20th International Conference on Structural Mechanics in Reactor Technology (SMiRT 20)
Espoo, Finland, August 9-14, 2009
SMiRT 20-Division 7, Paper 1684

Longevity Curves for Probabilistic Lifetime Assessment

Philippe MONETTE[a], Pierre JOLY[a], Vincent ROUX[a], Jean-Michel THIRY[a]

[a] *AREVA NP, Plants Sector, Paris and Lyon, France*
e-mail: philippe.monette@areva.com

Keywords: Longevity, Fragility, Probabilistic, Ageing.

1 ABSTRACT

This paper is a first attempt to introduce the concept of longevity curves as a tool to describe the time-dependent probability of failure of plant components subject to ageing. Longevity analysis allows taking a holistic view of the aging effects on component safety and by extension (i.e. through plant PSA modeling), on plant safety. The concept derives from that of seismic fragility curves which have been used extensively in Seismic PSA.

Longevity curves are associated with a particular age-related failure mode, affecting a long-lived component. They can be obtained from a full probabilistic analysis using time-dependent properties and damage modeling. Alternatively, they can be estimated through a progressive analysis of design safety factors that are treated as random variables characterized by their median value and standard deviations.

The conclusion is that a rational approach exists for estimating ageing induced probabilities of failure. Confidence bounds on such estimates can be developed to express the uncertainty in the parameters used. Dispersion due to inherent randomness is distinguished from the one due to uncertainty in the data.

2 INTRODUCTION

Seismic fragility analysis has become standard practice for assessing the seismic safety of NPPs for a range of earthquake magnitudes, extending beyond the design basis level. The methodology is well established, although it continues to rely on expert knowledge that is not widespread. Individual component seismic capacity is described by a family of “fragility curves”, defining the conditional probability of failure as a function of a ground motion parameter. The component fragility curves are often reduced to a high-confidence-of-low-probability-of-failure (HCLPF) capacity for each safety relevant component. The combination of component level HCLPF capacities, through boolean expressions describing safety system dependencies, provides a plant level HCLPF value that is viewed as the true reference seismic level up to which the plant can be considered as ”safe”. Typically, a plant that is designed to a 0.3g design basis earthquake can normally be shown to have a HCLPF capacity of 0.5g, thanks to conservatisms accumulated in the seismic design and analysis process.

The purpose of this paper is to study the technical value and practicality of adopting a similar methodology in an entirely different field, namely the assessment of plant safety for long term operation in the presence of ageing; the expected outcome being that one would likely be able to demonstrate a “high-confidence-of-low-probability-of-failure” life duration exceeding the design life. In such an assessment, emphasis is placed on “long-lived” passive components, i.e. those components which are not expected to be replaced, unless it is found through in-service inspections or ageing analysis that their remaining service life cannot be proven to match or exceed the plant design life.

While substantial work has been done in the area of Probabilistic Fracture Mechanics (PFM), risk-informed in-service inspection (RI-ISI), materials degradation assessment, there is no systematic or universal formulation for expressing the risk of failure due to ageing. This paper outlines the key elements of a longevity analysis that aims at bringing the different facets of ageing into a simple formulation that expresses risk over time.

3 AGEING ANALYSIS AND FIELD EXPERIENCE

3.1 Design Codes and Rules

Cumulative damage due to ageing is imperfectly covered in the design process. The main focus of design codes is on thermal fatigue of safety class 1 systems and components (constituting the RCS pressure boundary) and on irradiation embrittlement of the reactor pressure vessel (RPV) material.

In addition, the level of conservatism is not always well known or defined. As an example, the fatigue design curve entails a level of conservatism which varies according to different conditions, as further discussed in section 7.2. The amount of uncertainty can vary vastly, especially when the loadings are complex and exhibit a random nature, which is the case for thermal mixing phenomena (thermal fatigue), resonance of mechanical systems (vibration fatigue), etc.

No explicit rules are defined for designing against different forms of stress corrosion cracking (SCC). Many aging phenomena are thus left to proper material selection (... and therefore existing plants have to “live” with choices made long time ago), in-service inspection programs, laboratory experiments and, most importantly, feedback from service experience, in order to ensure that the expected level of safety is maintained over time.

3.2 Operating Experience

Service experience plays a crucial role in providing the feedback loop that is necessary to better control ageing degradation and effects, since they are only partly captured in the design process.

As a general statement, the failure history shows that ageing failures have resulted almost entirely from phenomena that were not anticipated or not properly accounted for in the design stage (e.g. cycling due to valve leakage, thermal stratification, vibrations, thermal fluctuations...) or resulted from improper material selection (e.g. Alloy 600 issues). Ageing failures have not resulted from the design rules themselves being unconservative, for the class of problems and ageing effects that were covered by those rules.

Service experience is represented by actual failures that have been reported; but it also includes in-service inspection history of each component. Overall, this represents a vast amount of data, which have been compiled and analyzed by various industry groups, as part of numerous research programs, e.g. U.S.NRC (2007), Chockie (2008), etc., as well as by plant designers and operators, as part of their day-to-day plant ageing management activities. Valid ageing prediction models have now been developed in many cases, which greatly enhance the understanding of the phenomena and the capability to prevent future failures from occurring.

This does not mean that perfect knowledge and control of ageing is achievable: ageing failures depend on many factors such as the service history (stressors), fabrication processes and intrinsic material susceptibility. Therefore it is important to recognize that large uncertainties may exist in one or more of these factors. Such uncertainties are to be modeled explicitly in the longevity analysis, as is detailed below.

4 LONGEVITY ANALYSIS

4.1 Longevity curves

The longevity of a structure or component (lat*: longaevus*, of a long age) is the proper term to describe its capacity to maintain its function over a long period of time.

The longevity analysis that is proposed here is based on a probabilistic formulation that comprehensively combines the various elements contributing to ageing failure. The main steps of the method are to:

(1) perform an engineering review to determine the governing ageing failure modes (from component design analysis, materials review as well as review of relevant service experience);

(2) establish a best estimate (or median) time to failure for the governing failure mechanism;

(3) quantify uncertainties about the median; both aleatory and epistemic uncertainty are to be considered

(4) develop a family of longevity curves (at different confidence levels) and define a high-confidence-of-low-probability-of-failure (HCLPF) value, meant to be a lower bound estimate of the component "safe" lifetime.

Example longevity curves are provided in Fig. 1 for a component with a median age at failure of 131 years and a HCLPF longevity of only 48 years.

Through application of this method to a large number of safety significant components, it is expected that consistency in lifetime margin assessment can be achieved across different components and failure mechanisms.

The method is not restricted to a particular failure mechanism; on the contrary it is designed to allow a common formulation for very different classes of ageing degradation: fatigue, corrosion of different kinds, wear, etc.

In essence, the longevity curves methodology is one particular form of structural reliability modeling (SRM), the goal of which is to predict structural failures, as a function of a limited number of essential parameters. One of the distinctive features is that it is expressed as a function of plant age.

Another distinctive element is that it relies heavily on expert knowledge, without excluding the use of sophisticated analysis such as Probabilistic Fracture Mechanics (PFM) and Monte Carlo simulations. Actually both simple and sophisticated models are valid elements of an ageing assessment, provided that the uncertainty bounds are truly representative of the dispersion that can be encountered in real life. PFM analyses, when used, must be checked for (1) completeness of the approach and range of issues considered, and (2) full applicability to the particular component under review.

4.2 Mathematical formulation

The entire mathematical procedure is a direct transposition of the fragility analysis method extensively used in Seismic PSA and first formulated in Kennedy et al. (1980), thirty years ago.

Similarly to the seismic fragility, the longevity of a structure or component is treated for simplicity and clarity as a product random variable A given by

$$A = A_m \; {}_R \; {}_U, \qquad (1)$$

where A_m is the best estimate of the longevity or median age at failure, ${}_R$ and ${}_U$ are lognormal random variables with unit median and logarithmic standard deviation ${}_R$ and ${}_U$, respectively.

${}_R$ expresses the dispersion in the achievable lifetime due to underlying randomness such as (1) the variability of service history, in the form of operating regime (pressure, temperature, chemistry) and transient occurrences, such that the ageing phenomena cannot be solely defined in terms of years of service; and (2) the variability of material properties and associated resistance to ageing. Essentially, ${}_R$ represents those sources of dispersion which cannot be reduced by more detailed evaluation or more data.

Uncertainty concerning the lifetime attainability is expressed by ${}_U$ which results from such elements as (1) lack of complete knowledge of structural material properties that influence ageing; and (2) errors in estimating ageing effects due to approximate modeling.

By this procedure the inherent randomness or *aleatory* uncertainty is clearly separated from the *epistemic* uncertainty associated with imprecise knowledge of essential parameters.

Eq. (1) enables the longevity curve and its uncertainty to be represented as shown in Fig. 1, i.e. as a set of shifted curves, with attached confidence levels. In short it is assumed that the uncertainty in the longevity curves can be expressed through uncertainty in its median alone.

The assumption that ${}_R$ and ${}_U$ are lognormally distributed, with ${}_R$ and ${}_U$ as standard deviations, has the following distinct advantages:

1. The entire longevity curve and its uncertainty can be expressed by only three parameters: A_m, ${}_R$, ${}_U$.

2. The formulation in Eq. (1) is very tractable mathematically and lends itself to decomposition in different factors, with their associated elementary uncertainties, that can be easily combined as described further below.

Another advantage of the lognormal distribution and Eq. (1) is that it is easy to condense the family of longevity curves into a composite mean longevity curve (i.e. one that does not separate out aleatory uncertainty from epistemic uncertainty) defined by:

$$A = A_m \quad _C \tag{2a}$$

where $\ _C$ is a lognormal variable with unity median and logarithmic standard deviation $\ _C$ given by:

$$_C = (\quad _R{}^2 + \quad _U{}^2)^{1/2} \tag{2b}$$

A conservative lower bound of the longevity is expressed by the high-confidence-of-low-probability-of-failure value:

$$HCLPF = A_m \exp\{-1.65 (\quad _R + \quad _U)\} \tag{3}$$

that corresponds to a 5% failure probability on the 95% confidence curve.

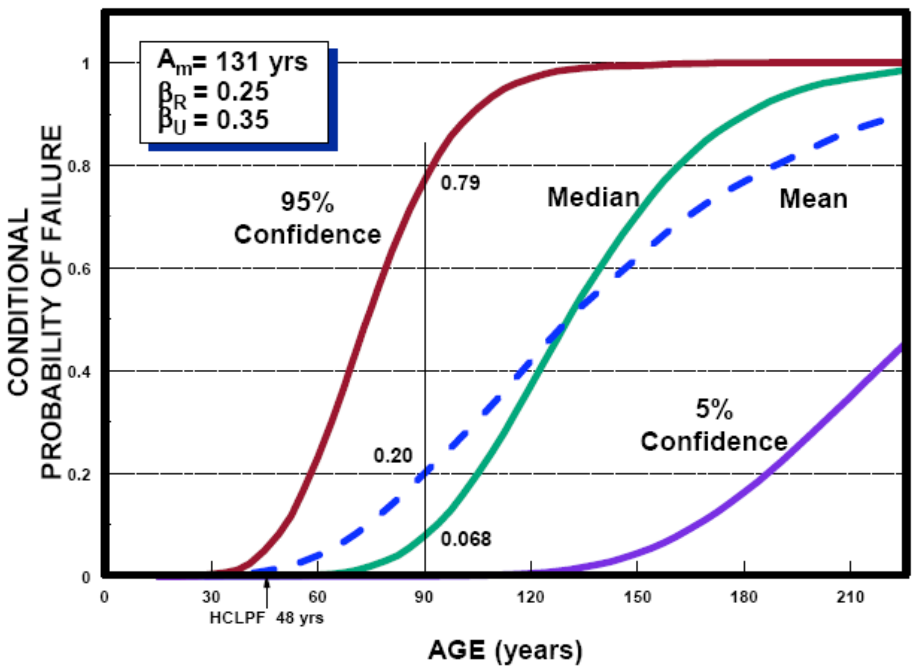

Figure 1 - Mean, Median, 5% Non-Exceedance and 95% Non-Exceedance Longevity Curves for a Component

4.3 Separation of Variables Approach

Longevity curves are associated with a particular age-related failure mode, affecting a long-lived component. They can be derived from a full probabilistic analysis using time-dependent properties and damage modeling, with probability distributions on the essential parameters. Alternatively, they can be estimated through a progressive analysis of design safety factors that are treated as random variables characterized by their median value and their standard deviations.

As in most classes of structural reliability problems, it is legitimate to separate the Demand side (D) from the Resistance (R) side, when characterizing the parameters that contribute to failure probability assessment according to the criterion:

Demand (D) $\leq$ Resistance (R)

A convenient way to separate ageing factors is therefore to consider:

- a load & environment factor, F_{LE}, that accounts for the time dependent solicitations in a broad sense (stresses, temperature, water chemistry, ...) – to be associated with the Demand side
- a material & design factor, F_{MD}, that accounts for the physical component properties, notably its resistance (or susceptibility) to ageing effects – to be associated with the Resistance side
- a defect tolerance factor, F_{DT}, that accounts for the remaining life of the component once an ageing effect has manifested itself through initial defects.

This breakdown can serve as a frame of reference, but is not to be taken as systematically valid. If it is found suitable, then the component longevity can be expressed as a product of safety factors:

$$A = F_{MD}*F_{LE}*F_{DT}*A_{Design} \qquad (3)$$

A_{Design} being the design life,

F_{MD}, F_{LE}, F_{DT} being factors of safety that are lognormally distributed with their respective median value and associated standard deviations.

The product $F = F_{MD}*F_{LE}*F_{DT}$ represents the overall factor of safety over the design life, characterized by its median value, i.e. the product of individual medians, and its variability parameters $_R$ and $_U$, obtained by SRSS of the individual $_R$, and $_U$ values.

Each of the factors themselves can often be decomposed into elementary factors of safety (such as the one affecting the number of transient occurrences, or the calculated stress amplitude, etc.) that are combined according to the same simple mathematical formulae.

The separation of variables approach is illustrated in Example 2 dealing with fatigue failures.

4.4 Ageing mechanisms and failure modes

Prior to generating longevity curves such as those in Fig. 1, it is necessary to develop a clear understanding of what constitutes failure for each of the safety-related structures and components. This definition must be agreed upon between the structural & material analyst engaged in generating the longevity curves and the systems analyst who must judge the consequences of failure of a component in order to estimate its safety importance, expressed in relative increase to core damage frequency (CDF) or large early release frequency (LERF).

The failure can be associated with different causes or mechanisms. It is necessary to clearly identify the governing failure mode and the most likely ageing sequence leading to failure.

Failure can be either:

- a loss of pressure retaining capability (leak) or
- fast fracture (break) of the component or
- a functional failure (e.g. affecting moving parts)

Obviously, failure is not to be confused with a code limit being exceeded. To the contrary, the longevity analysis aims at putting code requirements into perspective, in terms of their conservatism (or lack thereof).

The successive phases of ageing failure, e.g. crack initiation, crack growth, leak or break generally should be considered as part of the longevity calculation. If the analysis is limited to estimating the useful service life of a component in its original state (i.e. without considering repair), it is sufficient to consider the initial phase of crack initiation only.

It may be that more than one mode of failure (each with a different consequence) has to be analyzed, resulting in longevity curves being calculated for each of these modes.

Given the multiplicity of ageing failures and associated consequences, screening for ageing susceptibility as well as safety significance of age-related failures is recommended, so as to limit the longevity analysis to the most important items. The screening phase requires expert knowledge of the components, of their ageing susceptibility, and of their safety significance; only those components for which there is a clear knowledge of the stressors and demonstrated immunity (resistance) to ageing phenomena should be screened out of the evaluation. The others should be retained as potential ageing vulnerabilities.

The methodology for assessing the severity of consequences of failure is addressed in the next section.

5 PROBABILISTIC SAFETY ASSESSMENT

Probabilistic Safety Assessment (PSA) is a logic tool that can be used to identify the safety significant components and to verify the robustness of the plant to cope with individual failures.

Risk importance in the PSA can be expressed in term of Core Damage Frequency (CDF – Level 1 PSA) or Large Early Release Frequency (LERF – Level 2 PSA). The identification of the components that significantly contribute to CDF or LERF allows giving priority to manage their reliability level during the entire life of the plant.

As in seismic PSA, addressing ageing effects requires a major adaptation of the PSA model to include the passive components that are not modeled in the PSA. Ageing failure of passive components is a type of failure mode that intervenes mostly in modifying the frequency of initiating events, but it can also impact the probability of loss of availability of mitigating capability. For the different passive components considered in the aging effect analysis, it is necessary to assess the effect of the failure mechanisms, typically in terms of leak occurrence or quantification of the break size. Then, the impact on initiating event or/and mitigating functions shall be analyzed so that these components that are not modeled can be included in the PSA. For instance, different degradation mechanisms could lead to the following initiating events:

- PWSCC (and other SG tube bundle ageing issues) causing a SGTR initiating event,
- Flow accelerated corrosion (FAC) causing a steam line or feedwater line break,
- Fatigue in branch nozzle or piping or Pressurizer bottom leading to an unisolable leak in primary system,
- BMI nozzle break caused by PWSCC and creating a small LOCA…

Time coincidence of age related failures is considered unlikely, provided that the failure modes and effects manifest themselves in a short period of time and that consequences are "visible" to the plant operator. This is expected to be generally the case, except for rare situations such as generalized corrosion of buried piping, assuming it could remain undetected, or of embedded parts of steel containment and other safety important structural elements. These are hypothetical cases which can be handled through a "*caveat*" in the systems analysis: systems or components on the success path of the event tree must be checked against potentially undetected but severe ageing phenomena.

Overall, a PSA based analysis should aim at demonstrating only minimal increase of CDF due to ageing. The methodologies developed for risk informed in-service inspection (RI-ISI) show how the PSA can be used for such passive components, especially piping (EPRI, 1999; ENIQ, 2005; ASME, 2005) . The components can be ranked depending on the consequences of their failure. Importance factors are used to perform this ranking. These sensitivity studies point out the relative importance of age related component failure on the risk.

It is however more difficult to develop a PSA model that would take into account aging phenomena by modeling the risk increase with time. The current stage of development of Level 1 and 2 PSA models is not yet sufficient for ageing PSA analysis. Research & Development actions are necessary to support the set-up of a methodology for the development of PSA based "ageing margin" assessment.

6 ROLE AND IMPORTANCE OF IN-SERVICE INSPECTION

In-service inspection (ISI) is of primary importance for early detection of ageing degradation and for preventing its consequences from occurring. However ISI in no way affects the physical condition of the component and therefore has no influence on the age at failure, assuming no 'rejuvenating' intervention (mitigation, repair, replacement) has taken place.

Mathematically, this means that the median longevity curve, determined by A_m and $_R$, is independent from ISI; however the uncertainty $_U$ can be substantially reduced through inspection at appropriate intervals; and consequently, the HCLPF value can be increased substantially.

In recent efforts to quantify the probability of LOCA (small or large), see e.g. U.S.NRC (2008, 2009), the probability values were shown to largely depend on:

1. the specific design and material of the primary loop piping and welds (e.g. presence or absence of thermally aged cast elbows; susceptibility to IGSCC or PWSCC, etc.) inducing very distinct LOCA frequencies – this effect should be captured in a proper longevity analysis
2. the inspection program (scope, frequency).

This also underlines the value of clearly separating the random (aleatory) uncertainty from the uncertainty associated for instance with the lack of fabrication records, that affects the likelihood of a major pre-existing flaw. The method for incorporating ISI into the uncertainty parameters characterizing the longevity curves, e.g. through estimates of the Probability of Detection (POD) of pre-service and service-induced defects, requires further development.

7 EXAMPLES

The development of longevity curves is demonstrated on two examples. The first one relates to the longevity of bottom mounted instrumentation (BMI) nozzles of PWRs that are susceptible to PWSCC; a full Monte Carlo simulation was used. The second one deals with the fatigue life of e.g. RCS branch nozzles, for which the separation of variables approach is recommended.

7.1 Example 1: BMI nozzles subject to PWSCC

The susceptibility of Alloy 600 to Stress Corrosion Cracking in primary water at high temperature (PWSCC) has been studied extensively. In Benhamou & Amzallag (2009), a probabilistic model is used, that focuses on the parameters that influence PWSCC behaviour and their associated uncertainty. First, the distribution of the parameters and their influence on the time to crack initiation are defined empirically, thanks to a very rich data base of inspection data and cracking history of Reactor Vessel Head (RVH) nozzles, as well as through an extensive search of fabrication data for both RVH and BMI nozzles. Next, the empirical relationship for time to crack initiation is applied to each homogeneous subgroup of BMI nozzles and a sampling of the parameters is applied as part of the Monte Carlo simulations. Fig. 2a shows the 95% non-exceedance probability (NEP) curves for four different populations. Fig. 2b shows a set of longevity curves at different confidence levels for one particular subgroup of BMI nozzles.

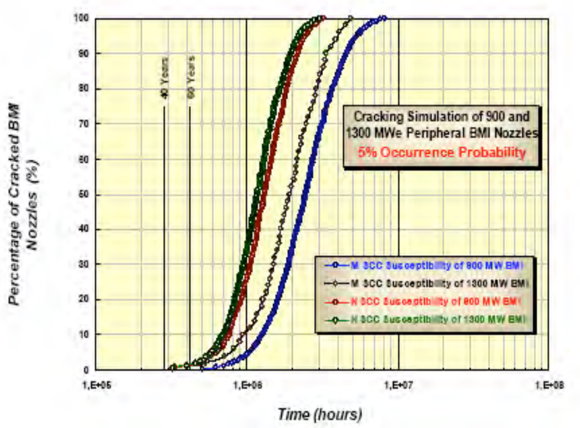

Figure 2a - 95% Non-Exceedance Curves for Different Subgroups of BMI Nozzles

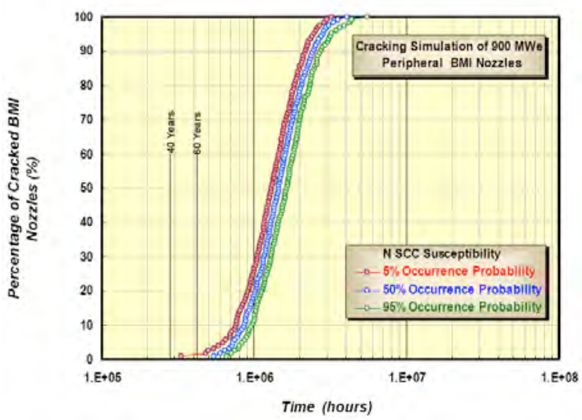

Figure 2b - 95%, 50% and 5% Non-Exceedance Curves for the Same Subgroup

(courtesy of C.Benhamou and C.Amzallag)

The longevity parameters can be derived from the numerical data. For the subgroup of Fig. 2b, namely 900 MWe plant peripheral BMI nozzles of material SCC susceptibility 'N', manufactured in France (with post-weld heat treatment of the bottom head), the longevity parameters are:

$A_m = 220$ yrs

$_R = 0,46$

$_U = 0,09$

HCLPF = 89 yrs

This HCLPF value represents a lower bound estimate of the durability of the reactor vessel bottom head without mitigation and repair. Note that this result should in no way be generalized to other bottom heads with different BMI nozzle material and/or fabrication process. The relatively low value of $_{U}$ reflects the precise knowledge of the material, thanks to high-quality fabrication records. The high HCLPF value is also due to the fact that the penetrations were stress relieved.

7.2 Example 2: Fatigue of RCS branch line nozzle

The fatigue design of class 1 components consists of a chain of design inputs and analytical steps that entail various but often cumulative levels of conservatism.

First, design transients are defined for the duration of plant life and aim at providing a conservative envelope of the loadings that the components will experience, both in terms of shape and number of occurrences.

Next, the components are calculated assuming the most penalizing combination of transient pairs. The calculations are often performed using simplified models that maximize the stresses. The design code also introduces penalizing factors such as K_e.

Finally, a fatigue usage factor is calculated on the basis of a fatigue design curve that is meant to be bounding for most of the practical cases.

The separation of variables approach described above is well suited for assessing the cumulative effect of those safety factors, in a probabilistic way.

It is convenient to estimate the time to crack intiation, A_{in}, as a product random variable:

$$A_{in} = A_{Design} * 1/\, u_{calc} * F_{trans} * F_{calc} * F_{curve} \qquad (4)$$

Each factor F_i is a random variable that can be characterized by its median (best-estimate) value and conservative upper bounds (1 or 2 standard deviations corresponding to 84% or 97.7% NEP). Each of them can be further decomposed into elementary factors with similar characteristics. Elementary factors are combined by their product and their standard deviations by SRSS (lognormal approximation).

In the above product, $A_{Design} * 1/\, u_{calc}$ is the simple extrapolation of fatigue design life A_{Design} based on the calculated usage factor u_{calc}; it is a deterministic number.

F_{trans} expresses the conservatism (or unconservatism) in the design transients, namely:

- number of occurrences
- transient shape and amplitude

Note: knowledge of transient history is necessary to estimate this factor. The potential for unanticipated transients (thermal cycling, deadlegs, stratification, fluid mixing phenomena...) must also be assessed in this step.

F_{calc} is the factor associated with the calculation of S_a and includes such elements as:

- the bias introduced by the modeling and calculation method, e.g. conservative transient grouping, use of simplified elastic-plastic analysis, etc.
- the conservatism in the code equations and intensification factors.

It is obtained by estimating a median reduction factor to be applied on S_a for the dominant transients, and by deriving the corresponding increase in allowable number of cycles along the fatigue design curve, as shown in the simplified fatigue diagram of Fig. 3.

F_{curve}.is the factor associated with the fatigue resistance, expressed by the design curve. It is obtained as follows, with due consideration of the factors that influence fatigue resistance:

- define a good estimate of the median curve, based on test data, environment condition, surface finish, size effect, etc., as can be found in Le Duff et al (2008 and 2009), Chopra et al (2007), Nakamura et al (2007)
- determine the ratio of allowable number of cycles between the median curve and the design curve, for the dominant transients and associated median S_a value;
- estimate the non-exceedance probability of the design curve.

A graphical representation of the combined effect of F_{calc} and F_{curve} is represented on Fig. 3.

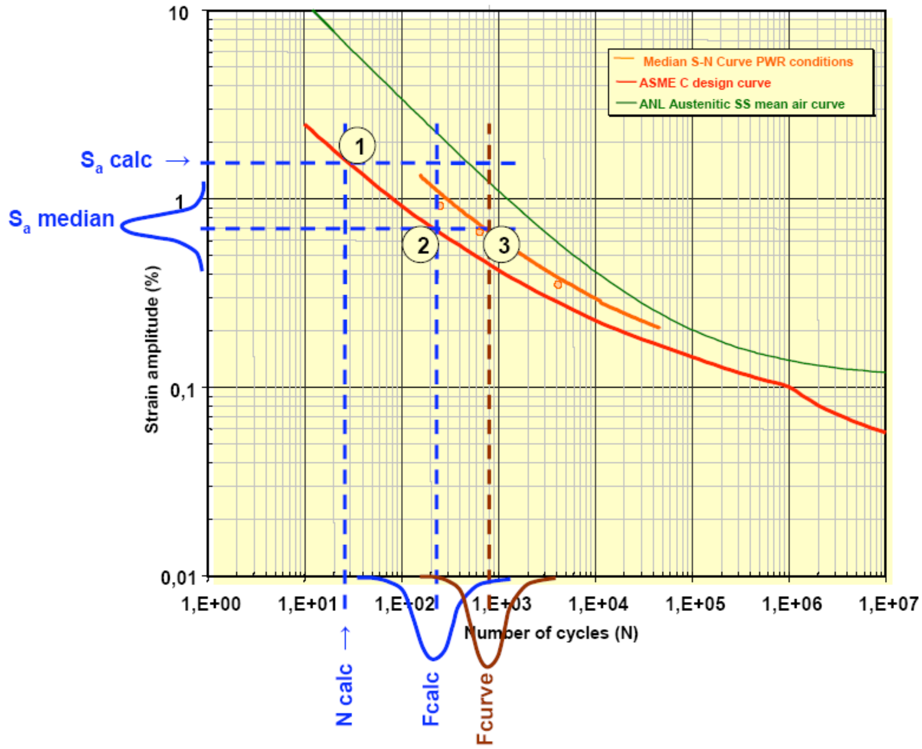

Figure 3 - Illustration of Fatigue Safety Factors for a RCS Branch Nozzle

Following the onset of crack initiation, time to leakage (or break) should be estimated, through fatigue crack growth calculation. A_{leak} is expressed by means of an additional factor multiplying the initiation time:

$$A_{leak} = A_{in} * F_{cg}, \qquad (5)$$

where F_{cg} is a kind of damage tolerance factor, with its own median and uncertainties. Caution must be exercised against accelerating effects such as the risk of vibration fatigue for smaller size nozzles, once a crack has initiated.

One difficulty in the estimation of the values is the segregation between aleatory and epistemic uncertainty. In short, while the transient and load history contains a great deal of randomness, the calculation part is mostly affected by uncertainty due to limited knowledge and approximate modeling.

The benefit of the separation of variables approach is that longevity curves can be obtained from a critical review of the design analysis, including design inputs and code requirements. It is however crucial to question the validity of the loadings assumed for design against operating experience.

8 COMPARISON WITH SEISMIC FRAGILITY ANALYSIS

One of the merits of seismic fragility analysis is its ability to express seismic-induced failures of each and every safety related structure or component (including functional failures) in a single and consistent format, as a function of a ground motion parameter.

Screening for seismic vulnerabilities is based heavily on earthquake experience data accumulated and codified in the 1980's.

Handling of a large amount of components is achieved through application of relatively simple techniques, but these demand a high level of knowledge and expertise. The essential part is to quantify the conservatism (sometimes unconservatism...) associated with the different inputs, hypotheses, analysis methods, analysis results, through the whole analysis chain, so as to derive a reasonable estimate of the median seismic capacity of individual components and structures. It is equally important to estimate the variability and uncertainty in the contributing parameters.

The model proposed herein for longevity analysis exhibits strong similarity with the former one:

- Expressing component probability of failures as a function of plant age as a common denominator
- Screening age-sensitive components through operating experience feedback (such as found in Generic Aging Lessons Learned document, or U.S.NRC (2007), but preferably operating experience that is directly applicable to the specific design at hand)
- Scrutinizing the conservatism (or possible lack thereof) in design inputs; codes & standards; analysis methods, ageing prediction models
- Recognizing and quantifying the uncertainty -which in some cases can be huge- in each important parameter.

The expected result is a much better appreciation of the design margins against ageing effects.

A last parallel to be drawn is the feedback loop to plant design, operation, and safety upgrades: here also, the longevity analysis allows focusing more attention and efforts to improving margins for weak longevity components, either through enhanced inspections (reducing uncertainties) or ageing mitigation (increasing A_m). The PSA can also be exercised for prioritizing equipment upgrades based on risk importance.

Finally, it is recognized that peer review or expert panels should be an essential element of the process.

9 CONCLUSION

The seismic fragility methodology provides a blueprint for developing a longevity analysis methodology, with necessary adaptations. The goal of the present paper was mainly to serve as a proof of concept. Longevity curves could provide a consistent framework for (1) assessing major component ageing issues in a probabilistic way and (2) linking them to plant safety and availability models.

Longevity curves are obtained by estimating the median value of all parameters that contribute to ageing failures, on the demand side as well as on the resistance side, and by quantifying the inherent variability of and uncertainty about those parameters. Using the mathematical expressions developed for seismic fragilities makes the whole process easier to integrate. There are a number of parallels that can be drawn between the two disciplines, which although quite distinct, are both related to structural risk and reliability. The nuclear industry would benefit from adopting a unified code of practice.

By definition, longevity curves are intended to capture all information that is relevant for estimating the probability of failure as a function of component age: design analyses, predictive models, operating experience, inspection data, etc. Needless to say, a multi-disciplinary approach is necessary to carry out longevity analyses, since these result from the integration of materials, structural and systems expertise. The use of expert panels and peer reviews is highly recommended.

Future development work is required and planned in the following directions:

- Conduct pilot longevity analyses for high impact components (considering both safety & cost impacts) subjected to various degradation mechanisms
- Method for incorporating ISI into the longevity assessment (e.g. use of POD)
- Choice of risk importance factors and PSA development.

Finally, it is hoped that longevity analysis can be used not only for proactive management of ageing degradation but also to better balance the conservatism in design requirements.

Acknowledgements

The authors wish to express their recognition to the "founding fathers" of the seismic fragility analysis method, who inspired this work and indirectly contributed to it.

REFERENCES

ASME section XI edition 2005 - Non-mandatory Appendix R

Benhamou,C. and Amzallag, C., 2009. Prediction of Stress Corrosion Initiation Time of Alloy 600 PWR Components. 14th Environmental Degradation of Materials in Nuclear Power Systems, Virginia Beach, USA

Chockie A.D. and Gregor F.E., July 2008. The Role of Failure Data in Plant Aging Management and Life Extension. PVP2008-61552, Chicago, Illinois, USA

Chopra O. and Shack W. J., February 2007. Effect of LWR Environments on the Fatigue Life of Reactor Materials. Final Report. NUREG/CR-6909 – ANL-06/08, Argonne National Laboratory

ENIQ Report Nr 23, March 2005. European framework document for Risk-Informed In-Service inspection. EUR 21581 EN

EPRI. July 1999. Revised Risk-Informed In-service Inspection Evaluation Procedure. EPRI TR-112657. Final Report, Rev. B

Kennedy, R.P., Cornell C.A., Campbell R.D., Kaplan S. and Perla H.F., August 1980. Probabilistic Seismic Safety Study of an Existing Nuclear Power Plant. Nuclear Engineering and Design, Vol. 59, No. 2, pp. 315-338

Le Duff J.A., Lefrançois A. and Vernot J.Ph., July 2008. Effects of Surface Finish and Loading Conditions on the Low Cycle Fatigue Behavior of Austenitic Stainless Steel in PWR environment. PVP2008-61894, Chicago, Illinois, USA

Lee T.H. and Hwang I.S. June 2008. Mechanism-based Ageing Management of Primary Stress Corrosion Cracking of Ni-base Components in PWR environments, ICAPP2008-8176, Anaheim, CA, USA

Nakamura T., Iwasaki M., Asada S., July 2007. Optimization of Environmental Fatigue Evaluation (Step 1). PVP2007-26247, San Antonio, Texas, USA

U.S.NRC, February 2007. Expert Panel Report on Materials Degradation Assessment. NUREG/CR-6923

U.S.NRC, March 2008. Estimating Loss-of-Coolant Accident (LOCA) Fraquencies Through the Elicitation Process. NUREG-1829 Vol.1

U.S.NRC, March 2009. Evaluations of Structural Failure Probabilities and Candidate Inservice Inspection Programs. NUREG/CR-6986, PNNL-13810