

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

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

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

## 2.2. Multiple aging states and failure modes transition diagrams for component categories

The plant availability and safety may decrease due to the aging 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 aging components could be identified:

- **Unrepairable or irreplaceable components (Category 1).**

The Category 1 components are those generally considered irreplaceable (e.g. RPV - reactor pressure vessel). They have binary (2 possible) states – normal (success) and failed (failure) but it is possible to take into account some partial restoration by unsteady change of the failure rate at a given moment (RPV annealing) – restorable irreplaceable components.

Therefore, two sub-categories of Category 1 could be determined:

- unrepairable (non-restorable irreplaceable components),
- restorable-irreplaceable components.

Repairable components:

- **Hard-to-replaceable (replaceable but costly) components (Category 2).**

The Category 2 components are replaceable but costly (e.g. SG – steam generator). They have 3 possible states success, outage/capital repair and failure. The partial restoration is also possible to include similar to Category 1 components and two sub-categoris of Category 2 could be identified:

- non-restorable hard-to-replaceable component,.
- restorable hard-to-replaceable components.

- **Replaceable on a routine basis (Category 3).**

The Category 3 and other components are the 'key' ones in terms of safety and reliability but susceptible to aging. They are replaceable and could be restored on a routine basis or according to specific reconstruction/modernization program:

- non-restorable replaceable components,
- restorable replaceable components.

The restorable components could be restored two or more times and accordingly they will have two or more aging normal states. Many components have more than one failure mode and accordingly they will have two or more aging failure states.
On FIG. 1 the state transition diagram of gradually aging component with multiple aging normal and failure states (modes) is shown.

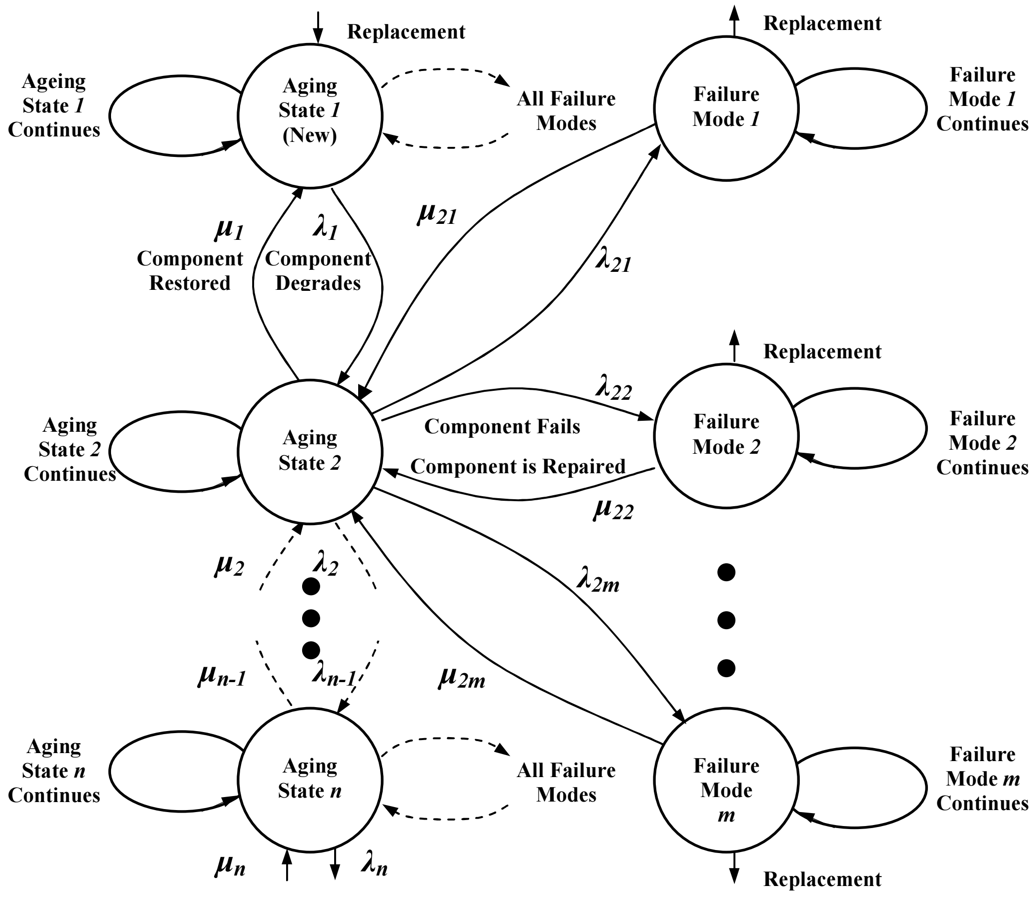



*FIG. 1. State transition diagram of gradually aging component with multiple failure modes*

The generalized transition diagrams of all sub-categories of components are presented on FIG. 1, 2, 3 and 4 as following:

1. restorable replaceble component – FIG. 1.
2. non-restorable replaceble component – FIG. 2.

3. restorable and non-restorable hard-to-replaceble component – FIG. 3a and 3b.
4. restorable and unrepairable (non-restorable) irreplaceble component – FIG. 4a and 4b.

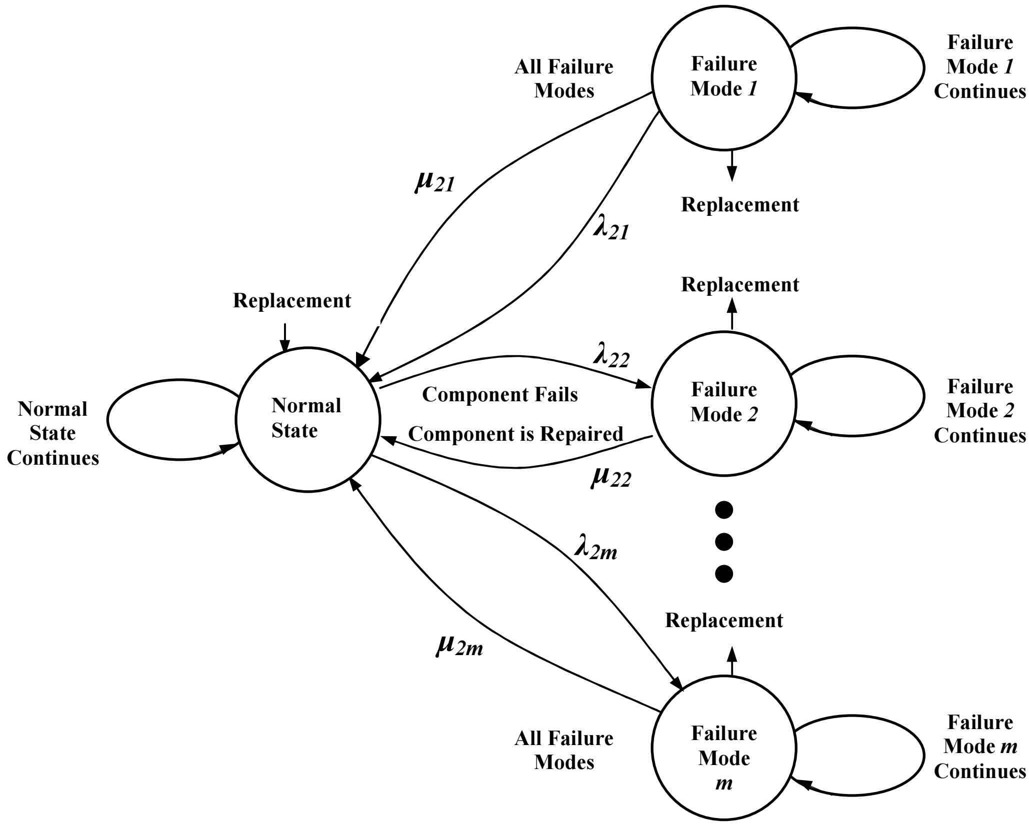



*FIG. 2. State transition diagram of non-restorable replaceable component with multiple* failures

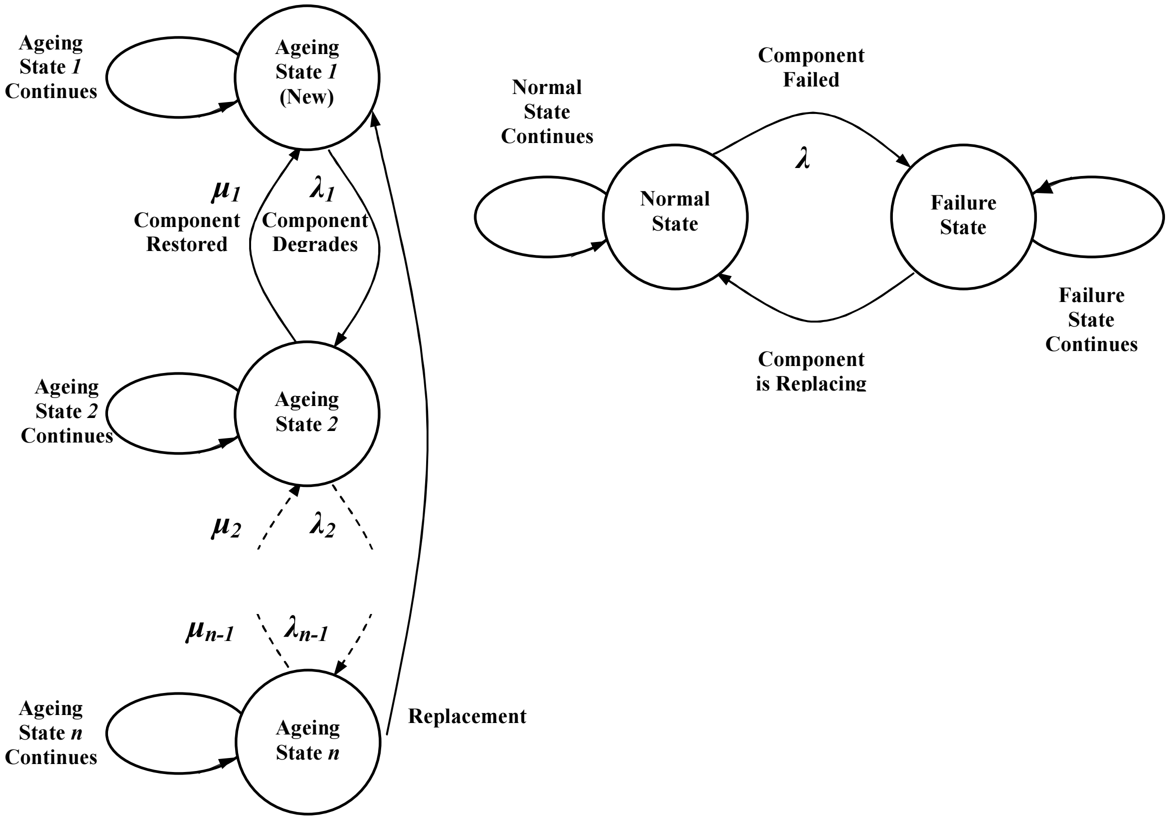



*FIG.3. State transition diagram of restorable (a) & non-restorable (b) hard-to-replaceable* component

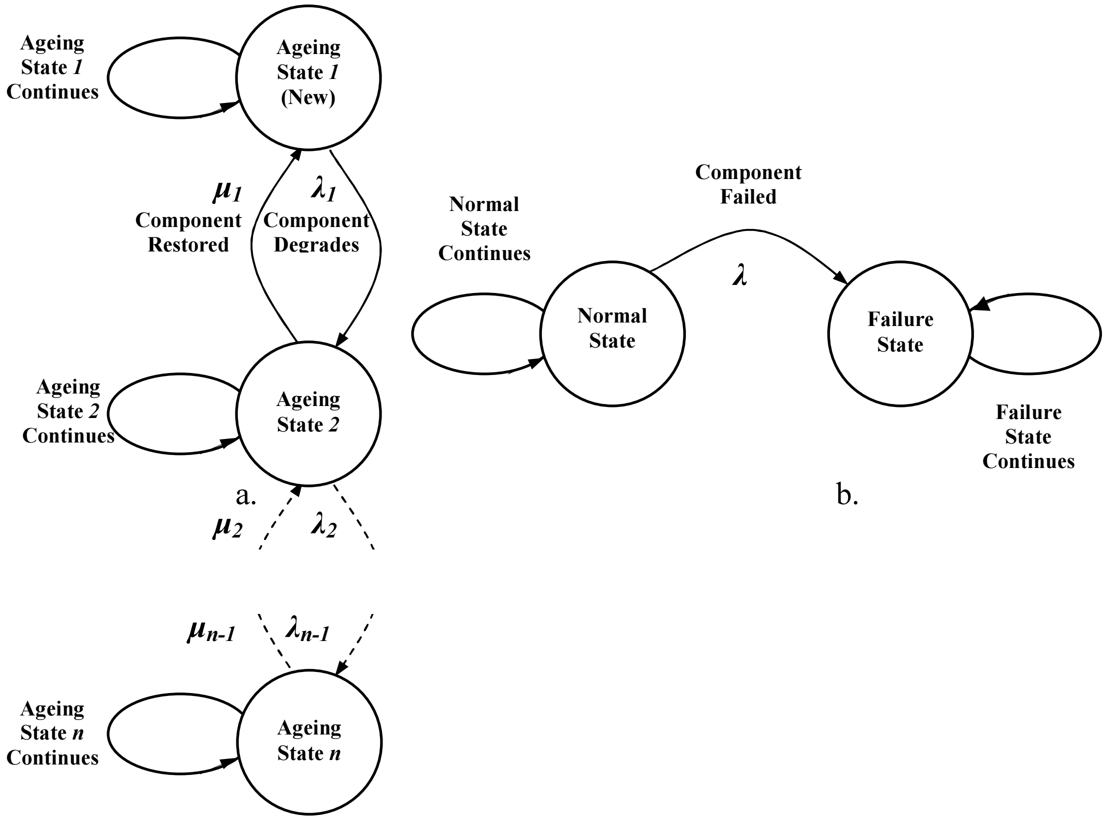



*FIG.4. State transition diagram of restorable (a) & non-restorable (b) irreplaceable component*

## 2.3. *Applicalble assumptions and reliability models for aging effects incorporation*

This state transition diagrams could be defined by two matrices and vectors/columns: matrix of failure rates $\Lambda=[\lambda_{ij}]$, matrix of repair rates $M=[\mu_{ij}]$ and vectors of degradation and restoration rates - $\lambda=\{\lambda_j\}$ and $\mu=\{\mu_i\}$.

(6)

$$\Lambda \equiv \begin{pmatrix} \lambda_{11}, \lambda_{12}, \ldots \lambda_{1m} \\ \lambda_{21}, \lambda_{21}, \ldots \lambda_{2m} \\ \ldots \\ \lambda_{n1}, \lambda_{n2}, \ldots \lambda_{nm} \end{pmatrix} \quad M \equiv \begin{pmatrix} \mu_{11}, \mu_{12}, \ldots \mu_{1m} \\ \mu_{21}, \mu_{21}, \ldots \mu_{2m} \\ \ldots \\ \mu_{n1}, \mu_{n2}, \ldots \mu_{nm} \end{pmatrix} \quad \lambda \equiv \begin{pmatrix} \lambda_1 \\ \lambda_2 \\ \ldots \\ \lambda_n \end{pmatrix} \quad \mu \equiv \begin{pmatrix} \mu_1 \\ \mu_2 \\ \ldots \\ \mu_n \end{pmatrix}$$

where i=1…n are numbers of possible aging states; j=1…m are numbers of possible failure modes.

The transition diagrams of all component categories could be quantified if the matrices Λ, M and vectors λ and μ are given.

Constant-failure, constant-repair and constant-restore 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 behavior for constant rate model are given by equations (7) and (8)

For renewable component Availability is

$$A(t) = \frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu} e^{-(\lambda+\mu)t}, \quad (7)$$

and Unavailability is

$$Q(t) = 1 - A(t) = \frac{\lambda}{\lambda+\mu}\left[1 - e^{-(\lambda+\mu)t}\right], \quad (8)$$

For unrepairable component Reliability is

$$R(t) = A(t) = \exp(-\lambda t), \quad (9)$$

and Unreliability is

$$F(t) = Q(t) = 1 - \exp(-\lambda t), \quad (10)$$

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

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

It is necessary to extend the PSA techniques for modelling of aging 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 every 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 modeled by 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 FIG 1÷4. However, a Markov analysis cannot handle the age-varying rates beacause the conditional intensities are age-varying unknowns. It is quite complicated to solve analytically the multiple state component model with many aging 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. 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:

- components interaction with each other and with environment.
- components response to initial perturbations and changes of process variables.
- configuration changes depending on the mission required or component failures occurrence.
- component characteristics depend 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, aging 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 to analyse them.

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 paper discusses the applicability of these dynamic system and process reliability methods for incorporation of age-dependent reliability parameters and data into the PSA model.

### 3.1. Applicalbility, spectrum and features of dynamic system reliability methodologies

The applicability of the alternative methodology for dynamic reliability and risk modeling depends on analysis level, qualitative and adequate database, available knowledge of structural, physical and functional system relationships and opportunity to compare, validate and verify the methodology results. The spectrum of some applicable dynamic system reliability methodologies for incorporation of aging effect could be classified as [5]:

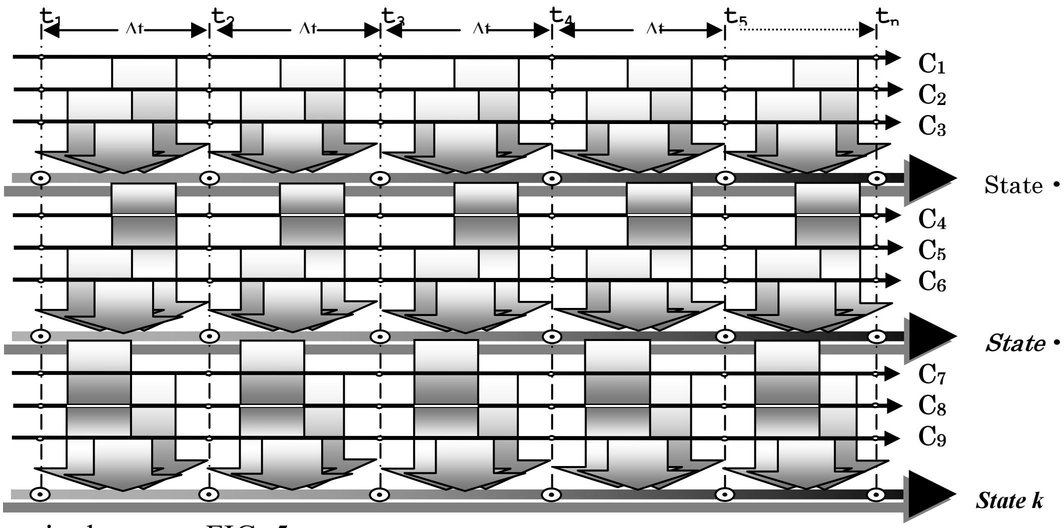
- ET-FT extensions - expanded ETs, GO-FLOW, digraph-based FT construction;

IAEA-CN-155-031

- 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).
- 

### 3.2. 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 FIG. 5.

*FIG.5. Conceptual image of GO-FLOW analysis procedure*

GO-FLOW does not trace each event sequence. It performs numerical calculation as early as possible in the process of analysis. On FIG. 5, $C_n$ 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 $\Delta t$, 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.

### 3.3. Explicit Markov chain models

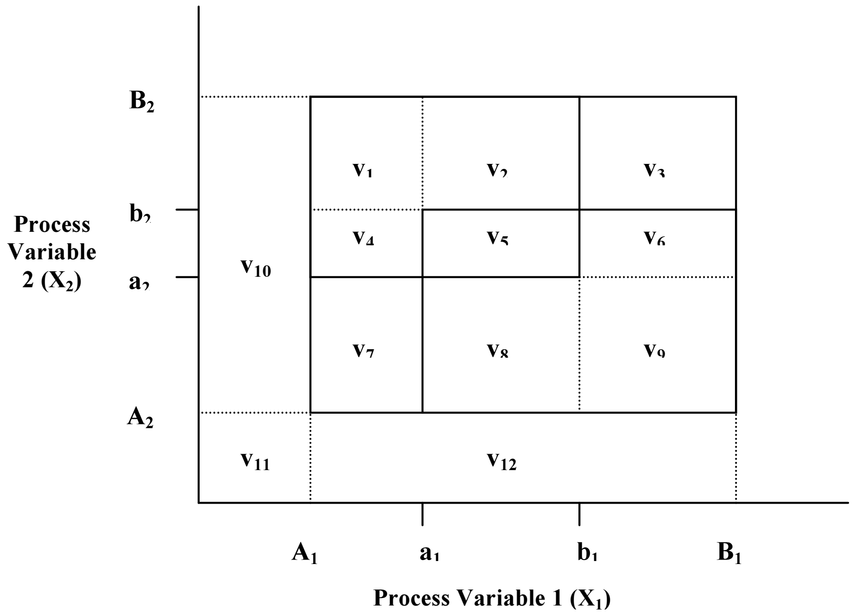
In these models the probabilistic system behavior is simulated by the Markov chains - a set of first order differential equations with feedback describing the interaction between system variables. Three spaces for the partitioning the set of item operability states into substates corresponding to a given level of its functioning quality described in terms of discrete physical states and relations between item parameter values are defined:

- reliability space - failure and repair rates for components,
- discrete state space – time representation of system dynamics,
- control space - the action of operational control components are specified by the control laws and the system fails if any process variable is outside the control space.

The models were developed for reliability analysis of such systems by Tunk Aldemir, Ohio State University, USA, in 1987. The explicit Markov chain procedure consists of:

1. Identifying the control regions;
2. Choosing a partitioning, shown on FIG. 6;
3. Determining operational and failed state;
4. Mechanized construction of transition matrix.

FIG. 6 Schematic partitioning of the set of system operability states by explicit Markov chain




models

The number of system states increases inadmissibly for complex systems. Because of this methods of absorption and truncation are used. The alternative methods include the use of function and regime decomposition.

### 3.4. Dynamic Logical Analysis Methodology

DYLAM is a computer program that combines process simulation and probabilistic model. It was developed by Cacciabue & Cojazzi (EU JRC Ispra, in 1983). The conceptual image of the DYLAM analysis procedure is shown on FIG. 7.

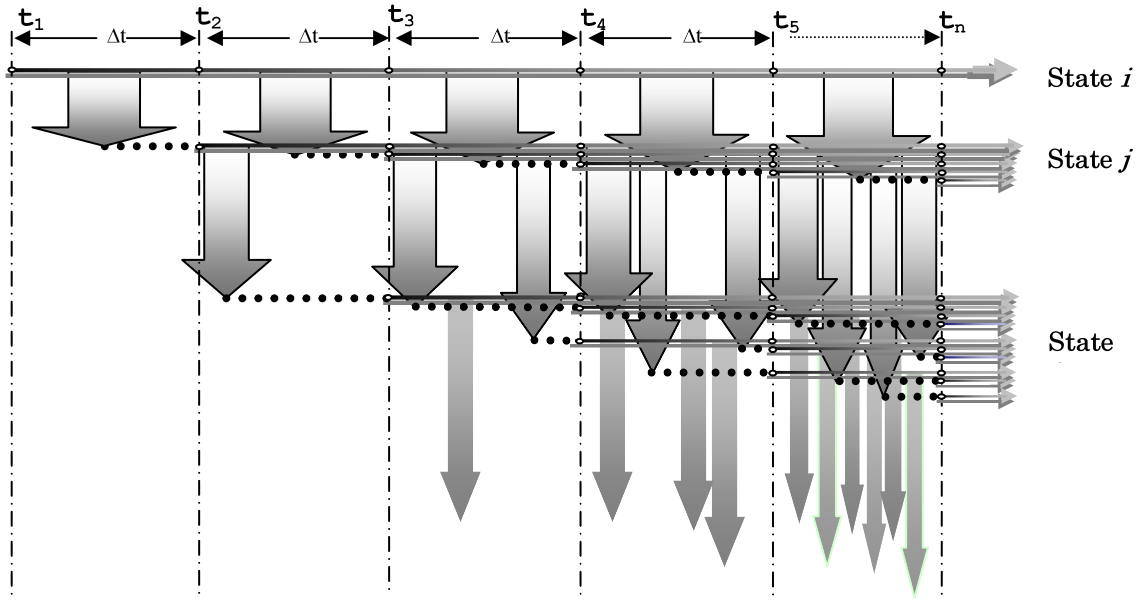



*FIG.7. Conceptual image of DYLAM analysis procedure*

DYLAM traces all the event sequences. System state i will change to state j, and from state j to state k. During each small time interval Δt (DTIME) transitions from state i to j or from j to k occur. The DYLAM methodology distinguishes sequences if transitions have occurred at different times. Therefore, a specific state (for example j) consists of many different sequences.

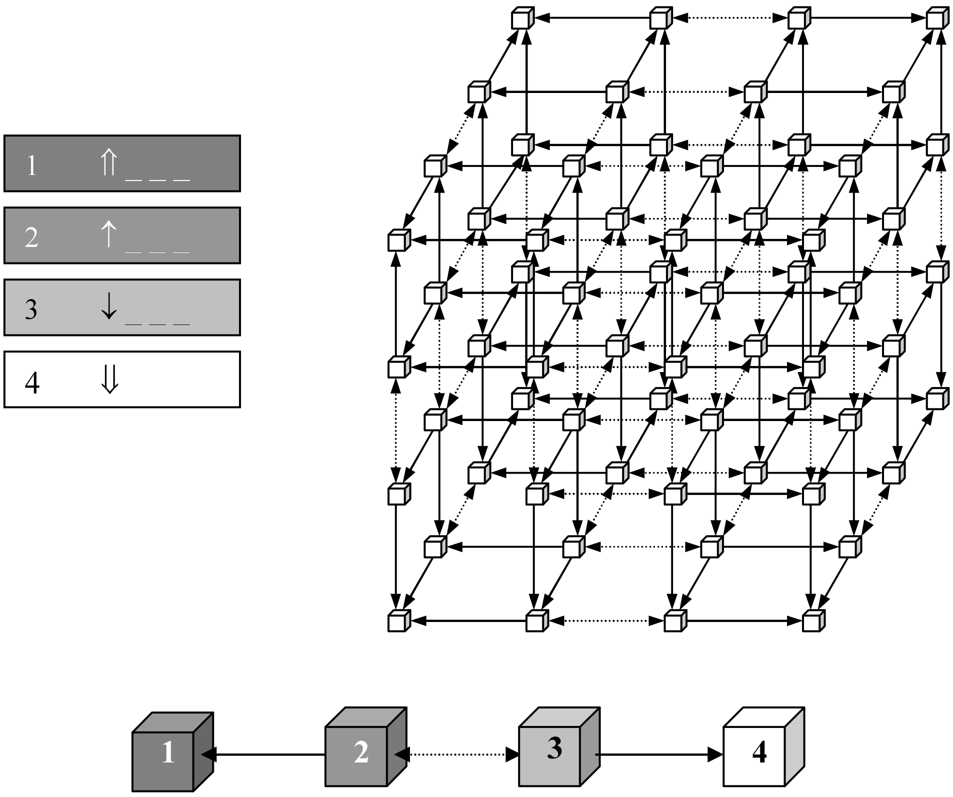
### 3.5. Analysis of Topological Reliability of Digraphs methodology

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 an entrance from limitations of the explicit methodology (Markov model) and to provide a physics-based context for component aging 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 FIG. 8.

*FIG. 8 Conceptual image of ATRD cell-to-cell analysis procedure*




## 4. Insights and intents of case study 'Age-dependent safety system reliability model'

This study investigates the feasibility of dynamic system reliability methods, GO-FLOW and ATRD, to model the availability of aging 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 aging 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 RHRS system has to perform two functions: 1) low pressure injection in case of large break lost of collant accidents (LOCA), and 2) emergency and planned core cooling. Each train consists of a pump, a heat exchanger, valves, check valves and a common tank for all three chanels.

Alternative methods have been applied for the feasibility studies of increasing of failure, restore and repair rates of all component categories or reducing the surveillance intervals of repairable components to take into account aging processes in plant availability. Some preliminary findings and insights for incorporation of age-dependent reliability parameters and data into the PSA model, based on the case study, are presented below.

The dynamic system reliability methods could be used to allocate the aging reliability data for basic events and aging failure mode and effect analysis (FMEA). The case study comrises three categories of aging components: restorable replaceble (FIG.1) – valves, pumps; non-restorable replaceble (FIG. 2) – check valves and pipes; restorable hard-to-replaceble (FIG.3a) – tanks and heat exchangers. The aging processes description of safety systems differs from the processes of normal operation systems and have to include aging in working (active) and stand-by (passive) states at different intervals. That is why the proposed above decomposition of aging states seems appropriate.

The failure mode database is concerned with component functions and rarely with physical component processes, including aging related processes. It means that only part of component failure modes should be suspected of aging. Therefore, the quantification of age-related degradation effects must be component and its function sensitive.

The GO-FLOW and ATRD methods could be used for calculation and synhronization the aging impact to the safety system component unavailabilities. They may extrapolate and predict the component unavailability curves up to stationary values, in different time intervals and to the end of plant lifetime. The ATRD seems more appropriate for explicit obtaining of dynamic component unavailability functions and data preparation because the GO-FLOW results depends on calculation step and available operator type values. However, the operator types have been increasing and extending [6]. The GO-FLOW could be especially useful for extrapolation of component/system unavailability curves in different time intervals (e.g. type 40 operator).

All dynamic system reliability methods could be used to propose the optimal periodical test and preventive maintenace intervals for components base on determined options and criteria. A practicable approach seems to be the use of different individual aging process and component degradataion and restoration factors. The shortening of surveilance intervals for renewable components, as an aging compensation measure, would be more explicitly modeled and treated in PSA if a restoration factor, similar to degradation factor $\gamma$ in (5), is introduced.

The case study will be continued and extended to assess system interactions based on degradation mechanisms an component aging behaviors, to identify the necessary FT modifications (additional gates, basic events, parameters and structure changes) and perform sensitivity study with the GO-FLOW and ATRD methods. Additionally, the impact of FT loop-free and Markov process' 'slow-fast' approximations is to be evaluated as well. A normal operation system aging case study should be conducted in parallel for better understanding how to incorporate aging effects into PSA applications.

## ACKNOWLEDGEMENTS

This research was initiated by the EC JRC Aging PSA network activities and partially supported by the IAEA Technical Cooperation Programme.

## REFERENCES

[1] SMITH C.L., SHAH V.N., KAO T. and APOSTOLAKIS, G. Incorporating Aging Effects into Probabilistic Risk Assessment – A Feasibility Study Utilizing Reliability Physics Models, NUREG/CR-5632. US Nuclear Regulatory Commission, Washington DC, 2000.

[2] SMITH C. Incorporating Reliability Physics Models into PSA, EC Enlargment and Integration Workshop on Use of PSA for Evaluation of Impact of Aging Effects on the Safety of NPPs, 2-5 October 2006, Bucharest, Romania, RC JRC IE.

[3] ANTONOV A.V. Age-dependent reliability models. Statistical data analysis and parameters estimation, EC Enlargment and Integration Workshop on Use of PSA for Evaluation of Impact of Aging Effects on the Safety of NPPs, 2-5 October 2006, Romania, RC JRC IE.

[4] KUMAMOTO H. and HENLEY E.J. Probabilistic Risk Assessment and Management for Engineers and Scientists, - 2nd ed., IEEE Press, ISBN 0-7803-1004-7, 1996, 598p.

[5] PETKOV G. Reliability and Risk Assessment of Dynamic Systems and Processes', JRC Information Day in Bulgaria, 28 April, 2006. http://www.jrc.cec.eu.int/default.asp@sidsz=more_information&sidstsz=info_day&surl=infodays_2f200604_bulgaria_2fdata_2fprogramme-final%20jrc-2006.htm

[6] MITOMO N.and OKAZAKI T. Case study on Incorporation of Aging and Maintenance Effects into System Reliability Models, Preliminary result using GO-FLOW, EC Enlargment and Integration Workshop on Use of PSA for Evaluation of Impact of Aging Effects on the Safety of NPPs, 2-5 October 2006, Bucharest, Romania, RC JRC IE.