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Reliability of Degraded Steam Generator Tubes

Leon Cizelj and Guy Roussel
[1]"Jožef Stefan" Institute,
[2]Vinçotte Nuclear Safety
[1]Slovenia
[2]Belgium

1. Introduction

Steam generators in the second generation nuclear power plants with pressurized water and CANDU reactors were in most cases of the shell-and-tube type. The reactor coolant passes through the tubes at the primary side and boils water on the outside of the tubes (secondary shell side) to make steam.

Typical dimensions of the tubes are the diameter of about one inch or less and the tube wall thickness of about 1 mm. A few thousand tubes with shape of inverted letter U were installed in a typical steam generator. The dominant choice of material was Ni-Cr-Fe alloy Inconel 600. After some years of operation the first degradations were detected. Degradations were caused by a variety of mechanisms and were not limited to Inconel 600. A good review of designs, materials and degradation mechanisms was given in (Shah and MacDonald 1993).

Replacements of steam generators solved the degradation problem mainly by the choice of different tubing material (IAEA 2008). A large number of original steam generators are still in operation and some of them may operate without replacement until the final shutdown of the plants. Consequently, the degradation of the steam generator tubes is still in the focus of research and maintenance activities. Recent examples include (Lee, Park et al. 2010), (Revankar, Wolf et al. 2009), (Hur, Choi et al. 2010), (Pagan, Duan et al. 2009) and (Pandey, Datla et al. 2009).

Our main purpose is a critical compilation of the past work in the field of probabilistic assessment of steam generator degradation and maintenance strategies. The probabilistic apparatus already proposed to serve in specific cases has been consolidated and generalized to accommodate a wide range of mechanistic and empirical models describing the tube failure modes.

1.1 Safety consequences of degradations

Steam generator tubes are exposed to thermal and mechanical loads combined with aggressive environmental conditions. Rather severe corrosion damage resulting in through wall flaws has been, among others, reported in tubes made of Inconel 600 (Shah and MacDonald 1993).

Through-wall flaws in ductile pressurized components may at appropriate conditions lead to detectable leaks long before the structural integrity of the component is challenged.

Through-wall leaks should in most cases be interpreted as a reliable call for a corrective action (repair or replacement). However, in some specific cases continued operation with controlled leaks within the safety, legal, economical or other constraints might be acceptable. The Inconel 600 mill annealed (MA) steam generator tubes in pressurized water reactors may serve as a good example of allowable continued operation with limited leakage. The tubes confine radioactivity from neutron activation or fission products to the primary coolant during normal operation. However, the primary reactor coolant is at a higher pressure than the secondary coolant, so any leakage through defects in the tubes is from the primary to the secondary side, and rupture of the steam generator tubing can result in release of radioactivity to the environment outside the reactor containment through the pressure relief valves in the secondary system.

Steam generator tubing represents a large part of the reactor coolant pressure boundary, which represents the second of three consecutive safety barriers preventing the release of the radioactive materials to the environment. The integrity of the reactor coolant boundary and therefore also of the steam generator tubes is therefore considered a paramount safety goal (Murphy 2007). Two potential failure modes of the tubes have received special attention (IAEA 1997):

i. single or multiple tube rupture and
ii. excessive primary-to-secondary leakage without tube rupture.

A sufficient safety margin against tube rupture used to be the basis for a variety of maintenance strategies, which were developed to maintain a suitable level of plant safety and reliability (see (Shah and MacDonald 1993) for more details). This topic will not be pursued further here. It will merely be noted that some of the maintenance strategies justified sufficient margin also for the tubes with through-wall flaws. Consequently, several through-wall flaws may remain in operation and potentially contribute to the total primary-to-secondary leak rate. Cases with up to 2000 flaws within a single steam generator have been reported to operate successfully (Cuvelliez and Roussel 1995).

1.2 Inspection and repair strategies

Traditionally, the steam generators were declared operable following a successful completion of the surveillance program. The surveillance program required periodic tube inspections. The inspection of tubes was typically performed using eddy current probes in intervals between 12 and 40 months. The required sample of the inspection depended on the number of defects found and ranged from 3 to 100% of the tubes. The tubes with damage exceeding the repair criteria, typically 40% reduction in the tube wall thickness, were required to be repaired (Murphy 2007). Repair typically included plugging or sleeving of the tube (Shah and MacDonald 1993). The aim was to preserve the integrity of the tube, both in terms of appropriate margins against tube rupture and leakage in normal and anticipated accidental conditions.

Significant degradation problems could result in increasing number of plugged tubes that could severely reduce the performance of the steam generators. At the same time, the eddy current errors and defect growth rates sometimes exceeded those allowed by the tube repair criteria. This motivated the regulators to move towards performance based requirements to ensure the integrity of the steam generators. These allowed for the use of defect specific inspection and repair strategies, which were supported by experimental and analytical findings. Probabilistic assessment became a frequent part of the analytical efforts to quantify

the success of inspection and repair strategies in terms of tube failure probability. The probabilistic assessment techniques are discussed in detail in the following sections. The overview of the performance based requirements in USA is given in (Murphy 2007).

1.3 Outline of this chapter

Section 2 (Probabilistic modelling) outlines the consolidated and generalized probabilistic apparatus already proposed to serve in specific cases and generalized in this section to accommodate a wide range of mechanistic and empirical models describing the tube failure modes. Section 3 (Numerical examples) provides illustrative and practical examples demonstrating and illustrating the performance of the generalized probabilistic apparatus. Section 4 (Information content of successful sampling inspections) investigates the inspection situation typical for replacement steam generators, where the inspection of a small random sample selected from all tubes reveals no defects. The probability of having certain number of defective tubes in the uninspected part of steam generator is discussed.

2. Probabilistic modelling

2.1 Basic assumptions

The following basic assumptions are used in the sections below:

- the defect size as measured by the non-destructive examination technique can be used to describe failure behaviour.
- The reliability and sizing accuracy of the non-destructive examination technique can be quantified.
- The repair of the defects with measured size exceeding allowable size is perfect. In other words, repair restores the virgin state of the tube or removes the tube from operation.
- There is a potential to predict the growth of the degradation in the period until the next inspection.
- There is exactly one crack per tube.
- The parameters governing the tube failure are statistically independent.

2.2 Failure integral

Let us assume that the failure behaviour of the damaged tube can be described using n random variables $\vec{x} = (x_1, \ldots, x_n)$ and a failure function $g(\vec{x})$. Further, let the failure function be defined so that $g(\vec{x}) < 0$ indicates the failure of the damaged tube. The probability of failure P_f of the population of tubes is then defined as (Madsen and Krenk 1986):

$$P_f = \int_{g(\vec{x}) < 0} f(\vec{x})\, d\,\vec{x} \tag{1}$$

Now, the probability that j tubes will fail within a steam generator with total of N tubes may be estimated using:

$$p(j) = \frac{\left(N\, P_f\right)^j}{j!} e^{-N\, P_f} \tag{2}$$

The probabilities that one or more tubes will fail are therefore given as:

$$P(j = 1) = N\ P_f\ e^{-N\ P_f} \tag{3}$$

$$P(j \geq 1) = 1 - \ e^{-N\ P_f} \tag{4}$$

2.3 Examples of failure functions

Examples of failure functions given in this section are based on specific types of defects found in steam generator tubes with respective defect specific maintenance strategies:

- Axial cracks in tube expansion transitions just above the tube sheet. The cracking resulted from primary water stress corrosion (cracks initiated at the tube inner surface) driven by substantial residual stresses in expansion transition zones (Fig. 1.). Only the tube rupture was considered as possible failure mode here. Special inspection techniques were developed to reliably and accurately measure the crack length. The tubes with measured crack length exceeding predefined repair limit were repaired. The leaks through safely short cracks were experimentally determined to be rather insignificant and also easily detectable (Esteban, Bolaños et al. 1990; Flesch and Cochet 1990).
- Outside diameter stress corrosion cracking under the tube support plates. The widely accepted root cause were aggressive impurities, which accumulated in the crevices between the tubes and tube support plates. These caused rather large network of intergranular cracks initiated at the outside tube surface. Some of the damaged tubes were pulled from the steam generators and served to establish empirical correlations between the defect size indicated by the inspection equipment on one side and the burst pressure and leak rate on the other side (see for example (Dvoršek, Cizelj et al. 1998) and the references therein).

Further examples of models, which may be used in the definition of the failure function for various degradation processes have been proposed in the literature. Recent examples include for example (Revankar and Riznic 2009), (Kim, Oh et al. 2010), (Hui and Li 2010), (Kim, Jin et al. 2008) and (Hwang, Namgung et al. 2008).

2.3.1 Axial cracks in expansion transition zones: tube rupture

Primary water stress corrosion cracking was one of the first degradation mechanisms which were tackled by the defect specific inspection and repair strategy (Hernalsteen 1993). In most cases it resulted in axial cracks, mainly driven by the residual stresses caused by the expansion process during the manufacturing of the steam generators.

Consider a long pressurized tube which is fixed into a drilled tubesheet by the means of expansion (Fig. 1.). The tube contains an axial through wall crack with length 2a. The failure mode of concern is the unstable (ductile) propagation of the crack leading to tube rupture.

Leak through the tube is not the concern. Nevertheless, the reader is referred to (Revankar, Wolf et al. 2009) for a recent review of available leak rate models through cracks in steam generator tubing.

The nuclear steam generator tubes are typically made of ductile Ni based alloys. A limit load model may therefore be appropriate:

$$g(\vec{x}) = \sigma_f - m_F\ \sigma_\phi \tag{5}$$

σ_f represents the flow stress, σ_ϕ is the pressure induced hoop stress and m_F the so called bulging factor (Erdogan 1976):

$$m_F = 0.614 + 0.386\, e^{-2.25\frac{a}{\sqrt{R\,t}}} + 0.866\,\frac{a}{\sqrt{R\,t}} \tag{6}$$

a represents the crack half length at the end of inspection cycle. *R* and *t* are the mean radius of the tube ($R_{out} - t/2$) and the tube wall thickness. The bulging factor essentially accounts for bending stresses at the crack lips, which bulge towards shape similar to fish mouth with increasing pressure or crack length.

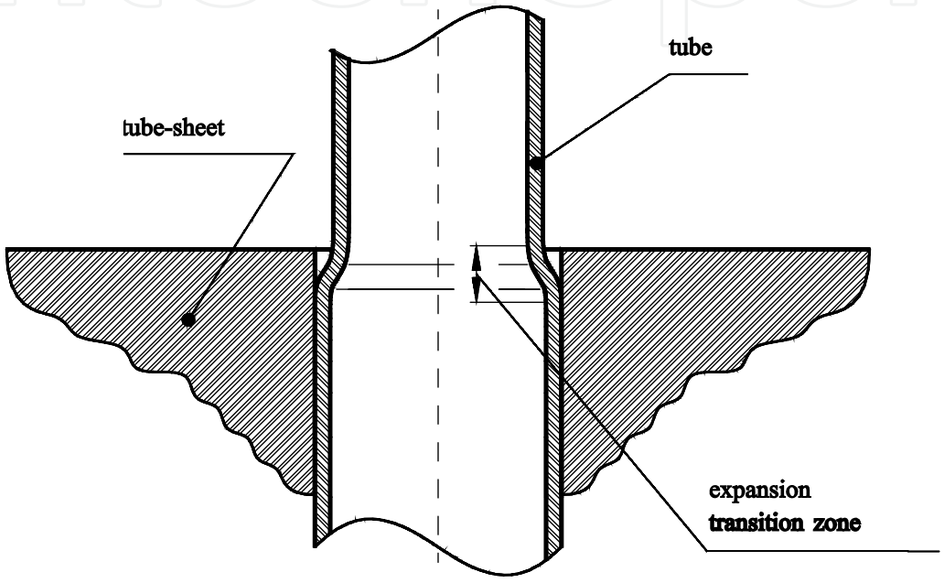


Fig. 1. A tube expanded into a tube sheet: expansion transition zone

The flow stress σ_f is defined by the yield strength σ_y and ultimate tensile stress σ_M of tube material and may be adjusted for operating temperature (δ_T), if the σ_y and σ_M were obtained at a different temperature:

$$\sigma_f = \kappa\left(\sigma_y + \sigma_M\right)\delta_T \tag{7}$$

κ is an experimentally determined constant which describes the degree of strain hardening behaviour of the tube material. Typical value for ductile metals in question is about 0.5. The hoop stress σ_ϕ represents the crack driving membrane stress perpendicular to the direction of the crack, which is governed by the pressure difference Δp:

$$\sigma_\phi = \Delta p\left(\frac{R}{t} - \frac{1}{2}\right) \tag{8}$$

Numerical values of the random variables indicated in eqs. (5) to (8) are detailed in Table 1.

2.3.2 ODSCC under tube support plates: tube rupture

The ODSCC under tube support plates resulted in complex networks of integranular cracks. The characterization of the crack networks by the non-destructive examination was not

sufficient to support a mechanistic model of stable and unstable crack growth. The failure assessment was therefore based on an empirical relation between the defect size as measured by the non-destructive examination method and the experimentally determined tube rupture pressures (EPRI 1993).
The failure function for the evaluation of failure probabilities was formulated as (Dvoršek, Cizelj et al. 1998):

$$g(\Delta p, \Delta p_f, a) = \Delta p - \Delta p_f(a) \tag{9}$$

Δp represents the loading expressed as the pressure difference across the tube wall. The highest pressure differences in the PWR NPP are typically caused by the accidents involving loss of secondary coolant system. The $\Delta p_f(a)$ denotes the burst pressure of the tube containing a defect of size *a*. This is given by an empirical relation (EPRI 1993) as :

$$\Delta p_f(a) = A + B \cdot \log_{10}(a) + \varepsilon \tag{10}$$

A and *B* are proprietary coefficients obtained by regression analysis of tube burst pressures measured on degraded tubes pulled from operating steam generators (EPRI 1993). At present, they are assumed constant. ε models the random error of the regression model.
The defect size is the direct reading from the measurement by the appropriately calibrated bobbin coil probes (eddy current technique). The result of the inspection, which is assumed to indicate the defect size, is the amplitude of the signal (measured in Volts) obtained from the bobbin coil. As a very general reference, the signal amplitude indicates the volume of the lost material in the sense that its value depends on the crack length, crack depth and crack opening.

2.3.3 ODSCC under tube support plates: excessive leakage

The extent and complex morphology of the ODSCC also required verification that the leaking through all defects will remain within statutory limitations. The assessment of the leakage was again based on an empirical relation between the defect size as measured by the non-destructive examination method and the experimentally determined leak rates at assumed fixed pressure differences (EPRI 1993). The failure function was formulated by (Cizelj, Hauer et al. 1998) and (Cizelj and Roussel 2003):

$$g(Q_{MAX}, Q_T) = Q_{MAX} - Q_T \tag{11}$$

Q_{MAX}represents the statutory leak rate limit which is not to be exceeded during all design basis events. Q_T is the total leak rate through all *n* defects:

$$Q_T = \sum_{i}^{n} Q_i(a_i) = \sum_{i}^{l} Q_i(a_i)|_{P_i>0} + \sum_{j=1}^{n-l} Q_j(a_j)\big|_{P_j=0} \tag{12}$$

The leak rates through the individual defects $Q_i(a_i)$ depend on the defect size a_i and operational parameters:

$$Q_i(a_i) = \begin{cases} Q(a_i, \Delta p, T, \ldots), & P_i(a_i) > 0 \\ 0, & P_i(a_i) = 0 \end{cases} \tag{13}$$

The operational parameters (pressure difference Δp, temperature T etc.) are for simplicity assumed constant over all defects considered. The individual leak rates are defined as an empirical function (EPRI 1993):

$$\log(Q_i) = b_0 + b_1 \cdot \log(a_i) + \varepsilon \tag{14}$$

b_0 and b_1 are proprietary coefficients obtained by regression analysis of tube leaks measured on degraded tubes pulled from operating steam generators (EPRI 1993). At present, they are assumed constant. ε models the random error of the regression model. The probability that a particular defect of size a_i is leaking is also given by an empirical function (EPRI 1993):

$$P(a_i) = \frac{1}{1 - \exp[-(\eta_0 + \eta_1 \cdot \log(a_i)) + z \cdot \sigma_n]} \tag{15}$$

η_0, η_1 and $z \cdot \sigma_n$ are proprietary coefficients obtained by regression analysis of tube leaks measured on degraded tubes pulled from operating steam generators (EPRI 1993). $z \cdot \sigma_n$ models the random error of the regression model. Recent research may enable future use of more mechanistic leak rate models (Hwang, Kim et al. 2005).

2.4 Size of the defects

In the field situations the information about the defect sizes comes from non-destructive examinations. It is therefore reasonable to reconstruct the distribution of actual defect sizes from the measured data. In this attempt, we assume a joint probability density of measured (m) and actual defect sizes (a) denoted by $p_{A,M}(a,m)$. The density of measured defect sizes $p_M(m)$ is then given by (Barnier, Pitner et al. 1992):

$$p_M(m) = \int_0^\infty p_{M|A}(m|a)\, p_A(a)\, da \tag{16}$$

Please note that the Bayes' theorem requires that

$$\begin{gathered} p_{A,M}(a,m) = p_{M|A}(m|a)\, p_A(a), \\ p_M(m) = \int_0^\infty p_{A,M}(a,m)\ da \ \text{ and } p_M(a) = \int_0^\infty p_{A,M}(a,m)\ dm \end{gathered} \tag{17}$$

Further, we may safely assume that not all defects are detected during the inspection. Let the probability that a defect of actual size a is detected be denoted as $P_{OD}(a)$. Then, the conditional probability density $p_{A|D}(a)$ that a defect of size a is detected is given as:

$$p_{A|D}(a) = \frac{p_A(a)\, P_{OD}(a)}{\int_0^\infty p_A(\acute{a})\, P_{OD}(\acute{a})\, d\acute{a}} \tag{18}$$

Equation (5) may now be combined with eq. (16) to yield:

$$p_M(m) = \frac{\int_0^\infty p_{M|A}(m|a)\, p_A(a)\, P_{OD}(a) da}{\int_0^\infty p_A(\acute{a})\, P_{OD}(\acute{a}) d\acute{a}} \tag{19}$$

Distribution of $p_A(a)$ may be estimated by inverting eq. (16). A useful numerical procedure has been proposed by (Barnier, Pitner et al. 1992). It requires a selection of functional form of

$p_A(a)$. Then, $p_M(m)$ is calculated using eq. (16), which depends on the unknown parameters of $p_A(a)$. These can be determined by fitting the calculated values of $p_M(m)$ to the empirical distribution of measured defect sizes by using for example minimization of χ^2.

2.5 Repair of the defects

Typically, the defects exceeding certain size, denoted repair limit *L*, need to be repaired. The defect of size *a* will therefore exceed the repair limit with probability:

$$P_L(a) = \frac{1}{\eta}\, P_{OD}(a) \int_L^\infty p_{M|A}(m|a)\, dm\, (1-\varepsilon_L) \tag{20}$$

$1/\eta$ represents the fraction of inspected tubes. A residual repair unreliability ε_L is provided to account for rare events like human error. The fraction of repaired defects is then given as:

$$\int_0^\infty p_A(a)\, P_L(a) da \tag{21}$$

Similarly, the probability that a defect of size *a* will not be repaired is given by:

$$p_A(a)\big(1 - P_L(a)\big) \tag{22}$$

2.6 Growth of the defects

The growth of the defects can be rather efficiently estimated from the successive inspections. A careful statistical analysis of inspection records may also provide a reasonable indication of measurement errors (Cizelj and Dvoršek 1999). The obvious drawback of such an approach is the need to rely entirely on historic data and operational conditions already observed. Since this approach is rather straightforward, it is not pursued further here.

Mechanistic models of crack growth, if available, may provide predictions for a wide range of operational conditions. As an example, the asymmetric crack growth law proposed for axial stress corrosion cracks in expansion transitions of steam generator tubes (Cizelj, Mavko et al. 1995) is given below.

The growth rate of a stress corrosion crack is given as (Cizelj, Mavko et al. 1995):

$$\dot{a}_{\pm a} = \left(\frac{da}{dt}\right)_{\pm a} = C_{\pm a}(K_{\pm a} - K_{ISCC})^m \tag{23}$$

Please note that the crack growth rate is different for both crack tips ($\pm a$, Fig. 2). The growth of the crack is accompanied by the moving center point, as indicated in Fig. 2. The stress intensity factors $K_{\pm a}$ are to be estimated from the quite irregular stress field indicated in Fig. 2. A rather simple procedure for stress calculations appropriate for reliability calculations is proposed in (Cizelj 1994). Material properties $C_{\pm a}$, K_{ISCC} and m are taken from literature (Scott 1991) and detailed in Table 2. The proportionality constant $C_{\pm a}$ is reported to be about 6 times higher in cold worked than in virgin material (Cassagne, Combrade et al. 1992).

The operational and residual stresses in are, together with stress intensity factors of both crack tips $K_{\pm a}$, analysed in detail in (Cizelj 1994).

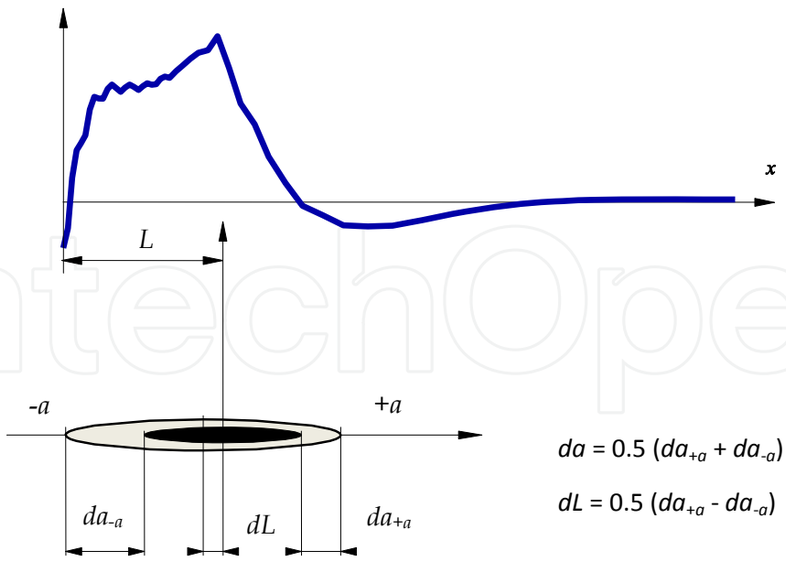


Fig. 2. Residual hoop stress in an expanded tube and asymmetric crack propagation. Reprinted from International Journal of Pressure Vessels and Piping, Vol. 63, L. Cizelj, B. Mavko, H. Riesch-Oppermann, A. Brücker-Foit, Propagation of stress corrosion cracks in steam generator tubes, p. 35, Copyrigt (1995), with permission from Elsevier

2.7 Numerical solutions of the failure integral

The basic numerical methods implemented to evaluate the numerical examples are briefly outlined in this section for completeness. These are the direct Monte Carlo (DMC) simulation and the First- and Second Order Reliability Methods (FORM and SORM). The reader is referred for example to (Madsen and Krenk 1986) for a more rigorous description. Other numerical methods have been proposed in addition to the DMC, FORM and SORM and are implemented in computational tools such as for example ZERBERUS (Cizelj and Riesch-Oppermann 1992), COMPROMIS (Pitner, Riffard et al. 1993), PFMAD (Beardsmore, Stone et al. 2010), PROBAN (Det Norske Veritas 2010) and ANL/CANTIA (Revankar, Wolf et al. 2009). Some of them also include useful fracture mechanics models.

Direct Monte Carlo corresponds to a sequence of numerical experiments. The failure function in eq. (1) is evaluated for n realisations of the random vector $\vec{x}$. Let n_f denote the number of realisations with $g(\vec{x}) < 0$. The estimator of the P_f is then given as:

$$P_f = \frac{n_f}{n} \tag{24}$$

The standard error of the estimator in eq. (24) is given as:

$$s = \sqrt{\frac{P_f\left(1 - P_f\right)}{n}} \tag{25}$$

Large number of repeated evaluations of failure function may be required for a reasonably small standard error. Less computationally intensive methods are available when dealing with complex failure functions that may only be evaluated using significant computational resources. Such methods on the one hand include Monte Carlo methods with variance

reduction sampling, such as for example latin hypercube sampling. On the other hand, approximate methods such as First- and Second Order Reliability Method (FORM and SORM, respectively) may offer reasonably accurate results with low computational intensity.
The First Order Reliability Methods (FORM) relies on the closed form solution of the failure integral in the case of standard normal variables and linear failure function, given as:

$$P_f = \Phi(-\beta) \tag{26}$$

Φ being the cumulative standard normal distribution and β the reliability index:

$$\beta = \frac{g_u(\vec{u}^*) - \vec{a} \cdot \vec{u}^*}{|\vec{a}|} \tag{27}$$

Reliability index is the minimum distance between the origin of space of standard normal variables and the failure surface. The point on the failure surface with the minimum distance to the origin is called the design point $\vec{u}^*$. Please note that $\vec{a} = \text{grad}\left(g_u(\vec{u}^*)\right)$.
For non-linear failure functions, the linearization of the failure function in the design point provides an approximate value of the failure probability:

$$P_f \approx \Phi(-\beta) \tag{28}$$

The non-normal basic variables are to be transformed from the physical $\vec{x}$ to the normal $\vec{u}$ space. The transformation of stochastically independent basic variables is given as

$$U_i = \Phi^{-1}(F_i(X_i)) \tag{29}$$

Its inverse is defined as:

$$X_i = F^{-1}(\Phi(U_i)) \tag{30}$$

The inverse transformation (eq. (31)) is also used to transform the failure function. The sensitivity of the failure probability to the scatter of basic variables is expressed as:

$$\frac{\partial \beta}{\partial u_i} = \frac{u_i^*}{|\vec{u}|} \tag{31}$$

The Second Order Reliability Method (SORM) may improve the accuracy of the FORM by approximating the failure function in the design point by a quadratic hypersurface, which preserves the main curvatures κ_i of the failure function. The failure probability is given:

$$P_f \approx S_1 + S_2 + S_3 \tag{32}$$

$$S_1 = \Phi(-\beta) \prod_{i=1}^{n-1} (1 - \beta\, \kappa_i)^{-0.5} \tag{33}$$

$$S_2 = [\beta\Phi(-\beta) - \varphi(\beta)] \left[\prod_{i=1}^{n-1} (1 - \beta\, \kappa_i)^{-0.5} - \prod_{i=1}^{n-1} (1 - (\beta + 1)\, \kappa_i)^{-0.5} \right] \tag{34}$$

$$S_3 = (\beta + 1)[\beta\Phi(-\beta) - \varphi(\beta)] \left[\prod_{i=1}^{n-1}(1 - \beta\,\kappa_i)^{-0.5} - \mathrm{Re}\left(\prod_{i=1}^{n-1}(1 - (\beta + \mathrm{i})\,\kappa_i)^{-0.5}\right)\right] \quad (35)$$

Re represents the real part of the complex argument and i the imaginary unit. φ is standard normal probability density function. The applicability and reasonable accuracy of FORM and SORM in the reliability analyses of the cracked steam generator tubing has been confirmed in (Cizelj, Mavko et al. 1994).

3. Numerical examples

Three numerical examples are provided to illustrate the results obtained using the probabilistic model outlined in section 2. All three numerical examples are based on the data obtained from regular inspections of steam generators in operating nuclear power plants at Krško, Slovenia and Doel, Belgium. All nuclear power plants mentioned in the examples have already replaced the steam generators.

3.1 Axial SCC in expansion transitions

This numerical example is based on the crack population detected in the nuclear power plant at Krško, Slovenia. The data on the geometry and material of the tubing is outlined, together with assumed distributions, in Table 1. The pressure difference Δp acting on the steam generator tubes corresponds to the maximal pressure difference mentioned in the plant safety analysis report and is representative for a limiting hypothetical accident "feedwater line break". The failure probabilities reported in this section are therefore conditional given that the feedwater line break has already occurred.

The distribution of actual crack lengths was described using the lognormal distribution with shape and scale parameters of 0.532 and 1.627, respectively. This was obtained using the measured crack length distribution (Krško SG #1, 1992, (Cizelj 1994)) and the procedure outlined in eqs. (16) through (19). Random measurement error with normal distribution with 0 mean and standard deviation of 0.75 mm and detection probability $P_{OD}(a) = (1 - e^{-0.9\,a})$ $(1 - \varepsilon OD$ were assumed. Possible systematic errors were not considered in this analysis. The residual non-detection and non-repair probabilities were assumed at $\varepsilon_{OD} = \varepsilon_L = 10^{-4}$.

All results presented in this section were obtained using the FORM and SORM as implemented in the code ZERBERUS (Cizelj and Riesch-Oppermann 1992). The stochastic parameters of the crack growth law (eq. (23)) are given in Table 2.

Basic variable	Distribution		Unit
	Type	Parameters	
R_{out}	normal	μ=9.525, σ=0.0254	mm
t	normal	μ=1.0922, σ=0.039	mm
κ	normal	μ=0.545, σ=0.03	-
δ_T	normal	μ=0.928, σ=0.003	-
σ_Y	normal	μ=362., σ=34.	MPa
σ_M	normal	μ=713., σ=25.	MPa

Table 1. Geometry and material data (Krško steam generator No. 1)

The resulting failure probabilities at different repair limits and time intervals between consecutive inspections are depicted in Fig. 3. The repair assumes that the detected cracks with measured lengths exceeding the repair limit are repaired. Beneficial effects of lower repair limit and shorter time between inspections are clearly shown. The plateau of all four curves below repair limit of approximately 13 mm is caused by the residual non-detection and non-repair limits $\varepsilon_{OD} = \varepsilon_L = 10^{-4}$.
An optimal repair limit is however clearly noted and varies from about 11 mm (15 months between inspections) and 13 mm (6 months between inspections). In the particular case studied, the gain of more frequent inspections may be seen as rather insignificant.

Basic variable	Distribution		Unit	Comments
	Type	Parameters		
C_{-a}	normal	μ=2.8·10^{-11}, σ=1.0·10^{-12}	m/s	Assumed
K_{ISCC}	normal	μ=9.0, σ=0.3	MPa m^{½}	Assumed
m	normal	μ=1.16, σ=0.03	-	Assumed

Table 2. Values of crack growth parameters in eq. (23)

The variables with the strongest influence on the failure probability are the exponent m in the crack growth law (eq. (23)), the wall thickness of the tube t and the flow stress factor κ (eq. (7)).

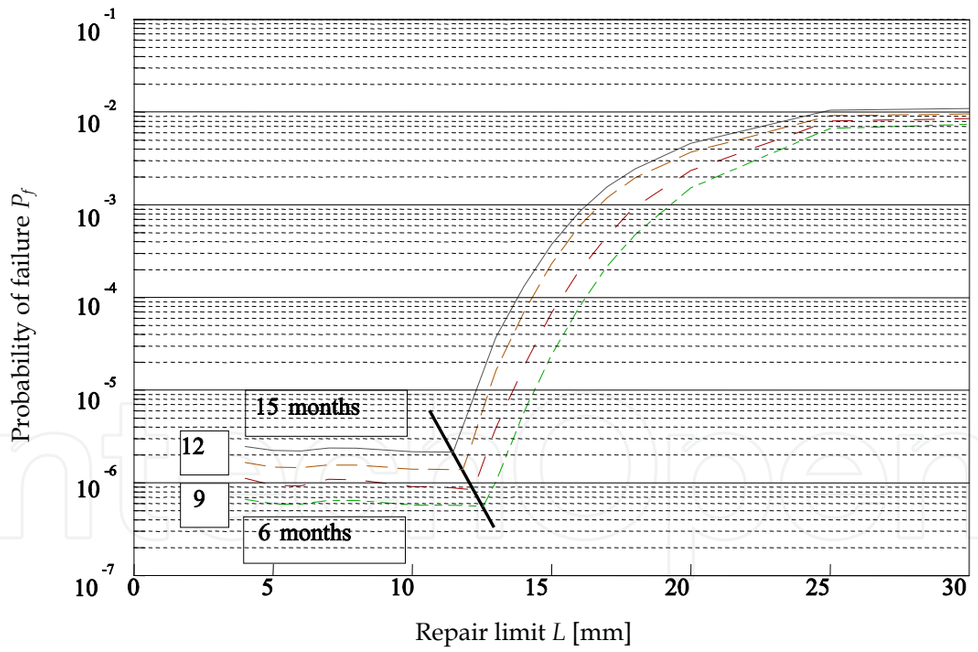


Fig. 3. Probability of failure P_f as a function of repair limit L and time between two consecutive inspections. Reprinted from Journal of pressure vessel technology, Vol. 118, L. Cizelj, B. Mavko, and P. Vencelj, Reliability of steam generator tubes with axial cracks, p. 441, Copyrigt (1996), with permission from ASME

The dependence of the failure probability on the number of repaired cracked tubes is depicted in Fig. 4. Please note that the failure probability is interpreted as probability of tube

failure (eq. (4)). 841 cracks were detected in the SG #1 in Krško NPP in 1992. The probability of tube failure is constant for repair limits below approximately 12 mm. At the same time, the number of cracks to be repaired (tubes to be plugged) is increasing very fast with decreased repair limit. The repair limit of 12 mm is therefore seen as an optimal choice preserving the most tubes in operation without sacrificing reliability and safety of the plant.

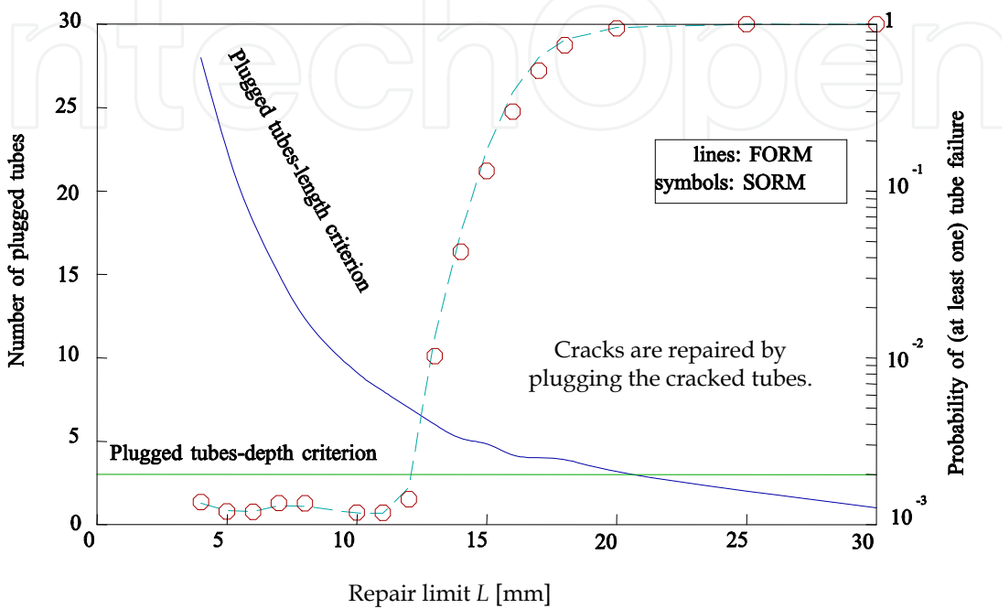


Fig. 4. Failure probability and the number of repaired tubes

The success of the traditional defect depth repair limit (40% loss of tube wall) is indicated assuming a poor correlation between the measurements of defect depth and defect length. The traditional repair strategy could therefore result in a moderate number of repaired tubes at the cost of a certain steam generator tube rupture following the feedwater line break.

3.2 Tube burst due to the ODSCC at tube support plates

Defect sizes as obtained from 5 consecutive (100%) bobbin coil inspections of one steam generator at the Krško NPP are shown in Fig. 5. The distributions remained fairly stable over the years in all cases analysed in this section. The tail of the measured sizes obtained during In-Service Inspection (ISI) 5 is getting fat as compared to the older data. The lognormal distribution was considered to provide reasonable fit (Dvoršek, Cizelj et al. 1998). We should note here that the number of defect sizes detected has grown from 261 in the first to over 2000 in the last inspection. Although the change in the number of tubes does not directly influence the calculation of failure probability (eq. (1)), it significantly influences the single SGTR probability (eq. (2)).

Distributions of defect growth depicted in Fig. 6 were obtained directly from each pair of two consecutive measurements available. The number of available data points grew from 80 in the first inspection to over 1300 in the last. Reasonably stable distribution of positive growth was observed over all years, tending to get a more fat distribution tail in ISI 5.

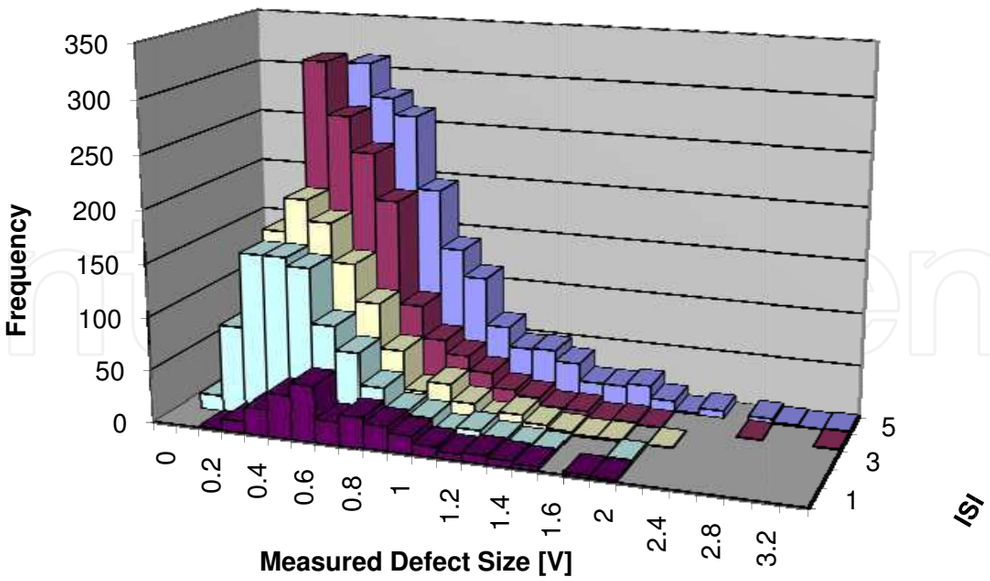


Fig. 5. History of defect sizes

Only the data points exhibiting positive growth were used to directly fit the distributions of measured defect growth, which is consistent with routine analyses of Krško ODSCC at tube support plates. Reasonable fits were provided by either lognormal or gamma distributions. Lognormal distributions were used in subsequent calculations since they are known to cause larger failure probabilities than gamma distribution.

The negative growth is attributed to the measurement error. The data on the negative growth may therefore be directly used to infer the stochastic properties of the measurement error (Cizelj and Dvoršek 1999).

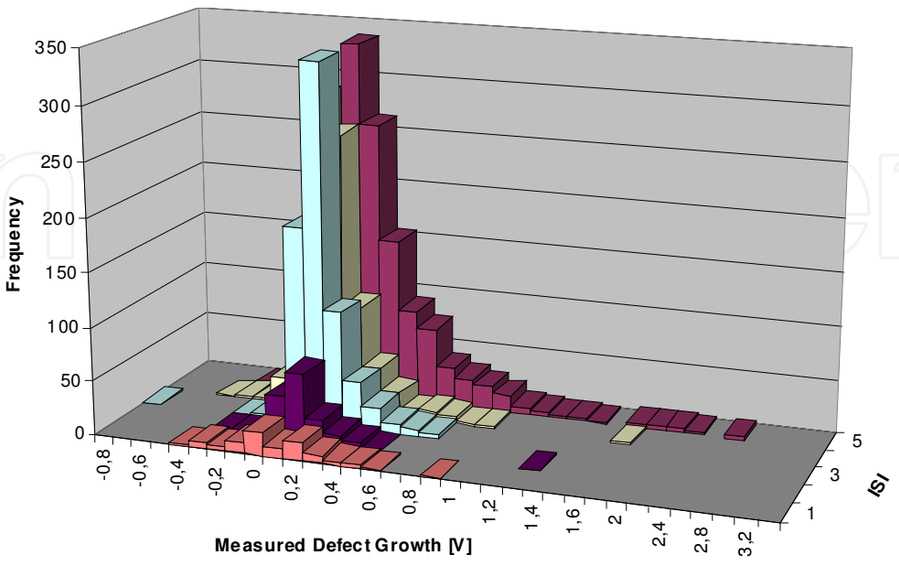


Fig. 6. Defect growth

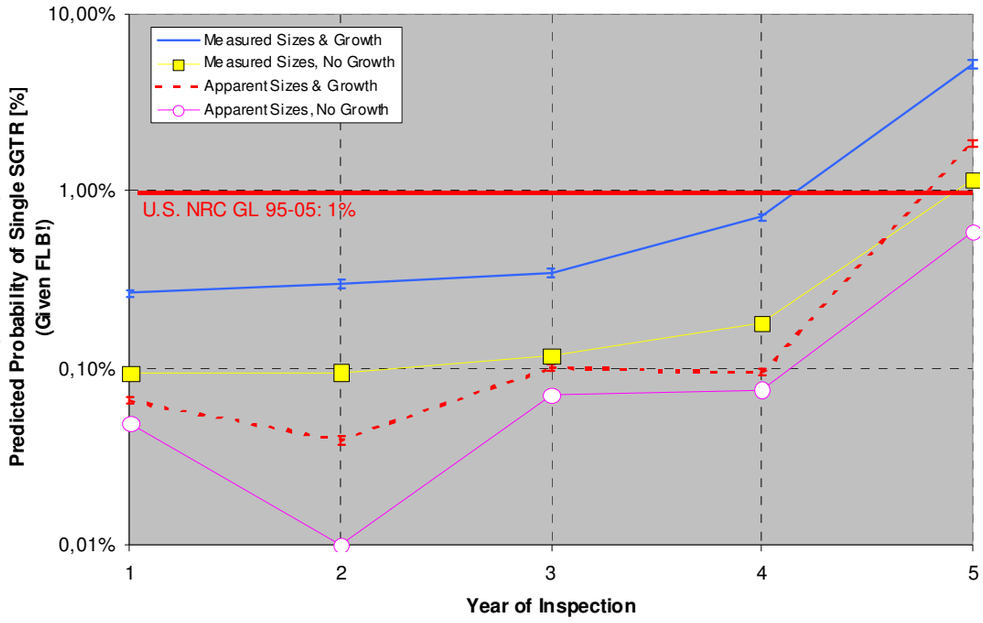


Fig. 7. Failure probabilities with time and different assumptions on measurement errors and defect growth

To estimate the tube rupture probability a postulated Feedwater Line Break (FLB) accident was assumed with differential pressure of 195.6 bar (2850 psi).

In this section we present the single tube rupture probabilities. The estimated probability of multiple tube rupture was in all cases at least two orders of magnitude lower than for the single tube rupture probability. Thus, the multiple tube rupture event was not considered to be of particular importance at this time.

The absolute values of the single tube rupture probabilities are depicted in Fig. 7 as a function of time. In addition, impact of different assumptions on the defect sizes and defect growth on the single tube rupture probability is given, exhibiting a considerable impact of about one order of magnitude. All of them are however depicted without tube repair. It is clear from Fig. 7 that all of the tube rupture probabilities except in the year 5 were estimated to be less than 1%, which is in agreement with U.S. NRC requirements [10] (Nuclear Regulatory Commission 1995). In the year 5, a repair of a moderate number of tubes would be required to stay below 1%.

The estimated single tube rupture probabilities are conditional, given a postulated FLB accident.

3.3 Leakage through ODSCC at tube support plates

Two numerical examples were chosen to illustrate the performance of the proposed probabilistic approach. They are based on the inspection data obtained from Slovenian Krško and Belgian Doel-4 steam generator tubes (3/4 inch tubes made of Inconel 600 Mill Annealed) in (Cizelj and Roussel 2003).

In operation, the defect size is generally a time dependent variable. In this analysis, two points in time are of concern and fully define the defect size: (1) beginning (BOC) and (2)

end (EOC) of the cycle between two consecutive inspections. Thus, the prediction of the EOC defects sizes includes stochastic combination of BOC defect sizes and defect growth.
The distribution of defect sizes in the Krško plant at the BOC is given in Fig. 8. In the calculations, empirical and fitted lognormal distributions of defect sizes at BOC were used. The differences between failure probabilities obtained with different defect size distributions were comparable to the statistical noise of the Monte Carlo simulation. Nevertheless, the empirical distribution consistently leads to higher values of the probability of exceeding the allowable leak rate and was therefore selected as representative input data model for subsequent analysis. The total number of defects detected was 492.
Allowances for defect growth (with 52,6 % of defects exhibiting nonnegative growth, compare Fig. 6) and measurement errors were also provided and yielded the defect size at EOC.
Fig. 9 depicts probability of excessive leakage as a function of allowable total leak rate. Three different curves are given to illustrate the effect of defect progression: BOC (no defect progression), EOC with 52,6% of defects exhibiting growth (which is consistent with field observations in Krško) and EOC with 100% of defects exhibiting growth. The Krško specific growth rate is used in the analysis and is shown to contribute less than one order of magnitude.

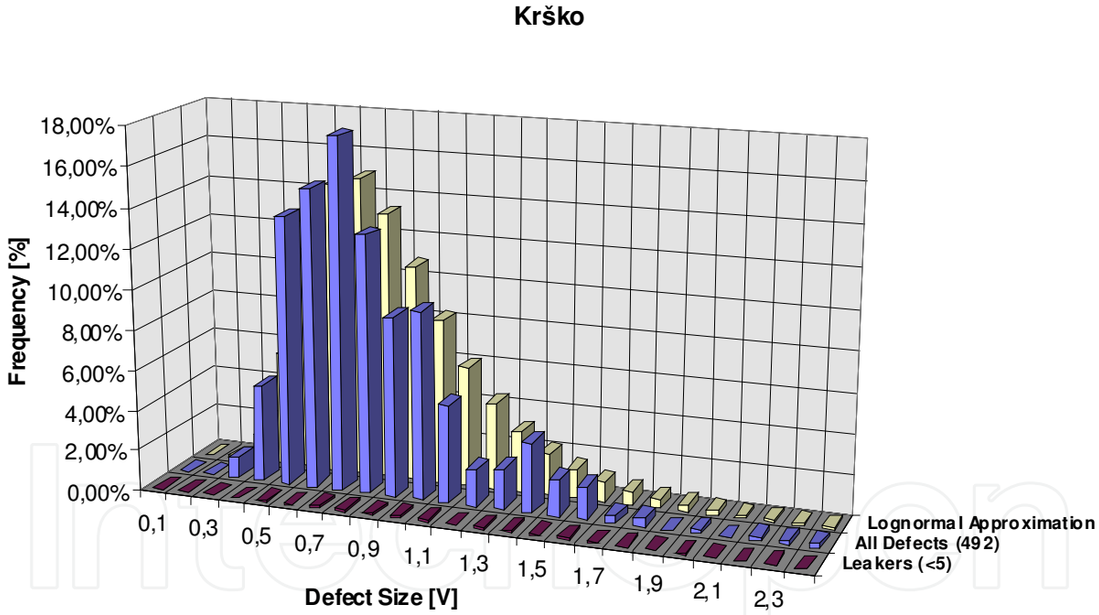


Fig. 8. Distribution of BOC defect sizes-Krško plant. Reprinted from Nuclear Engineering and Design, Vol. 185, L. Cizelj, I. Hauer, G. Roussel, C. Cuvelliez, Probabilistic assessment of excessive leakage through steam generator tubes degraded by secondary side corrosion, p. 347, Copyrigt (1998), with permission from Elsevier

The statistical standard error of Monte Carlo simulations is represented by error bars in Fig. 9. It is in the order of 0.1% and is considered to have negligible influence on the quality of results presented here. Further, simulations revealed that only about 5 (1%) out of 492 potential leakers would really leak given assumed model (recall eqs. (13) and (15)) and postulated hypothetical accidental conditions - steam line break.

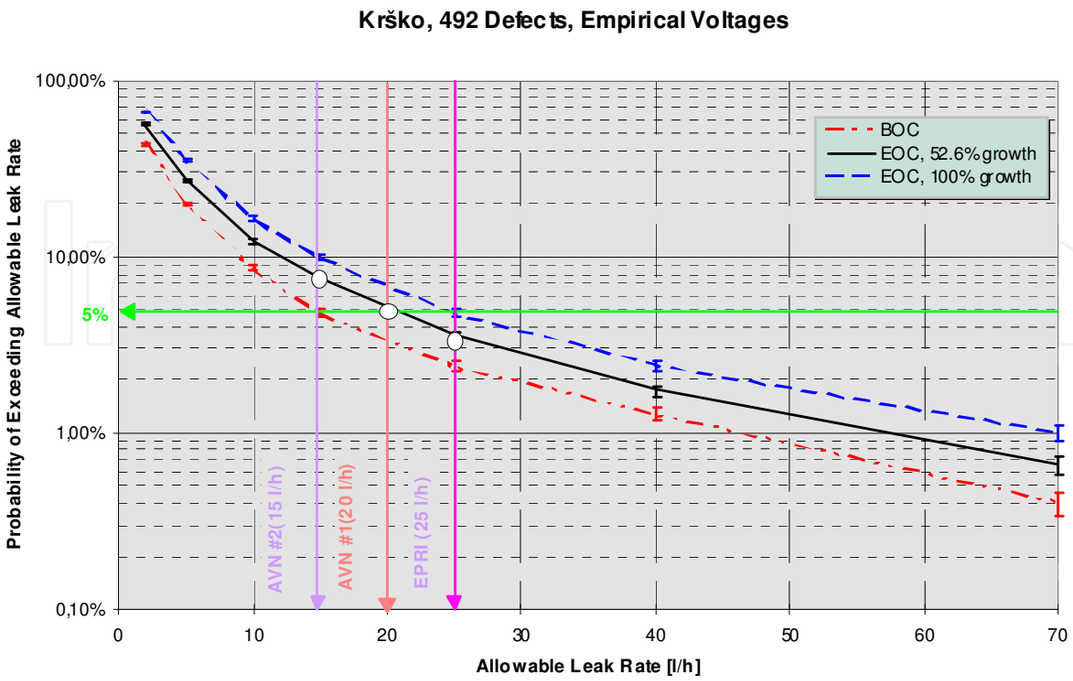


Fig. 9. Probability of Exceeding Allowable Leak Rates - Krško plant. Reprinted from Nuclear Engineering and Design, Vol. 185, L. Cizelj, I. Hauer, G. Roussel, C. Cuvelliez, Probabilistic assessment of excessive leakage through steam generator tubes degraded by secondary side corrosion, p. 347, Copyrigt (1998), with permission from Elsevier

The labels AVN#1, AVN#2 and EPRI denote empirical estimators aiming to predict the value of the total leak rate at or exceeding the cumulative probability of 95%. The AVN#1 and AVN#2 estimators were proposed in (Cuvelliez and Roussel 1995) as alternatives to the proposal by EPRI (EPRI 1993). The properties of all three estimators are analyzed in detail in (Cizelj, Hauer et al. 1998). For the purpose of this section, they are considered as empirical estimators of the 5% failure probability and are used to validate the probabilistic results.

The results of the three estimators are visualized by vertical lines at appropriate values of total leak rates (Fig. 9). Thus, for EPRI estimator, the failure probability is defined by the intersection of curves denoted by EOC, 52,6% growth and EPRI (25 l/h). Its value is about 3.5%. The AVN estimators #1 and #2 tend to 5 and 11%, respectively.

The distribution of defect sizes from Belgian Doel-4 plant is given in Fig. 10. The number of defects detected is 1960 (significantly more than in Krško). The size of defects is rather large with a maximum of 18.9 V. It should be however noted that Belgian inspection standards differ from EPRI standards. Appropriate correlation between "Belgian" and "EPRI" bobbin coil signal amplitudes was implemented to generate input data. This may be an additional source of uncertainties, which was not further investigated (Cizelj and Roussel 2003).

The presence of large defects is due to the use of a specific repair criterion allowing defects of about 10V to remain in service. The distribution of defects shown in Fig. 10 is the raw distribution as given by the bobbin coil. Also, a fit of lognormal distribution to the empirical distribution is depicted in Fig. 10. No defect progression was considered in the calculations.

The subpopulation of tube leakers in Fig. 10 illustrates the sample distribution of defects with $P_i(a_i) > 0$ (eq. (15)). The simulations revealed that approximately 330 (17%) defects would leak in this particular case. It is clearly shown in Fig. 10 that larger defects tend to leak more frequently, which is in accordance with eq. (15).

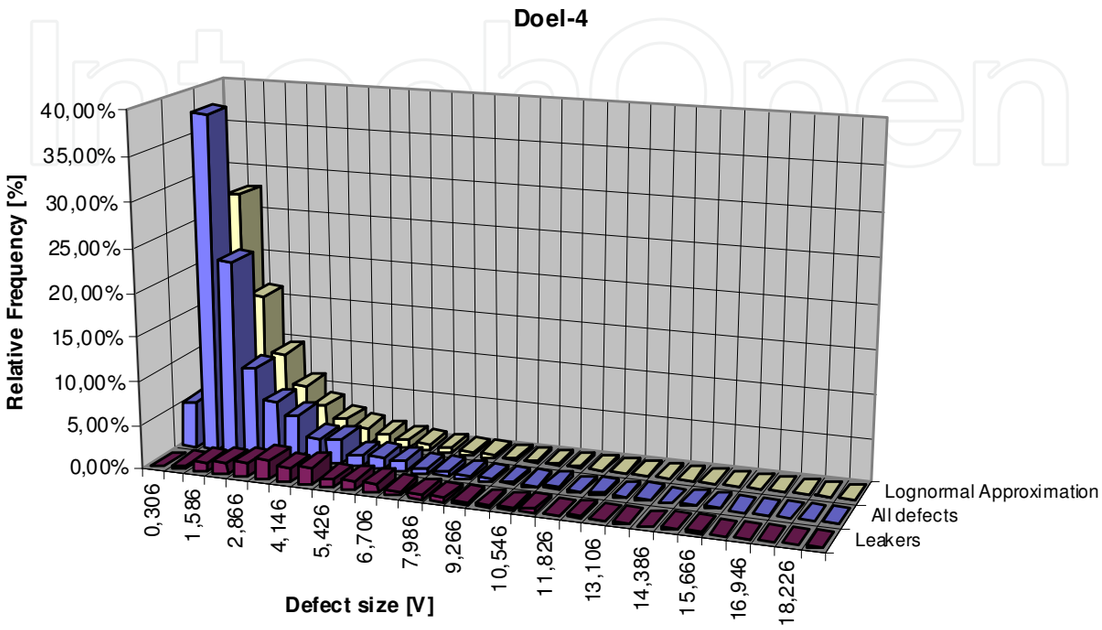


Fig. 10. Distribution of BOC defect sizes - Doel-4 plant. Reprinted from Nuclear Engineering and Design, Vol. 185, L. Cizelj, I. Hauer, G. Roussel, C. Cuvelliez, Probabilistic assessment of excessive leakage through steam generator tubes degraded by secondary side corrosion, p. 347, Copyrigt (1998), with permission from Elsevier

The probability of excessive leakage is depicted in Fig. 11 as a function of allowable total leak rate. Results obtained by two different input distributions of defect sizes are shown. The histogram of all defects shown in Fig. 10 served as the empirical distribution. On the other hand, the lognormal distribution was fitted to the raw inspection data. The rather large difference between both curves is caused by two facts:

- lognormal distribution explicitly allows for rare events. In other words, it allows for occurrences of large defects, which exceed the measured maximum of 18.9 V.
  the probability of leakage eq. (15) is approaching 1 as the defect size is approaching 20 V. Thus, the uncertainties in the leak rate model are not dominant in this region which increases the sensitivity to the input data as compared to the Krško case.

Again, the results of three estimators are comparatively depicted in Fig. 11. All of them rely on empirical distributions of the defect sizes, which suggests the comparison with probabilities of excessive leakage obtained from empirical distribution. The results of two estimators appear to be slightly conservative (EPRI 1.8%, AVN#1 3.5%) while AVN#2 tends to the expected 5%. On the other hand, if the lognormal distribution is used, EPRI estimator seems to be realistic (leading to failure probability of 6%) while the AVN estimators lead to failure probabilities exceeding 10% (AVN#1 11%, AVN#2 16%).

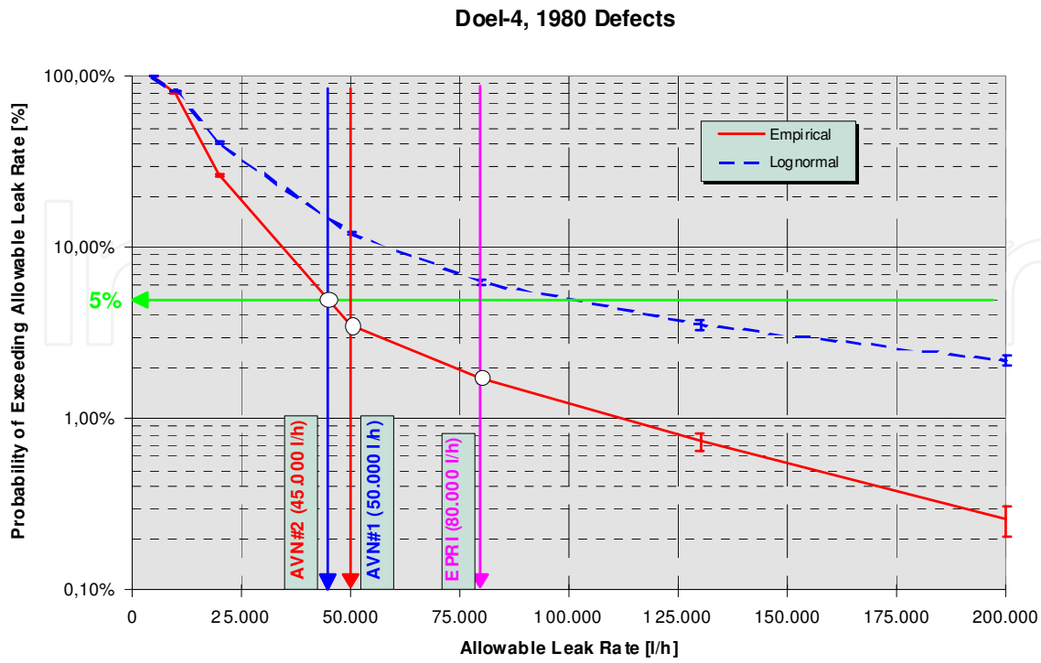


Fig. 11. Probability of exceeding allowable leak rates – Doel-4 plant. Reprinted from Nuclear Engineering and Design, Vol. 185, L. Cizelj, I. Hauer, G. Roussel, C. Cuvelliez, Probabilistic assessment of excessive leakage through steam generator tubes degraded by secondary side corrosion, p. 347, Copyrigt (1998), with permission from Elsevier

4. Information content of successful sampling inspections

In replaced steam generators, the in-service inspection may be performed within a rather limited sample of tubes. Since the main objective of the in-service inspection is to provide reasonable insurance of tubing integrity, the information gained about a limited sample of steam generator tubes must be used to make predictions about the entire population.

The case where the inspection of a small sample selected randomly from the population of all tubes showed exactly zero defects is investigated in this section. In particular, the probability of having certain number of defective tubes in the finite population in the case of zero defects found is discussed. To this end, some closed-form solutions derived using the Bayesian probability theory in (Roussel and Cizelj 2007) are used. The main assumptions made in (Roussel and Cizelj 2007) were:

1. all steam generators perform in a like manner;
2. only one flaw may affect a steam generator tube;
3. the samples are selected on a random basis;
4. the probability of detection for flaws with size larger than the detection threshold is 1.

4.1 Basic relations

Consider multiple N units of the same type. It is expected that there are a few defective units present. Before inspection, however, there is no known reason to distinguish between different units as far as their individual plausibility to be defective is concerned.

Random sampling of n units from the lot may be considered as a random drawing without replacement of n units. Put S_n the number of defective units in a random sample of size n. The case where n=N means that the sampling without replacement has been performed until all units have been drawn and hence S_N is the number of defective units contained in the lot.

In the case where the lot is known to include k defective tubes, the probability of l defective units among any random sample of size n follows the hypergeometric distribution and is given by

$$P(S_n = l | S_N = k) = h(l, n, k, N) = \frac{\binom{k}{l}\binom{N-k}{n-l}}{\binom{N}{n}} \tag{36}$$

In the case where the composition of the population is unknown, the probability of l defective tubes among any random sample of size n is given by the mixture of hypergeometric probabilities by application of the rule of total probabilities:

$$P(S_n = l) = \sum_{k=1}^{N-n+l} P(S_n = l | S_N = k) P(S_N = k) = \sum_{k=1}^{N-n+l} h(l, n, k, N) P(S_N = k) \tag{37}$$

In the Bayesian approach, the prior belief about the probability of k is quantified by a probability distribution, the prior distribution of k, i.e., $P(S_N = k)$. Data l are then collected, and the likelihood function $h(l, n, k, N)$ is constructed. Finally, the posterior distribution $P(S_N = k | S_n = l)$ is constructed, by combining the prior distribution $P(S_N = k)$ and the likelihood function $h(l, n, k, N)$:

$$P(S_N = k | S_n = l) = \frac{P(S_n = l | S_N = k) P(S_N = k)}{P(S_n = l)} \tag{38}$$

And finaly,

$$P(S_N = k | S_n = l) = \frac{h(l, n, k, N) P(S_N = k)}{\sum_{k'=1}^{N-n+l} h(l, n, k', N) P(S_N = k')} \tag{39}$$

The posterior distribution (eq. (39)) shows the updated belief about the values of the probability that accounts for the observed data. The summation in the denominator ensures that the right hand side of the equation is properly scaled. In any case, it is just a constant that is independent of the values of the parameter k.

4.2 Prior and posterior distributions

The choice of the prior distribution of defective tubes $P(S_N = k)$ is subjective. In the following, a few examples of prior distributions are discussed. They share a very useful feature: a closed-form posterior density.

In absence of any information it may be useful to consider a non-informative uniform prior distribution:

$$P(S_N = k) = \frac{1}{N+1} \quad 0 \le k \le N \tag{40}$$

This leads to the closed form posterior in the form of:

$$P(\,S_N = k|\,S_n = 0\,) = \frac{1+n}{1+N}h(0,n,k,N) \tag{41}$$

We may also assume that the number of defective tubes in the finite population follows the binomial distribution with expected number of defective tubes being pN:

$$P(\,S_N = k\,) = \binom{N}{k}p^k(1-p)^{N-k} \quad 0 \le k \le N \tag{42}$$

This in turn leads to the closed form posterior in the form of:

$$P(\,S_N = k|\,S_n = 0\,) = \binom{N-n}{k}\,p^k(1-p)^{N-n-k}\,h(0,n,k,N) \tag{43}$$

Further details on derivation and properties of the above posterior distributions are given in (Cizelj and Roussel 2003).

4.3 Numerical example

Predicting the results of measurements is the forward problem. The inverse problem consists of using the actual results of measurements to infer the values of the parameters that characterize the system. The main characteristic of the inverse problem is that it does not have a unique solution. Because of this, in the inverse problem, a priori information about the model parameters is needed. In this case, inferring the number of defective tubes in the whole population from the results of an inspection of a random sample is an inverse problem. In the probabilistic formulation of the inverse problem, a priori information about the probability distribution of the system parameters is needed.

The choice of the particular prior in Bayesian analysis is usually interpreted as the knowledge or belief the analyst has about the investigated problem. Now, let us examine two rather extreme states of knowledge assumed by our imaginary analyst:

1. The material and design improvements made in the replacement steam generators are believed to be so efficient that active degradation processes are extremely unlikely. At the same time it is acknowledged that rare events might occur. Our prior information about the condition of the tubes then appears described correctly with a binomial distribution associated with a low value of the probability p.
2. On the other hand, we may acknowledge the material and design improvements made in the replacement steam generators. At the same time, we are convinced that the nature is more imaginative than the most experienced engineers. Then, our belief may well be that no knowledge about the condition of the tubes exists prior to the inspection. In such situation, the uniform distribution may appear to be a well-suited distribution.

At the first glance, it might appear that the binomial distribution expresses more information about the actual proportion of defective tubes in the steam generators than the uniform distribution. However, comparing eqs. (42) and (43) reveals that the posterior in eq. (43) is identical to the prior (eq. (42)) we would have postulated for any subset of N-n tubes in the population. Otherwise stated, the data collected during the in-service inspection of the first sample (n) tells us nothing at all about the unsampled tubes (N-n). Indeed, the choice of a binomial prior introduces a strong belief that there is a limited and rather well

characterized subpopulation of defective tubes. Since we do not find any defective tubes during the inspection of the sample n, the entire defective subpopulation must have survived the inspection and remains in the uninspected set of the tubes.

The explanation of the uniform prior requires numerical example. The steam generator contains N=10,000 tubes in all subsequent discussions. The definition of the relative sample size always refers to N. For example, a 10% sample would consist of n=1000 tubes.

Let us reiterate that the choice of uniform prior introduces the a-priory belief that any number of defective tubes is equally probable. This results in the posterior density (eq. (41)) of the number of defective tubes left in uninspected tubes, given the random sample of size n revealed zero defective tubes. Posterior densities for selected inspection samples are plotted together with the prior density in Fig. 12.

The non-informative uniform prior has a value of about 10^{-4}, which is independent of the number of defective tubes in the steam generator. Now, assume that inspection of a small (0,5%) random sample has been performed without finding any defects. Our information about the uninspected tubes improved drastically: The probability of having small number of defects increased for about two orders of magnitude. At the same time, although not shown in Fig. 12, the probability of having large number of defects in the uninspected part of the steam generator also decreased significantly. The expected number of defective tubes, which was 5000 for the uniform prior, decreased to 191 (yellow dots in Fig. 12).

Further increases in sample size are shown to increase the knowledge about the uninspected part of the population significantly. Inspecting the 20% random sample (without finding any defects) results in expected number of remaining defects at about 4 and in very fast decrease of probability of having larger numbers of defects.

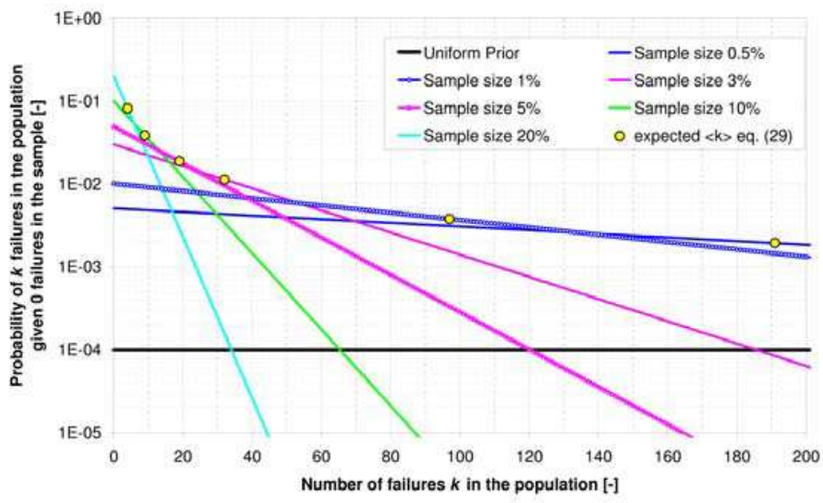


Fig. 12. Posteriors with different sample sizes. Uniform prior and 0 defects in the sample. Reprinted from Journal of pressure vessel technology, Vol. 129, Guy Roussel and Leon Cizelj, Propagation of stress corrosion cracks in steam generator tubes, p. 109, Copyrigt (1996), with permission from ASME

Expected number of defective tubes in the uninspected part of the population is plotted as a function of the sample size in Fig. 13. In addition, the 90% and 99% confidence curves are

plotted based on the expected number of degraded tubes and its variance defined in (Cizelj and Roussel 2003). Without inspection, the expected number of defects is 5000. It diminishes fast with increasing inspection sample. 3% inspection is shown to give 90% confidence, that there are less than 80 defective tubes left undetected. Similarly, 20% inspection is shown to give 99% confidence, that there are fewer than 11 defective tubes left undetected.

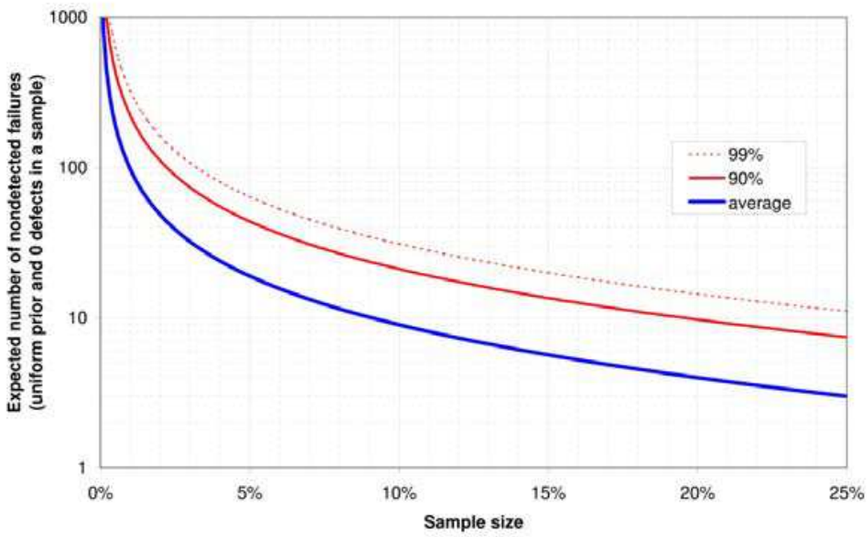


Fig. 13. Expected number of undetected defective tubes. Uniform prior and 0 defects in the sample. Reprinted from Journal of pressure vessel technology, Vol. 129, Guy Roussel and Leon Cizelj, Propagation of stress corrosion cracks in steam generator tubes, p. 109, Copyrigt (1996), with permission from ASME

The confidence to be placed in the results of the sampling inspection therefore depends mainly on the knowledge about the defective tubes existing prior to the inspection. As a rough practical guide, sampling inspection will only improve our knowledge about the defective subpopulation if we had very poor or no knowledge about it prior to the inspection. The sampling inspection (with uniform prior) may therefore be trusted as long as no defects are detected. With first failures detected, however, other inspection approaches might give more reliable results. This will be one of the topics of future investigations.

5. Summary

A critical compilation of the past work in the field of probabilistic assessment of degradation and maintenance strategies for degraded steam generator tubes was performed. The probabilistic apparatus previously proposed to serve in specific cases has been consolidated and generalized to accommodate a wide range of mechanistic and empirical models describing the tube failure modes. Realistic numerical examples provided illustrative and practical demonstration of the generalized probabilistic apparatus. Results include tube rupture probabilities, excessive tube leakage probabilities and comparisons of different maintenance approaches in probabilistic terms.

The basis for determining the size of the small random samples of tubes to be inspected in replacement steam generators is revisited. It is assumed that the probability of finding a

defective tube in a random sample is exceedingly small. A procedure to estimate the maximum number of defective tubes left in the steam generator after no defective tubes have been detected in the randomly selected inspection sample is proposed.

The confidence to be placed in the results of the sampling inspection has been found to depend mainly on the knowledge about the defective tubes existing prior to the inspection. As a rough practical guide, sampling inspection will only improve our knowledge about the defective subpopulation if we had very poor or no knowledge about it prior to the inspection.

The future work is expected to be focused mainly on the mechanistic models describing the rupture and leakage properties of various defects found in steam generator tubes. This will improve the predictive capabilities of the probabilistic framework described here.

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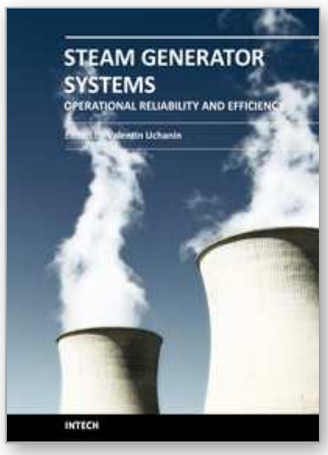
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The book is intended for practical engineers, researchers, students and other people dealing with the reviewed problems. We hope that the presented book will be beneficial to all readers and initiate further inquiry and development with aspiration for better future. The authors from different countries all over the world (Germany, France, Italy, Japan, Slovenia, Indonesia, Belgium, Romania, Lithuania, Russia, Spain, Sweden, Korea and Ukraine) prepared chapters for this book. Such a broad geography indicates a high significance of considered subjects.

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InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
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InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

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