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NB-3650M FATIGUE CALCULATION PROCEDURE

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BACKGROUND AND GOAL

Fatigue is considered a significant long-term degradation mechanism for safety significant pressure equipment in nuclear power plants. The ASME Section III [1] procedure aims to prevent formation of fatigue cracks during the specified service period. Several studies performed in the USA and Japan indicated sihnificant environmental effects. This has yielded a methodology as described in the NUREG/CR-6909 [2] and the JSME S NF1-2006 [17]. From an analytical point of view the NB3600 (engineering approach) and NB3200 (detailed 3D analysis) fatigue analysis methodology and the one in the NUREG/CR-6909 (full time history) are not compatible. In the work presented here a methodology was developed to combine these methods.

The main reasons for the ASME NB-3650M (modified) procedure development are:

- The original design-lifetime is running out and will be extended (to 60 years). As reanalysis has to be done this was a good moment to look at the analysis methodology.
- As well for the RI-ISI procedure that is presently in use as for the coming probabilistic RI-ISI procedure it is necessary to determine the cumulative fatigue usage in such a way that cumulative usage factors are commensurate.
- In the classic ASME NB-3600 procedure only scalar stress differences are used and the actual time and location of the stress in the pipe cross section is lost. To study the influence of the coolant on fatigue a procedure was developed and documented in the NUREG CR/6909. This procedure uses the change of strain over the time and is thus not compatible with the classic procedure. To enable the best possible application of this procedure it was necessary to develop a strain based transient fatigue analysis procedure.
- As the operational record of the present plants in the world shows that low-cycle fatigue is not actually a problem the increase of conservatism due to the application of the NUREG CR/6909 procedure has to be partly covered by a reduction of the intrinsic conservatism in the classic NB3600 fatigue analysis procedure. To reach this goal application of a best estimate procedure is necessary.

The development, testing and validation was organized as follows:

- The actual method development was mainly done by FEMdata and TVO. At the beginning of the project there was some involvement of VTT and FORTUM.
- Programming was done by FEMdata [7] and [8] and tested by FEMdata, TVO and VTT. For the testing the feedwater system of the Olkiluoto plants was used [10] and [11].
- A comparison was made with an Inspecta analysis [16], the latter being more simplified.
- In a Master's Thesis the method was even applied with a full 3-D volume model [12].
- The new full transient stress analysis as well as the ASME NB-3650M procedure and the results for both have been validated by VTT [3], [4] and [5].
- In order to learn more about the new methodology a mutual project was initiated between TVO and VTT to study the influence of different parameters and compare previous and present analysis results. This is reported in [18]

METHODOLOGY DESCRIPTION FOR ANALYSIS OF ONE CROSS SECTION

The main means to achieve the goal are described below:

1. Determine the full stress/strain time history at distinct locations around the circumference and both at the inside and outside of the pipe, see figure 1 and 2.
2. Determine the local temperatures, stresses and strains in all directions.
3. The tests on which the NUREG CR/6909 procedure is based were 1-D axial monotonic tests in constant temperature water. Obviously application is not straightforward. To approach the NUREG test situation in the distinct locations defined above the full fatigue analysis is performed separately for every requested angle φ, see figure 1.
4. Shear stresses have been fully taken into account in the determination of the true strains. True strain is here defined as the actual deformation of the material in a distinct direction.
5. The sign of tensional and compressive stress and strain components is taken into account at all times and in all equations. In the classic ASME NB-3600 procedure the sign is lost but the sign is necessary for the NUREG CR/6909 procedure.
6. Stress indices are separately defined for all relevant stress directions and types and taken into account for the stress and strain component that is actually affected.
7. True strains are determined with analytical equations.
8. Fatigue strain cycles and associated time periods are determined with an adapted rainflow method.
9. The allowable number of cycles is directly obtained with help of the fatigue strain cycle.
10. Once looking in one direction only it is also possible to take the unidirectional NUREG/CR-6909 procedure into account.

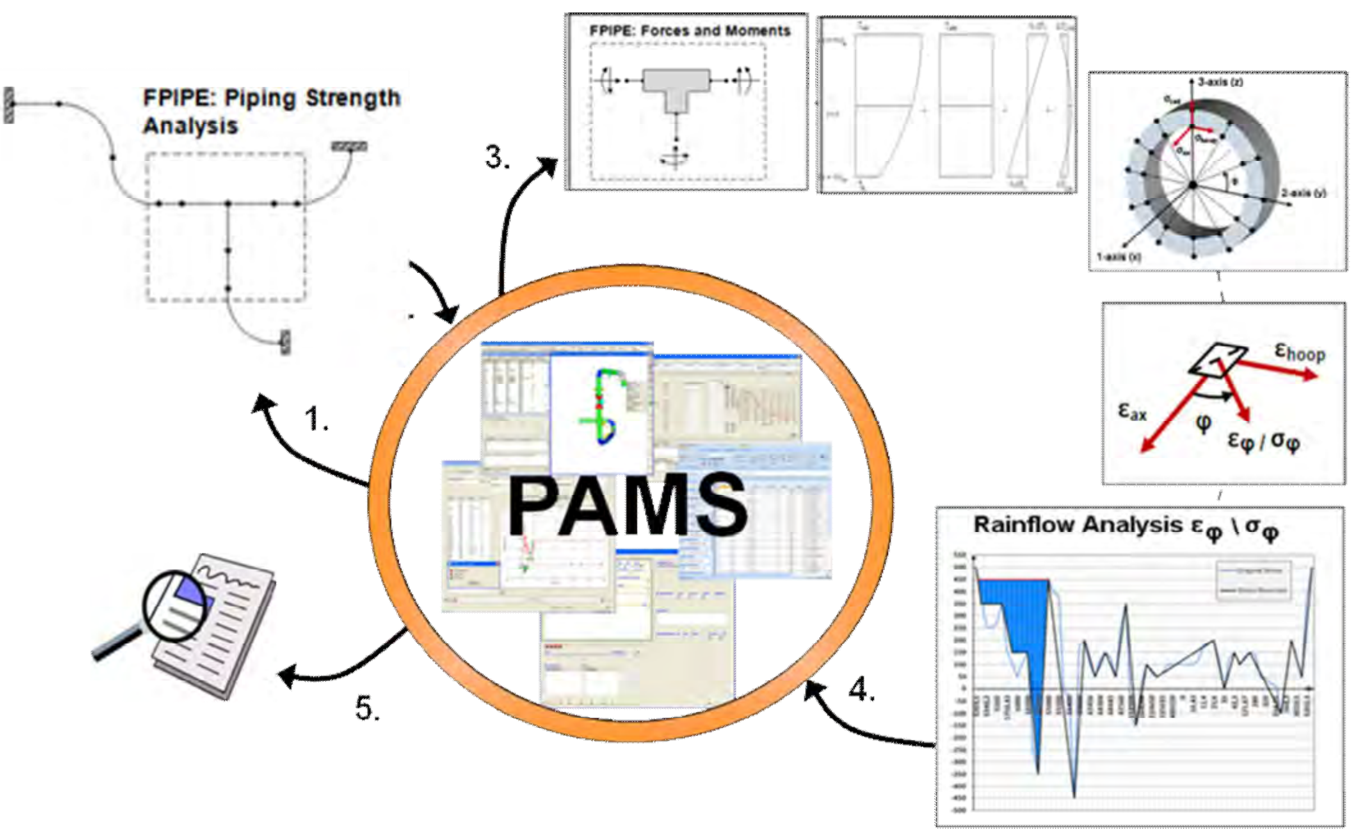

Figure 1. Work flow for the fatigue analysis

ANALYSIS PARAMETER SETTINGS

In the analysis the following parameters can be set:

- Angle θ defining the number of points to be analyzed around the circumference ➔ circumferential output angle 0° … 360°, default step 30°, see figure 2.
- Angle φ defining the directions to be analyzed angles between the angles 0° and 90° alternatively 0° and 180° in case $\tau_{range} > 10$, default step 15°, see figure 2.
- $\Delta\sigma_{fen}$: thermal stress resolution to save analysis time, as a default no time step may yield a thermal stress change of more than 5 MPa.
- IFEN: F_{en} method choice: J1, J2, V1 and V2. These different stress (J) and strain (V) based fatigue analysis methods are later discussed in more detail.
- Design fatigue curve selection: ASME, ANL, or user defined (in input data).
- ε_{th}: threshold value for strain amplitude, default from [1] (A-8) (A-13) (A-18)
- $\varepsilon ps_{th}+$: strain increase to start Fen analysis, default same as for ε_{th}
- $\varepsilon ps_{th}-$: strain decrease to reset $F_{en,nom}$ to 1, default $\varepsilon ps_{th}- = \varepsilon ps_{th}+$
- SIGTOL ($\Delta\sigma_{tol}$): stress cycles with range less than $\Delta\sigma_{tol}$ omitted from fatigue analysis, default 10 MPa.
- IHIST10: (φ constant over whole analysis, results for “most severe” φ are displayed)
- 0 ➔ load cycles calculated individually, usage factors (same φ) are summed
- 1 ➔ calculation over plant history, best estimate for unidirectional fatigue

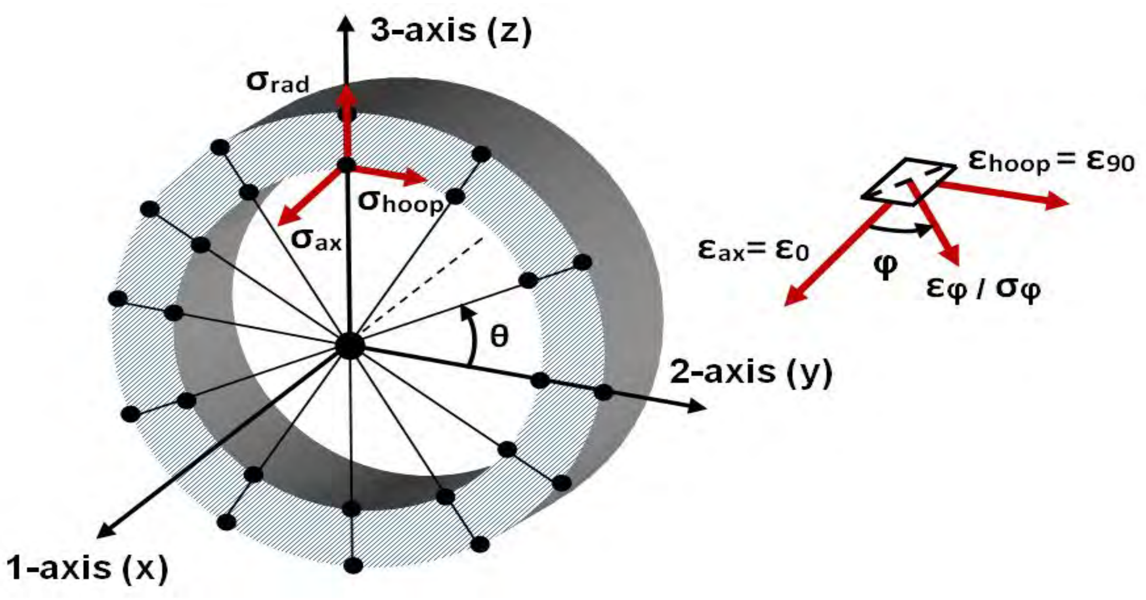

Figure 2. Discrete locations around the circumference of the node and stress/strain directions.

STRESS ANALYSIS

In the fatigue analysis first the nominal transient stresses due to internal pressure, moments and thermal loading are separately determined. Then these nominal stresses are multiplied by the applicable stress indices. Separate stress indices were defined for longitudinal and transverse welds and for the load cases internal pressure, moments and thermal loading [6]. These were defined with use of the stress indices from [2] table NB-3681 (a)-1. For different locations around the circumference different sets of stress indices can be defined, see figure 2. In case for instance the weld does not coincide with a transition of the cross section different analysis can be defined for these cross-sections. After being multiplied with the stress indices the stresses are used to determine the stress time histories and strain time histories in the locations requested. In these locations the fatigue is separately determined in every direction φ, see figure 2, with help of the following equations:

$$\varepsilon_\varphi = \tfrac{1}{2}\,(\varepsilon_{axial} + \varepsilon_{hoop}) \;+\; \tfrac{1}{2}\,(\varepsilon_{axial} - \varepsilon_{hoop}) \times \cos(2\varphi) \;+\; \tfrac{1}{2}\,\gamma \times \sin(2\varphi)$$

$$\sigma_\varphi = \tfrac{1}{2}\,(\sigma_{axial} + \sigma_{hoop}) \;+\; \tfrac{1}{2}\,(\sigma_{axial} - \sigma_{hoop}) \times \cos(2\varphi) \;+\; \tau \times \sin(2\varphi)$$

RAINFLOW METHOD G

As a starting point both rainflow methods CEN/TC147/WG2 N23 (ISO) and ASTM E1049-85 were investigated. These methods give the same stress and strain cycles but the time information of the cycle is lost. This is a problem with regard to the application of the NUREG CR/6909 procedure that requires a strain based integration over the time. Therefore, based on the aforementioned methods, an adapted method called method G was developed, see figure 3 below.

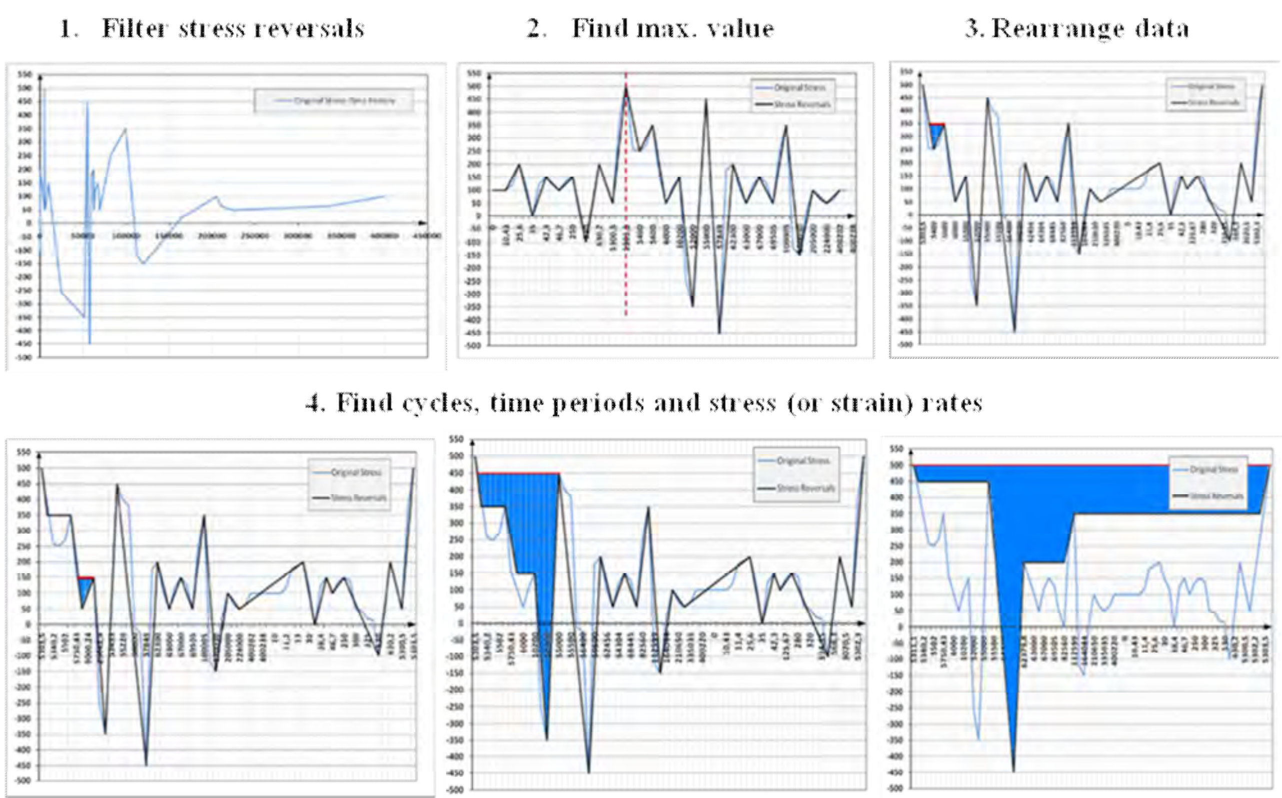

Figure 3. adapted rainflow analysis method, method G.

STRESS BASED METHODS J0, J1 AND J2

Stress cycles are determined with the classic rainflow method CEN/TC149

- **J0**: Fen = 1, environmental effects are not taken into account.

Stress cycles and associated time steps with rainflow analysis procedure G

- **J1**: Fen_i is determined for the whole load cycle i and used for all of its stress cycles *m*
- **J2**: $Fen_{i\text{-}m}$ is determined for every stress cycle *m* based upon the time spans from the rainflow analysis procedure G.

Strain / Fen	Method J1, J2 Stress intensity	Equations used in the flowchart
ε_j	$S_{12} = \sigma_\varphi$ (Inner surface and Fen) $S_{12} = \sigma_\varphi - \sigma_{\varphi+90}$ in case the sign of σ_φ and $\sigma_{\varphi+90}$ is different	$S_{12} = \sigma_\varphi$ ($\Delta\sigma_{rad} \cong 0$) $S_{12} = \sigma_\varphi - \sigma_{\varphi+90}$
ε_{hoop}	$S_{23} = s_{hoop} - s_{radial}$ (Same as $s_{90} - s_{rad}$)	$S_{23} = \sigma_{90} - \sigma_{rad}$
ε_{axial}	$S_{31} = s_{radial} - s_{axial}$ (Same as $s_{rad} - s_0$)	$S_{31} = \sigma_{rad} - \sigma_0$

Table 1, Determination of S_{12}, S_{23} and S_{31} for the stress based methods J0, J1 and J2

STRAIN BASED METHODS V1 AND V2

Strain cycles and associated time steps are determined with rainflow analysis procedure G. At present the strain based methods are used for Fen-analysis:

- **V1**: Fen_i is determined for whole load cycle i and used for all of its strain cycles *m*
- **V2**: $Fen_{i\text{-}m}$ is determined for every strain cycle *m* based upon the time spans from the rainflow analysis procedure G.

Strain / Fen	Method V1, V2: Strain intensity, only when F_{en} is computed	Equations used in the flowchart
ε_{axial}	$S_{31} = \varepsilon_{axial} \times E$	$S_{31} = \varepsilon_0 \times E$
ε_{hoop}	$S_{23} = \varepsilon_{hoop} \times E$	$S_{23} = \varepsilon_{90} \times E$
ε_j	$S_{12} = \varepsilon_j \times E$ ($\Delta\varepsilon_{rad} \cong 0$)	$S_{12} = \varepsilon_j \times E$ ($\Delta\varepsilon_{rad} \cong 0$)

Table 2, Determination of S_{12}, S_{23} and S_{31} for the stress based methods V1 and V2

DETERMINATION ON THE F_{EN}

The following definitions are used:

- $\mathbf{F_{en,k}}$ Instantaneous $\mathbf{F_{en}}$ factor ($\mathbf{F_{en,nom}}$ in [1])
- $\mathbf{F_{en,r}}$ $\mathbf{F_{en}}$ factor for strain rise *r*
- $\mathbf{F_{en,\varphi\_m}}$ $\mathbf{F_{en}}$ factor for stress cycle *m*
- $\mathbf{F_{en,\varphi\_i}}$ $\mathbf{F_{en}}$ factor for load cycle *i*

The main steps of the $\mathbf{F_{en}}$ computations for the considered strain history are computation of $\mathbf{F_{en,k}}$ values, computation of $\mathbf{F_{en,r}}$ values and finally computation of final Fen values $\mathbf{F_{en,\varphi\_m}}$ or $\mathbf{F_{en,\varphi\_i}}$. The instantaneous $\mathbf{F_{en,k}}$ value for a time step k and time interval $t_1 \ldots t_2$ is calculated with the NUREG/CR-6909 Appendix A Equations (A.2) ... (A.18), where:

Strain increase	$\Delta\varepsilon_k = \varepsilon_2 - \varepsilon_1$
Strain rate	$\dot{\varepsilon}_k = \Delta\varepsilon_k / (t_2 - t_1) > 0$
Inner surface temp.	$T_k = \max[T_1, T_2]$
Dissolved oxygen level	$O_k = \max[O_1, O_2]$
Sulfur content	S

For austenitic stainless steels: $F_{en,k} = \exp(0.734 - T'\ O'\ \dot{\varepsilon}')$

F_{en} for one strain rise, $F_{en,r}$ is determined from eq. (30) [1]: $F_{en,r} = \sum_{k=1}^{n} F_{en,k}(\dot{\varepsilon}_k, T_k) \dfrac{\Delta\varepsilon_k}{\varepsilon_{max} - (\varepsilon_{min} + \varepsilon_{th})}$

According to [17] the F_{en} factor for one stress cycle or for the whole load history, $F_{en,\varphi}$ is calculated as:

$$F_{en,\varphi,m} \text{ or } F_{en,\varphi,i} = \frac{\sum (F_{en,r} \times (\varepsilon_{max,r} - (\varepsilon_{min,r} + \varepsilon_{th}))}{\sum (\varepsilon_{max,r} - (\varepsilon_{min,r} + \varepsilon_{th}))}$$

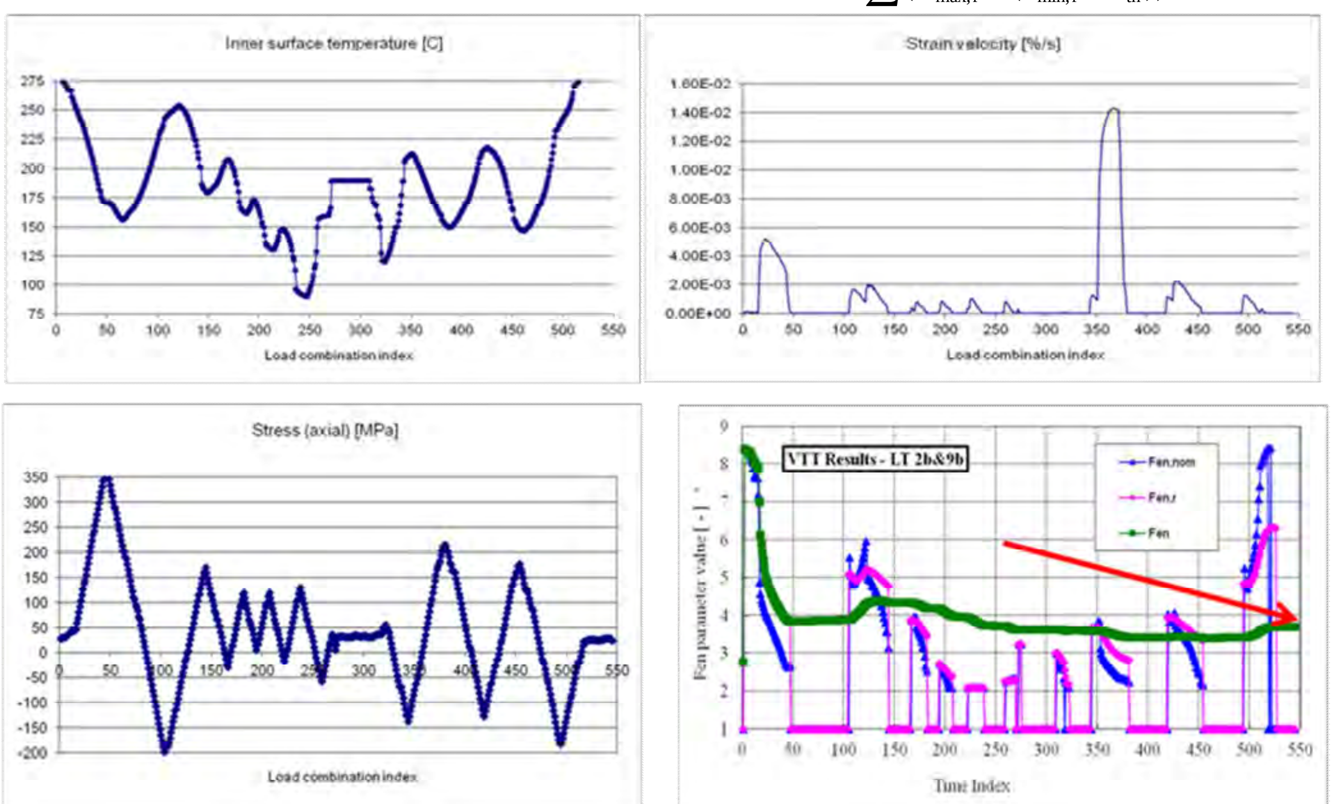

Figure 4, Determination of the Fen factor for method V2.

RESULT PRESENTATION

Below some results are summarized for the ASME NB-3650M cumulative usage factor analysis for Node ID 69 (Weld1.312-3 9B) and for Method V2. Cumulative usage factor is calculated for each circumferential angle θ, at inside/outside surface and for direction angle φ:

POINT 5 MEMBER 1 NODE 2
SUMMARY OF LOCAL USAGE FACTORS ALONG CIRCUMFERENCE:

ANGLE [deg.]	SURFACE	USAGE FACTOR	TOTAL NUMBER OF STRESS CYCLES	MAX RANGE [MPa]	FOR STRESS DIFFERENCE	ANGLE [deg]
0.00	IN	0.305261	12279	994.06	S12	0
0.00	IN	0.273361	12274	977.28	S12	15
....						
150.00	IN	0.383262	12879	1049.90	S12	0
150.00	IN	0.341927	12809	1031.94	S12	15
150.00	IN	0.282664	12656	968.60	S12	30
....						
150.00	OUT	0.067687	12266	638.44	S12	0
150.00	OUT	0.054845	12266	606.19	S12	15
....						
LOCATION WITH MAX. USAGE FACTOR:						
150.00	IN	.383262	12879	1049.90	S12	0

*** NB-3650M TOTAL USAGE FACTOR 0.383262 = Uen = U * Fen= 0.155090 * 2.47

Below a more detailed result listing for the ASME NB-3650M total usage factor calculation for Node ID 69 (Weld1.312-3 9B) and for Method V2: Circumferential angle θ = 150°, Inside surface, Stress Intensity S12, Direction angle φ = 0° is presented.

POINT 5 MEMBER 1 NODE 2 ANGLE **150. deg., INSIDE,** RADIUS 146.25 mm

LOCATION WITH MAX. USAGE FACTOR:FATIGUE FACTOR Fen CALCULATIONS V2 FOR STEEL TYPE MCUR=12:AUSTENITIC STAINLESS NUREG/CR-6909 IDENTIFICATION OF STRESS INTENSITY **S12** CYCLES BY HYSTERESIS COUNTING (RAINFLOW)Ke = ELASTIC-PLASTIC FACTOR USED WHEN RANGE EXCEEDS 3*Sm

LOAD SET INDEX	PAIR INDEX	STRESS RANGE	STRESS CYCLES	CYCLES ALLOWABLE	Ke	Fen	USAGE FACTORS INCREMENT W/O FEN	CUMULATIVE FEN INCLUDED
344	7346	14.68	290	99999999	1.00	1.00	0.000000	0.000000
50	84	41.62	290	99999999	1.00	1.00	0.000000	0.000000
307	328	96.44	290	99999999	1.00	1.00	0.000000	0.000000
....								
5121	5160	364.62	280	143095	1.00	9.58	0.001957	0.144635
4692	5028	1049.90	280	3045	1.00	2.59	0.091954	0.382880
5840	5941	526.22	5	33618	1.00	1.00	0.000149	0.383028
6629	6705	384.45	25	112363	1.00	1.00	0.000222	0.383251
7003	7052	200.69	100	9130375	1.00	1.00	0.000011	0.383262

END OF TABLE

*** NB-3650M TOTAL USAGE FACTOR 0.383262 = Uen = U * Fen= 0.155090 * 2.47

The actual documentation will be made directly from the PAMS database system with a postprocessor program that is designed to fill a template report with tables, figures and pieces of text while taking care of the index and source reference lists [13], [14] and [15].

FUTURE DEVELOPMENT

In the future the following items will be studied:

1. Simplify and improve the consistency in the determination of the stress intensities, as well with regard to the procedure used as to the type of fatigue testing behind the procedure.
2. Investigate the influence of the temperature used in the different parts of the different analysis steps to make the use of the temperature as consistent as possible, see table 3 below.

Calculation Step	Classic ASME NB-3600	ASME NB-3650M
FPIPE forces and moments	$E = E_h$: Max. T_{ave} for the transient α : T_{ave} for load case at current time	Same
1-D Thermal shock analysis (in FPIPE and ASME NB)	λ : T_{ave} C_p : T_{ave}	Same
Stress components from thermal gradients	E: At room temperature (T_{room} = 20 °C) α: At room temperature (T_{room} = 20 °C)	E : $(T_{in} + T_{out}) / 2$ α : $T_{integ\_location}$ or $(T_{in} + T_{out}) / 2$
K_e factor	S_m : Max. T_{ave} for the loadset pair	Same
Design fatigue curve correction factor (E_{design}/ E_c)	E_{design} : For design fatigue curve E_c : At cold state (T_c = ?)	Same
Stress Ratchet check	S_y : average T_{in}	Same
Discontinuity stress	E: At room temperature (T_{room} = 20 °C) α: At room temperature (T_{room} = 20 °C)	E_a : T_{ave_a} and E_b : T_{ave_b} ν_a : T_{ave_a} and ν_b : T_{ave_b} α_a : T_{ave_a} and α_b : T_{ave_b}
Fen,k	-	T^* : Max. $\{T_{in\_time\_1}, T_{in\_time\_2}\}$
Strain φ	-	E : $(T_{in} + T_{out}) / 2$ ν : $(T_{in} + T_{out}) / 2$
Stress Intensities	-	E : $(T_{in} + T_{out}) / 2$

Table 3, Influence of the temperature used in the different parts of the different analysis steps

3. EPRI Report[9] presents an improved approach to perform simplified elastic-plastic fatigue analysis by analytical equations. This could be incorporated into ASME NB-3650M fatigue analysis method.

CONCLUSIONS

The system is now taken into use and compared with elder analyses without Fen. The increase of the cumulative usage is moderate depending on the chosen analysis method. The most consistent method is method V2. This is a consistent strain based method that determines the Fen for every separate strain cycle. Comparison between the classic method and the V2 method showed that increase appears only in a few locations. The number of performed analyses is however not yet large enough to draw any general conclusions. It seems that the extra overconservatism induced by the NUREG/CR-6909 is compensated by the more accurate and less overconservative analysis by the new methodology. When looking at the low cycle fatigue induced crack records in the nuclear world this is a good thing.

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