Strål
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Swedish Radiation Safety Authority

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Research

2011:30

A fatigue analysis including environmental effects for a pipe system in a Swedish BWR

Report number: 2011:30 ISSN: 2000-0456
Available at www.stralsakerhetsmyndigheten.se

SSM perspective

Background

The effect of the environment on fatigue design has been the subject of intense study in USA, Japan and elsewhere. Several reports indicate a potentially large influence of the environment, leading to the proposal of entirely new analysis procedures. SSM has in an earlier project sponsored research to evaluate the technical basis for these proposals, see SSM Research Report 2011:04. In the current report, the consequences for a Swedish BWR piping system are evaluated using the new analysis procedure including environmental effects on fatigue.

Objectives

The principal objective of the project has been to find out the consequences for a Swedish BWR piping system using the new analysis procedure to include environmental effects on fatigue. Another objective has been to find out how well the commercial code Pipestress can handle environmental effects on fatigue.

Results

- Introducing the new NUREG/CR-6909 procedure in fatigue assessments will add substantial complexity to the analysis procedure.
- The stainless steel pipe system, with moderate usage factor U = 0.2, will have a usage factor of 0.9 after 60 years when both a new fatigue curve and an environmental correction factor Fen are considered.
- If maximum temperatures are combined with average strain rates the correlation between the results from Pipestress and the detailed method is quite good. Conservatism in relation to the detailed method is obtained if lower bound strain rates are used as input instead of mean values.
- The model examples show the importance of the temperature values for the computed Fen values. The strain rate is of less importance, however not negligible.
- The environmental factors were larger for the ferritic steel piping than for the austenitic steel piping by a factor to the order of 2-2.5 for identical transients.
- Pipestress, with its current implementation for environmental factors, should not be used as a research tool for environmental effects on fatigue. However, Pipestress can be used as an effective tool for considering environmental effects in an engineering fatigue analysis of piping systems. It is then recommended that the maximum transient temperature is always chosen for input.

Need for further research

The results are important in order to make relevant fatigue assessments of nuclear components in reactor water environments. More research is needed for the further investigation of the best way to include environmental effects in fatigue analysis, both for design and for evaluating the risk of fatigue failure of ageing nuclear components.

Project information

Contact person SSM: Björn Brickstad
Reference: SSM 2009/4145, SSM 2010/3296

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Table of content

1. Summary

A BWR feed water piping system (austenitic steel) has been analyzed with two different fatigue curves and environmental factors. Original fatigue curve from ASME is compared to a new fatigue curve; ANL. The influence of environmental correction factors (F_{en}) is studied further for the piping system. It is noted that the results apply for this particular system, and general conclusions should be cautiously drawn. Typical for this system is that all dominant loads are within the low-cycle regime. This implies that the change of fatigue curve only leads to limited increases in usage factors. Larger changes can occur if larger number of cycles is within the high-cycle regime.

- The new fatigue curve ANL increases the usage factor to the order of 50-100% for a system with dominant low cycle fatigue
- The influence of the environmental correction factor is substantial, about 300% on the usage factor
- The results indicate that the environmental factor should be fairly independent of the location in the system. This result is of practical importance, but should however need further study to be confirmed.
- Combining the two effects, this system with moderate usage factor U=0.2, will have a usage factor of 0.9 after 60 years.
- Introducing the NUREG/CR-6909 procedure in fatigue assessments will add substantial complexity to the calculation procedure.

Implementation of the procedure in commercial codes would be very helpful. However, the procedure is not clearly described. Hence, the implementation should be examined closely and evaluated before being universally introduced in applications.

Therefore, the implementation for the environmental factor, F_{en}, in the commercial analysis program Pipestress has been investigated in an appendix to the present report. The investigation was carried out by analysis with three transients on a model piping system. The Pipestress results were compared with results obtained by the detailed procedure, based on the instructions in NUREG/CR-6909. The comparisons were performed for austenitic and ferritic steels.

- The implementation of the environmental factor computation in Pipestress is simple. No detailed integration with time varying parameters is performed. Instead all parameters remain constant throughout the transients.
- The parameter values are given as default by Pipestress unless other values are provided by the analyst.
- The comparison shows that these constant parameter values for Pipestress must be chosen with care in order to obtain results comparable to those obtained by the detailed calculations.
- Calculations with mean transient temperature values as input should be avoided, since the environmental factors tend to become significantly low-

er than the values derived by the detailed calculations. Instead maximum transient temperatures should be used as input.

- If maximum temperatures are combined with average strain rates the correlation between Pipestress and the detailed method is surprisingly good. Clear conservatism in relation to the detailed method is obtained if lower bound strain rates are used as input instead of mean values.
- These model examples show the importance of the temperature values for the computed F_{en} values.
- The strain rate is of less importance, however not negligible.
- The local stress indices K_3, raise the stress ranges up to three times the value for a straight pipe. However, this only results in 15-30 % increase of the F_{en} value. Hence, the computed F_{en} is fairly independent of the component type.
- The environmental factors were larger for the ferritic steel piping than for the austenitic steel piping by a factor to the order of 2-2.5 for identical transients.

Pipestress with its current implementation for environmental factors should not be used as a research tool for environmental effects. However, Pipestress can be used as an effective tool for considering environmental effects in the engineering analysis of piping systems. It is recommended that the maximum transient temperature is always chosen for input.

2. ANL vs. ASME

A Swedish class 1 BWR feed water piping system has been analyzed for 60 years of operation. The piping system is made of conventional austenitic stainless steel. The pipe system is originally modeled with Pipestress /3/ and the fatigue calculation in Pipestress is based on a fatigue curve from ASME. A new fatigue curve, ANL, from NUREG/CR-6909 /1/ is proposed that has a factor 12 on life and 2 on stress versus the ASME curve that has a factor of 20 on life and 2 on stress. Moreover, the mean data differ between the two design curves, which leads to the significant difference in the high cycle regime. See Figure 1 where the two fatigue curves are compared.

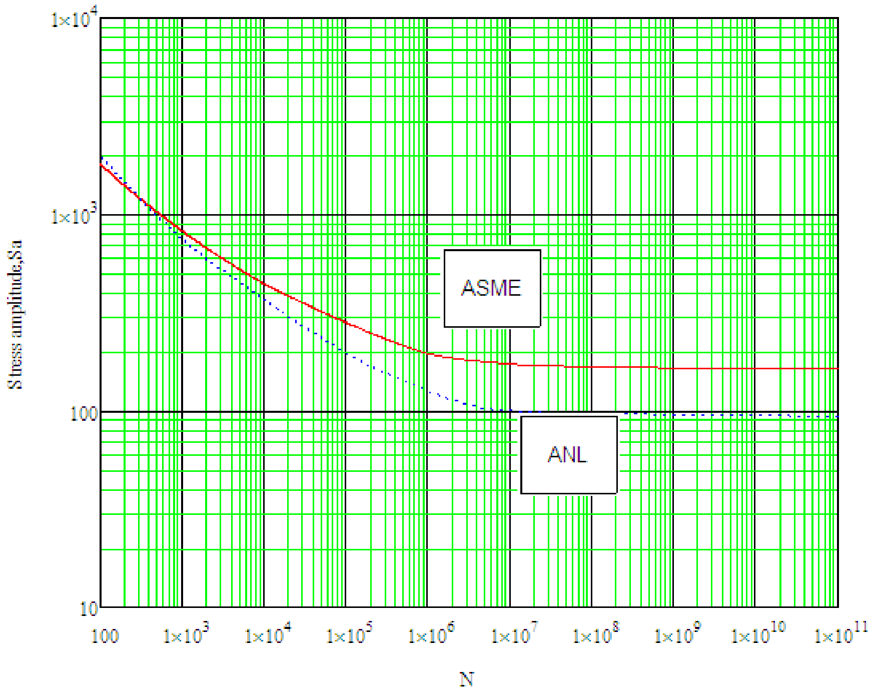

Figure 1: ASME compared to ANL fatigue curve

In all cases of fatigue calculations the ANL curve will lead to a higher usage factor than the ASME curve, see Figure 2 and Figure 3. The impact is most prominent for lower loads, but also for lower usage factors. The usage factors are increased to order of 50% -100% for all the fatigue limiting locations. The majority of the fatigue load is within the low-cycle fatigue regime.

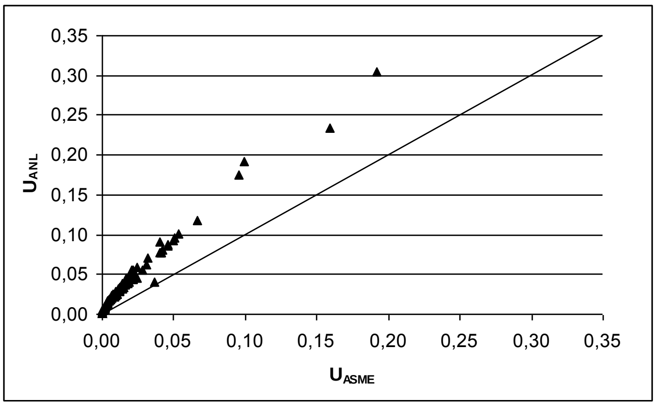

Figure 2: Usage factor of ASME vs. usage factor of ANL

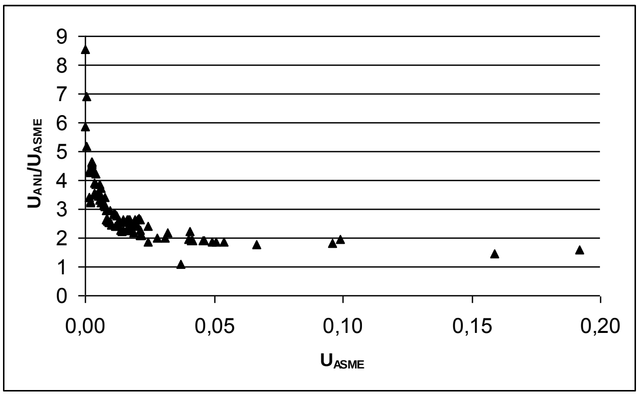

Figure 3: Usage factor of ASME vs. the ratio of usage factors of ANL and ASME

3. Environmental fatigue life correction factor (F_{en})

3.1. The method of computing F_{en} and the usage factor

Appendix A in NUREG /1/ describes how to calculate F_{en}. Several simplified methods (presumably more conservative) exist, but Inspecta has chosen to use the most detailed method. For a transient the nominal $F_{en,nom}$ is calculated for every time step in the transient.

$$F_{en,nom} = \exp(0{,}734 - T'O'\dot{\varepsilon}') \qquad (1)$$

For the whole transient the F_{en} is calculated with the modified rate approach /1/.

$$F_{en} = \sum_{k=1}^{n} F_{en,k}(\dot{\varepsilon}_k, T_k) \frac{\Delta\varepsilon_k}{\varepsilon_{\max} - \varepsilon_{\min}} \qquad (2)$$

The environmental correction factor changes with temperature and strain rate, see Figure 4. The value of F_{en} is sensitive to temperature especially at low strain rate. Also it can be noticed is that the F_{en} is discontinuous, i.e. jumps from 1 to 2.08 as soon as the conditions applies.

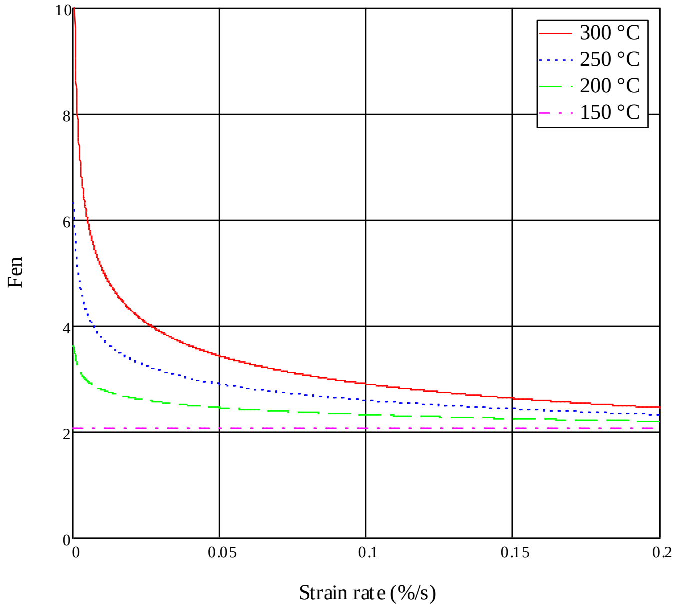

Figure 4: F_{en} as a function of different temperatures and strain rate

The procedure for calculating F_{en} in real cases needs some clarifications. As indicated by Eqn. 1, F_{en} is obtained by integrating over the strain. A unique value of F_{en} is obtained for each stress range. See the example in Figure 5 and Equation 3. The combination of the two transients in the figure sums up to two strain ranges, $\Delta\varepsilon = \varepsilon_2 - \varepsilon_5$ and $\Delta\varepsilon = \varepsilon_7 - \varepsilon_3$. (It is assumed, for simplicity, that the strain levels at 1, 4 and 6 are the same.) The cycle counting follows the procedure in ASME III /4/.

$$F_{en5-2} = \left(\sum_{\text{point5}}^{\text{point6}} F_{en,k}(T',\dot{\varepsilon}') + \sum_{\text{point1}}^{\text{point2}} F_{en,k}(T',\dot{\varepsilon}')\right)\frac{\Delta\varepsilon_k}{\varepsilon_2 - \varepsilon_5} = \tag{3}$$
$$= \frac{1}{\varepsilon_2 - \varepsilon_5}\left(F_{en1-2} \times (\varepsilon_2 - \varepsilon_1) + F_{en5-6} \times (\varepsilon_6 - \varepsilon_5)\right) = F_{en,1}$$

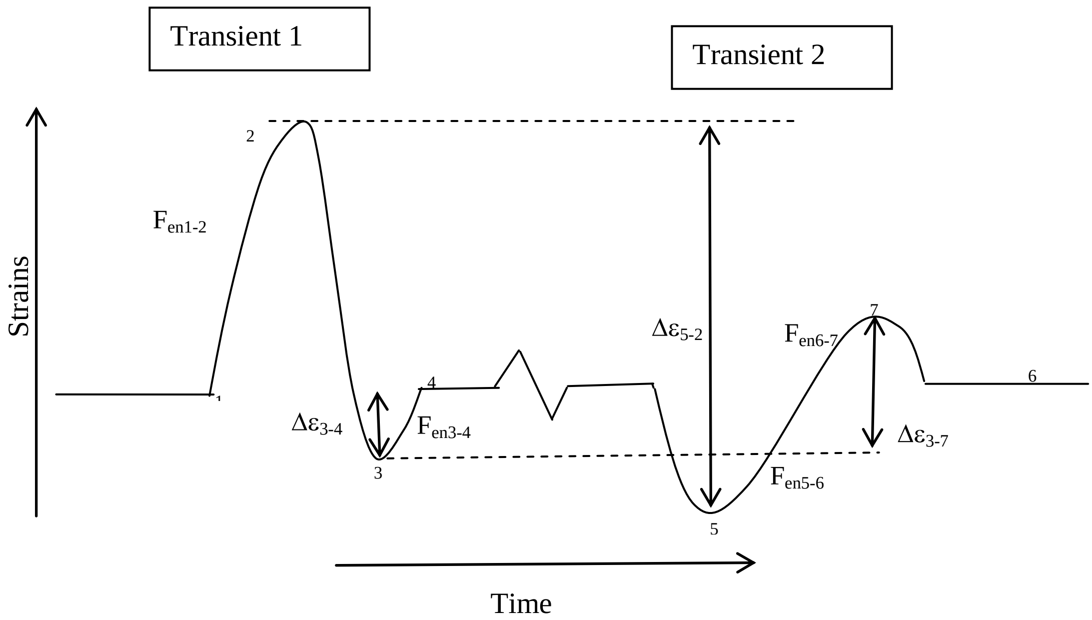

Figure 5: Two transients, strain as a function of time

Finally to evaluate the usage factor the sum of all usage factors on two transients together are multiplied with the F_{en} for that combination of transient.

$$U_{en} = U_1 \cdot F_{en,1} + U_2 \cdot F_{en,2} + U_3 \cdot F_{en,3} + U_i \cdot F_{en,i} .... + U_n \cdot F_{en,n} \tag{4}$$

See for example Asada /2/ for a more comprehensive description of the procedure. The procedure used by Inspecta follows Asada and should be in agreement with international praxis. This has been confirmed in communication with other international organizations (NRC, TVO, etc,) involved in the study of environmental effects.

3.2. F_{en} applied on a realistic BWR system with the NUREG 6909 method

Current fatigue tools are not well suited for computing F_{en}. For this case the strain rate is needed and that information is not accessible from Pipestress /3/ directly, in the revision available for Inspecta Technology during this work. Therefore ANSYS is used for modeling of the through the wall temperature gradient and extracting the corresponding stresses. Moment stresses are obtained by scaling the maximum moment, under the assumption that the moment stresses vary linearly with the average wall temperature. The stresses due to the pressure are obtained directly from the pressure given in the load definition.

The node in the pipe system that had the highest usage factor is studied further. At the node F_{en} was computed for the dominant transients. This node has a computed usage factor from Pipestress /3/; $U_{ASME}=0.2$ and with the ANL curve the usage factor gave; $U_{ANL}=0.3$.
Pipestress /3/ gives usage factor for two transients together. These transients are simulated with a small axisymmetric straight pipe model in ANSYS.
Only temperature transients are modeled with ANSYS. The stress from pressure is calculated separately and stress from moment is calculated by linearization. For a linear transient in temperature a certain value for the moment is obtained from Pipestress /3/ that will give a linear response in accordance to the mean temperature in the pipe model. The sum of stresses from thermal, moment and pressure are used to calculate the total strain, and from that the strain rate is obtained, see equations (5) and (6). Figure 6 shows a transient combination and Figure 7 shows the strain vs. time for that specific transient combination.

$$\varepsilon_{total} = \frac{\sigma_{thermal} + \sigma_{moment} + \sigma_{pressure}}{E} \tag{5}$$

$$\dot{\varepsilon}_{total} = \frac{\Delta\varepsilon_{total}}{\Delta t} \tag{6}$$

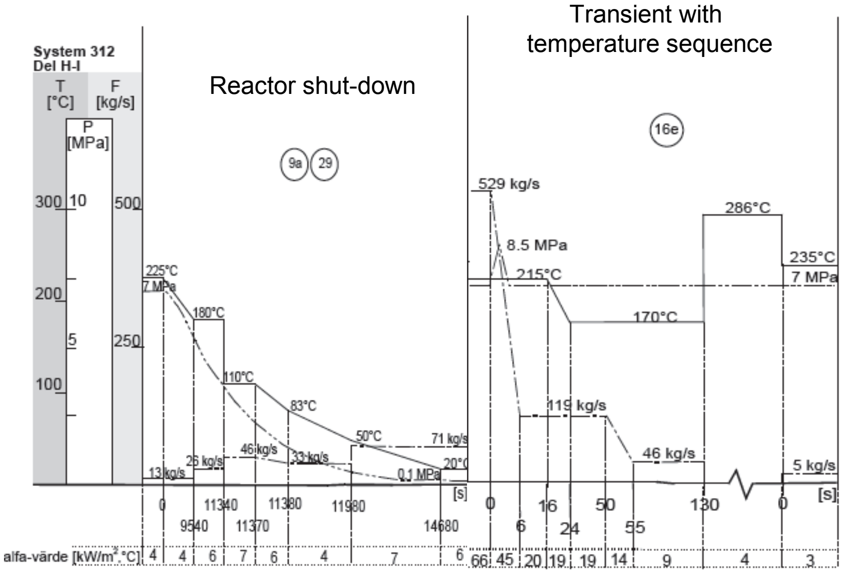

Figure 6: Transients 9a29 and 16e, that combine to Fatigue cycle 6.

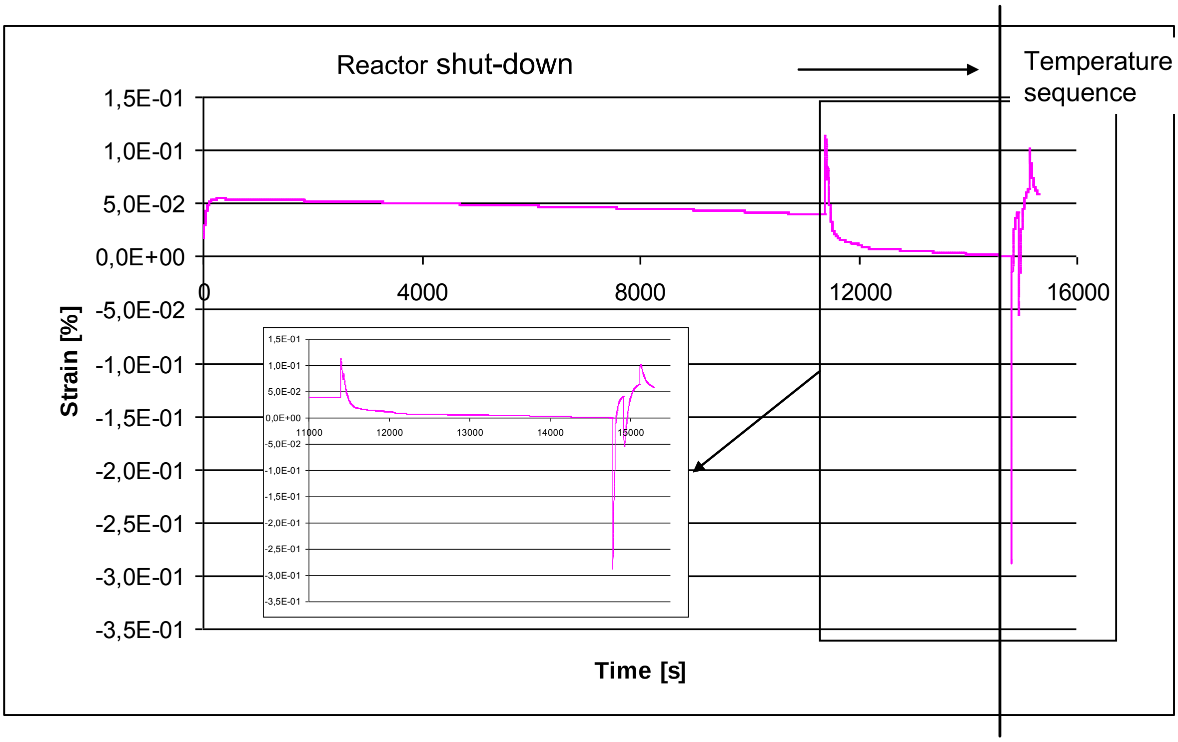

Figure 7: Time vs. strain (Transients 9a29 and 16e), Fatigue cycle 6

Many of the fatigue cycles that are applied, see Table 1**,** have the 16c transient that gives about 4 in the F_{en} value. The other fatigue cycles that also results in a higher value of F_{en} is cycle 2 (transient 9a29 and 16f) and cycle 27 (transient 16e and 16d). They give a F_{en} little over 4. Other transient combinations do not give as high value for F_{en}.

Table 1: The usage factor (ANL) corrected for environment.

Fatigue cycle	**U_{ANL}**	**F_{en}**	**U_{ANL}*F_{en}**
1	0.057	2.15	0.123
2	0.028	4.12	0.115
3	0.016	3.07	0.049
4	0.004	2.85	0.012
5	0.004	3.9	0.014
6	0.093	2.77	0.258
7	0.006	2.6	0.014
8	0.005	4	0.019
9	0.001	1	0.001
10	0.001	1	0.001
11	0.001	1	0.001
12	0.016	4	0.064
13	0.008	4	0.034
14	0.002	1	0.002
15	0.001	1	0.001
16	0.005	4.01	0.019
17	0.013	2.45	0.032
18	0.012	2.77	0.033
19	0.002	1	0.002
20	0.002	1	0.002
21	0.007	4.01	0.029
22	0.001	1	0.001
23	0.001	1	0.001
24	0.001	1	0.001
25	0.001	1	0.001
26	0.004	3.9	0.016
27	0.004	4.5	0.017
28	0.004	2.53	0.011
	0.3		0.9

The F_{en} factors for these dominant fatigue cycles give an increase about 215 – 450 %. The total usage factor will increase by a factor of 300 %, so the usage factor will be around 0.9. Note that the F_{en} has only been calculated for the dominant transients, colored green, the others are assumed to have negligible influence on F_{en}. Inspectas results have been shown to representatives from NRC (USA) and TVO (Finland, together with VTT), which have performed previous studies on environmental factors. When compared to other international studies on the environmental factor, it shows similar results for the value of F_{en}. Note that Inspecta computed F_{en} independently, separated from the stress ranges in Pipestress. Hence, the stress ranges in Inspectas computations and Pipestress may differ, at least slightly. In order to examine this, a stress raise factor, K, was applied to the total stress range. The calculations on F_{en} value are done with K factor equal to one. When calculating the F_{en} value with $K=2$, F_{en} decreases 7 %. Hence doubling the stress range had no substantial influence in this case. This indicates that the value of F_{en} should be rather independent of the location in the piping system. This should, however, need a further study to be confirmed.

It is of interest to see what is contributing to high F_{en} values as in fatigue cycle 13. In Figures 8 - 11, F_{en} and other contributing factors are graphically displayed. See Figure 8 and Figure 9 for the strain and temperature interaction. Note how the strain increases with increased temperature and then how the strain rapidly increases when the temperature drops from 286 to 250 ˚C. In Figure 10 and Figure 11 the environmental factor, F_{en} is plotted against the strain rate and the temperature and one can see how they affect the value of F_{en}. The strain rate, temperature and F_{en} are connected by equation (1)

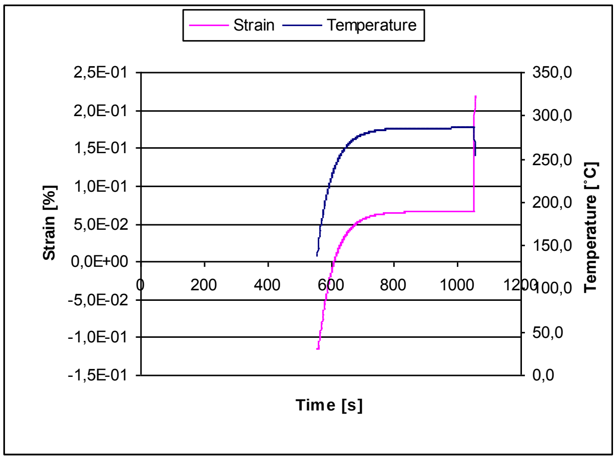

Figure 8: Strain and temperature vs. time, only for the calculated time step that produces F_{en}

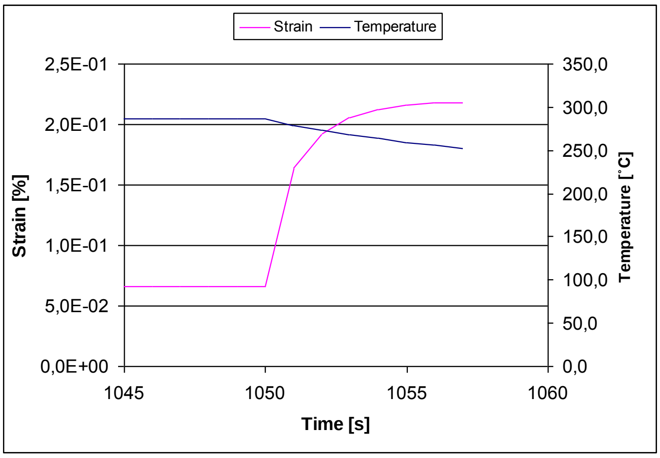

Figure 9: Strain and temperature vs. time, when the temperature drops from 286 to 250 ˚C

A closer look at Figure 10 and Figure 11 tells that there are three significant changes of F_{en}, initial increase, thereafter decrease and final increase. There is an initial increase in temperature and a small decrease in strain rate till the F_{en} value has reached its maximum value. Thereafter F_{en} decreases, probably due to the increase in strain rate. The final increase of F_{en} seems to depend primarily on the strain rate decrease. These figures readily show how the parameters temperature and strain rate simultaneously affect the value of F_{en}.

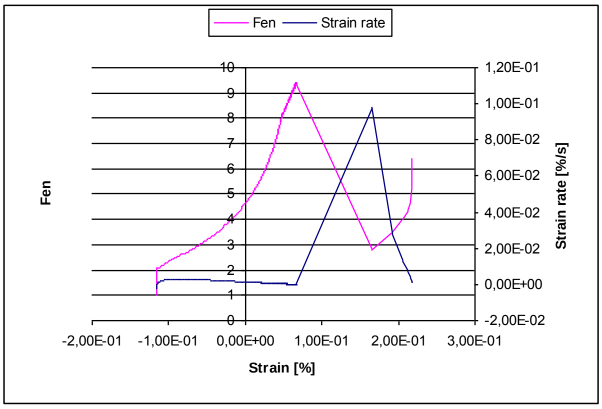

Figure 10: F_{en} and strain rate vs. strain

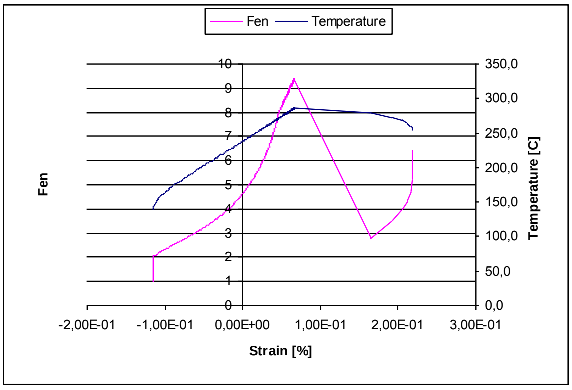

Figure 11: F_{en} and temperature vs. strain

4. Conclusions

It is noted that the results apply for this particular system, and general conclusions should be cautiously drawn. Typical for this system is that all dominant loads are within the low-cycle regime. This implies that the change of fatigue curve only leads to limited increases in usage factors. Larger changes can occur if larger number of cycles is within the high-cycle regime.

- The new fatigue curve ANL increases the usage factor to the order of 50-100% for a system with dominant low cycle fatigue
- The influence of the environmental correction factor is substantial, about 300% on the usage factor
- The results indicate that the environmental factor should be fairly independent of the location in the system. This result is of practical importance, but should however need further study to be confirmed.
- Combining the two effects, this system with moderate usage factor U=0.2, will have a usage factor of 0.9 after 60 years.
- Introducing the NUREG 6909 procedure in fatigue assessments will add substantial complexity to the calculation procedure.
- Implementation of the procedure in commercial codes would be very helpful. However, the procedure is not clearly described. Hence, the implementation should be examined closely and evaluated before being universally introduced in applications.

5. References

/1/ Chopra, O. K, Shack, W. J., *Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials*, NUREG/CR-6909, ANL-06/08, 2007.

/2/ Asada, S., *Proposal for determination of strain rate in environmental fatigue correction evaluation*, Proceedings of the ASME 2009 Pressure Vessels and Piping Division Conference, 2009.

/3/ Pipestress, DST, Version 3.5.1.

/4/ ASME Boiler & Pressure Vessel Code, ASME III, Division 1, 2007.

Appendix A

Pipestress

An evaluation of the fatigue life environmental factor

A1. Nomenclature

D	Diameter of pipe
E	Young's modulus
ε	Strain
$\dot{\varepsilon}'$	Transformed strain rate
F_{en}	Environmental correction factor
O'	Transformed oxygen level
S'	Transformed sulfur content
t	Wall thickness of pipe
T'	Transformed temperature
U	Usage factor
ν	Poisson's ratio
α	Expansion coefficient
λ	Thermal conductivity
C_v	Thermal Capacity
h	Heat transfer number

A2. Pipe system and loading

A2.1. Pipe system

A model pipe system is developed for the analysis of environmental effects. The model system contains several of typical piping components such as elbows and tee junctions and should be fairly realistic.

The diameter D and the thickness t is the same for the whole system, D = 323.9 mm and t = 17.5 mm. The internal pressure is *7 MPa* at all time and two different materials are tested; austenitic steel, 1.4306 and ferritic steel, 15Mo3. The pipe system is presented in Figure A1.

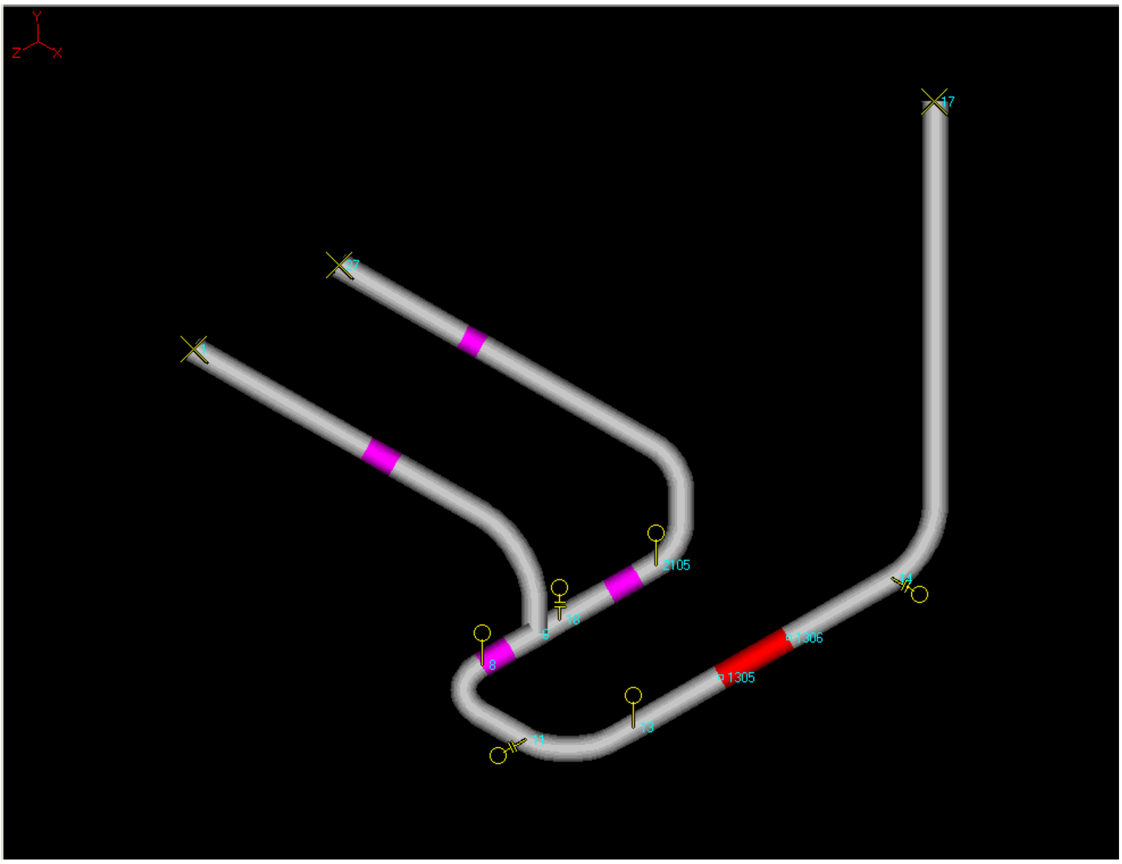

Figure A1: The pipe system in Pipestress

A2.2. Load cases

Three different transients are defined and applied to the model pipe system. The transients are chosen to have different characteristics in terms of strain rate and temperature. Transient 1 and 3 is rapid whereas transient 2 is considerably slower. Moreover, transient 3 covers a larger temperature range and thus passes over the temperature threshold at 150 °C. The transients are illustrated in Figure A2:.

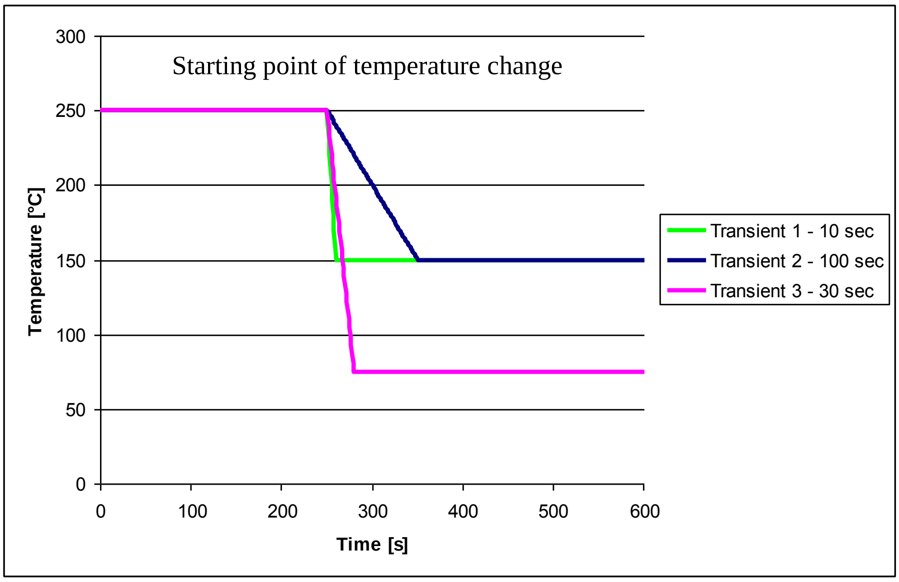

Figure A2: Three different transients that are applied at the pipe system

- Transient 1: Temperature drops from 250°C to 150°C in 10 seconds
- Transient 2: Temperature drops from 250°C to 150°C in 100 seconds
- Transient 3: Temperature drops from 250°C to 75°C in 30 seconds

Since Pipestress needs transients to be combined in pairs and allow the comparison for full fatigue cycles each transient is input in pairs, i. e. in full temperature cycles. This means that the temperature change displayed in Figure A2 is first applied, thereafter the temperature is held at steady state for a longer time, and finally the temperature is returned to the originating temperature (by mirroring the temperature change in Figure A2:). This is illustrated for transient 2 in Figure A3, which shows the pipe response to the applied transient.

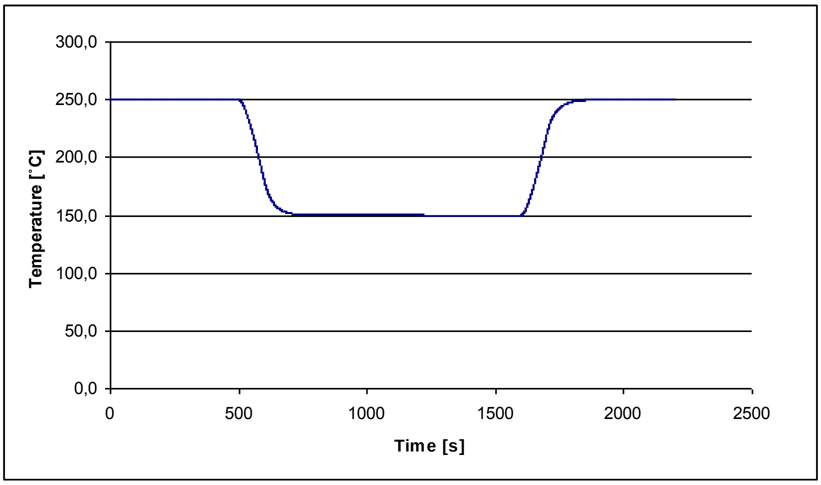

Figure A3: Transient pair 2 - the temperature drops from 250 °C to 150 °C and then reversed.

The pressure is kept constant and will have no influence on environmental factors and stress ranges. All analyses are fully elastic.

A3. Environmental fatigue life correction factor (F_{en})

A3.1. The Inspecta method of computing F_{en} and the usage factor according to NUREG/CR-6909

Appendix A in NUREG/CR-6909 /A3/ describes how to calculate F_{en}. For a transient the nominal F_{en} is calculated for every time step in the transient.

$$F_{en,nom} = \exp(0.734 - T'O'\dot{\varepsilon}') \qquad \textit{(austenitic)} \qquad \text{(A1)}$$

The parameters T', O' and $\dot{\varepsilon}'$ are transformed temperature, strain rate, and dissolved oxygen, DO, defined as

$T' = 0$	if $T \leq 150°C$
$T' = (T - 150)/175$	if $150°C < T < 325°C$
$T' = 1$	if $T > 325°C$
$O' = 0.281$	all DO levels
$\dot{\varepsilon}' = 0$	if $\dot{\varepsilon} > 0.4$ %/s
$\dot{\varepsilon}' = \ln(\dot{\varepsilon}/0.4)$	if $0.0004 \leq \dot{\varepsilon} \leq 0.4$ %/s
$\dot{\varepsilon}' = \ln(0.0004/0.4)$	if $\dot{\varepsilon} < 0.0004$ %/s.

$$F_{en,nom} = \exp(0.632 - 0.101S'T'O'\dot{\varepsilon}') \qquad \textit{(ferritic)} \qquad \text{(A2)}$$

The parameters are dependent on dissolved oxygen content in the water, DO, the sulphur content in the steel, S, the temperature, T and the strain rate, $\dot{\varepsilon}$, defined as

$S' = 0.015$	if $DO > 1.0$ ppm
$S' = 0.001$	if $DO \leq 1.0$ ppm and $S \leq 0.001$ wt.%
$S' = S$	if $DO \leq 1.0$ ppm and $0.001 < S \leq 0.015$ wt.%
$S' = 0.015$	if $DO \leq 1.0$ ppm and $S > 0.15$ wt.%
$T' = 0$	if $T \leq 150°C$
$T' = T - 150$	if $150°C < T < 350°C$
$O' = 0$	if $DO \leq 0.04$ ppm
$O' = \ln(DO/0.04)$	if 0.04 ppm $< DO \leq 0.5$ ppm
$O' = \ln(12.5)$	if $DO > 0.5$ ppm

$$\dot{\varepsilon}' = 0 \qquad \text{if } \dot{\varepsilon} > 1\%/\text{s}$$
$$\dot{\varepsilon}' = \ln(\dot{\varepsilon}) \qquad \text{if } 0.001 \le \dot{\varepsilon} \le 1\%/\text{s}$$
$$\dot{\varepsilon}' = \ln(0.001) \qquad \text{if } \dot{\varepsilon} < 0.001\ \%/\text{s}.$$

The modified rate approach /A3/ for calculating F_{en} is assumed to be the most accurate method in that it integrates over each time in the transient and thus takes instant temperatures and strain rates into account.

$$F_{en} = \sum_{k=1}^{n} F_{en,k}(\dot{\varepsilon}_k, T_k) \frac{\Delta\varepsilon_k}{\varepsilon_{max} - \varepsilon_{min}} \qquad \text{(A3)}$$

It is a prerequisite for environmental effects to be active that the strain rate is positive. Negative strain rate is assumed to give no contribution to the environmental effects.

The expression in equation (A3) is then integrated over the strain and a unique value of F_{en} is obtained for each stress cycle. These values then give a representative value of F_{en} for the transients to enable a direct comparison with Pipestress. The method has a threshold value that is defined for a stress amplitude, the limit is 195 MPa for Austenitic steel and 145 MPa for Ferritic. Below that value the F_{en} factor will result as 1.

A more precise description of the detailed method is found in previous works by Inspecta, ref. /A4/. A procedure for the detailed method was implemented by Inspecta. The environmental factor F_{en} is then computed in a stand-alone procedure intended for the environmental factor only. The stress amplitudes are also computed but not intended for design, only for comparison. In this method the influence of the type of component is considered by applying an appropriate stress raise factor, K to the total stress range/amplitude. This factor is generally set to the same as the factor K_3 in equation (A5) below. The computed stress amplitudes will be given for comparison.

A3.2. The method of computing F_{en} and the usage factor according to Pipestress

DST has implemented the requirements of US NRC Regulatory Guide 1.207 /A5/ in version 3.6.2 of the program Pipestress /A1/.

Constant values for F_{en} are used in Pipestress through the entire transient. These values are either user provided or default. The stepwise integration in equation (A3) is not used with Pipestress. Instead, the transformed temperature, strain rate, dissolved oxygen and sulfur content are all held constant over the full transient. Thus, the user has to set appropriate values for each case or use the in-built default values for some of the constants. The default values correspond to the most conservative settings possible, i. e. those that give a high F_{en} as possible.

For the temperature, DST recommends using the average temperature over the load set, the maximum value is considered to be too conservative.

An important observation is that Pipestress will use the same F_{en} over the entire piping system, unless the user provides differentiated parameters for each location.

In the present study, four different Pipestress analyses are performed for each transient, with different parameter value combinations for the strain rate and temperature. For the temperature, the average and maximum temperature will be used.

F_{en} will be computed with two different strain parameter values. The default strain rate in Pipestress represents lower bound strain rates. The other parameter is represented by the average strain rate, which is calculated manually. The average strain rate input is calculated in a simple way based on nominal transient times and stress range. This simple way is used since it requires no detailed modeling of strain rates, which is assumed to be the usual case for a common design situation. Mathematically, the mean strain rate is computed by simply dividing the elastic stress range with the nominal transient time. This will provide an estimate of the average tensile strain rate, see Table A1.

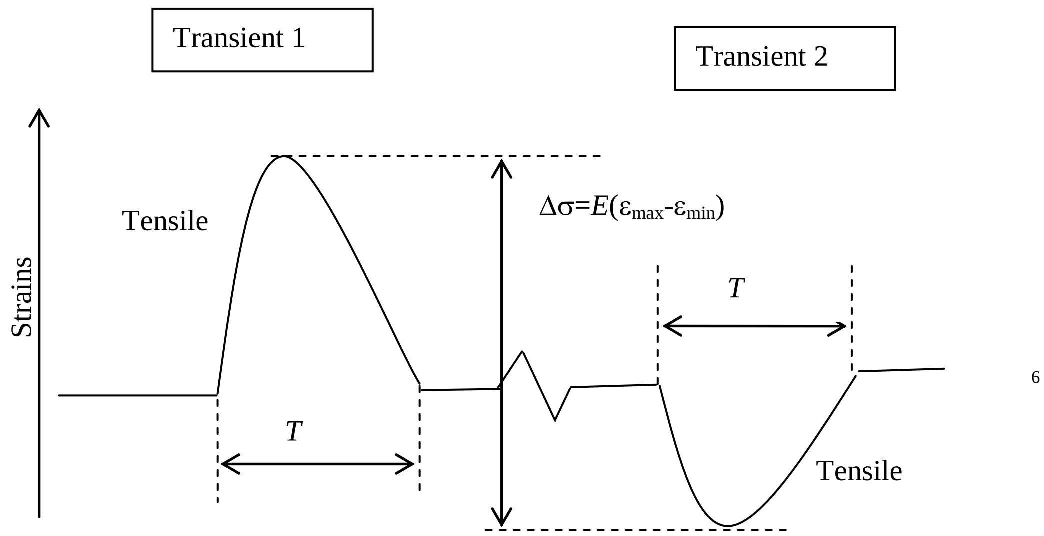

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Figure A4: Figure illustrating how the average tensile strain rate is derived. The stress range is divided by the time, T.

The parameters used in the study are shown in Tables A1-A3. Notably, Table A1 contains those parameters that are varied in order to investigate the results dependency on these parameters.

$$\dot{\varepsilon}_{average} = \frac{\Delta\sigma_{MAX} / E}{T} \qquad \text{(A4)}$$

In this case the transient time, T, will be 10, 100 and 30 seconds for transient 1,2 and 3 respectively.

Table A1: Parameter set up combination for Pipestress

Pipestress parameter set-up combination	Strain rate	Temperature	DO (Ferritic material only)	S (Ferritic material only)
A (def st, mean T)	0,0004%/s (Default)	Mean, see Table A2-A3	0.4 ppm (Default)	0.015 weight % (Default)
B (var st, mean T)	Transient average, see Table A2-A3	Mean, see Table A2-A3	0.4 ppm (Default)	0.015 weight % (Default)
C (def st, max T)	0,0004%/s (Default)	250 °C (Max)	0.4 ppm (Default)	0.015 weight % (Default)
D (var st, max T)	Transient average, see Table A2-A3	250 °C (Max)	0.4 ppm (Default)	0.015 weight % (Default)

Table A2: Complementary Pipestress values for Austenitic steel

	Straight pipe			**Tee joint**			**Elbow**		
Transient	1	*2*	*3*	*1*	*2*	*3*	*1*	*2*	*3*
Mean temperature [°C]	200	200	162.5	200	200	162.5	200	200	162.5
Stress amplitudes [MPa]	305	95 1)	385	462	155 1)	620	729	254	1006
Strain rate [%/s]	0,016	0,0005	0,007	0,025	0,0008	0,01	0,04	0,0014	0,018

1) Below the threshold value for environmental effects in austenitic steels

Table A3: Complementary Pipestress values for Ferritic steel

	Straight pipe			**Tee joint**			**Elbow**		
Transient	1	2	3	1	2	3	1	2	3
Mean temperature [°C]	200	200	162.5	200	200	162.5	200	200	162.5
Stress amplitudes [MPa]	185	32 1)	179	296	53 1)	292	478	86 1)	477
Strain rate [%/s]	0,01	0,0002	0,003	0,016	0,0003	0,005	0,025	0,0005	0,008

1) Below the threshold value for environmental effects in ferritic steels

A4. Data

The material data used in the calculations are shown below.

Table A4: Data for the Austenitic 1.4306 steel at 200 °C

E [MPa]	$185 \cdot 10^3$
ν [-]	0.29
α [1/°C]	$15 \cdot 10^{-6}$
λ [W/m°C]	17
ρ [kg/m^3]	7900
C_v [J/kg°C]	525
h, [W/m^2°C]	15000

Table A5: Data for the Ferritic 15Mo3 steel at 200 °C

E [MPa]	$189 \cdot 10^3$
ν [-]	0.30
α [1/°C]	$13 \cdot 10^{-6}$
λ [W/m°C]	47
ρ [kg/m^3]	7800
C_v [J/kg°C]	533
h, [W/m^2°C]	11500

A5. Result

The detailed analysis can be regarded as the target analysis for the piping system shown in Figure A5. For Pipestress results to be acceptable they should not deviate too much from those produced by the detailed model. In the ideal situation, Pipestress, employing the more approximate method, should provide results that are somewhat conservative in comparison to the detailed method. However, taken the large uncertainty regarding the complex phenomenon of environmental effects the relative un-conservatism should certainly be accepted. A sensitivity analysis was performed for two parameters that have the most influences on the F_{en} value; the transformed stain rate and temperature. Also a comparison for different local stress indices has been evaluated. In equation 11 in ASME /A6/ for the peak stress intensity range, see equation (A5), the K values are the local stress indices.

$$
\begin{aligned}
S_p &= K_1 C_1 \frac{P_0 D_0}{2t} + K_2 C_2 \frac{D_0}{2I} M_i + \frac{1}{2(1-\nu)} K_3 E \alpha |\Delta T_1| \\
&+ K_3 C_3 E_{ab} \times |\alpha_a T_a - \alpha_b T_b| + \frac{1}{1-\nu} K_3 E \alpha |\Delta T_2|
\end{aligned} \qquad (A5)
$$

The value of K_3 has the most influence on the stress range since the temperature stresses are highest. A closer look is done at three different locations on the pipe structure where a different value for the K_3 factor is applied from Pipestress. The results from Pipestress are compared with numerical calculations performed with the NUREG/CR-6909 /A3/ method by Inspecta, named detailed method below.

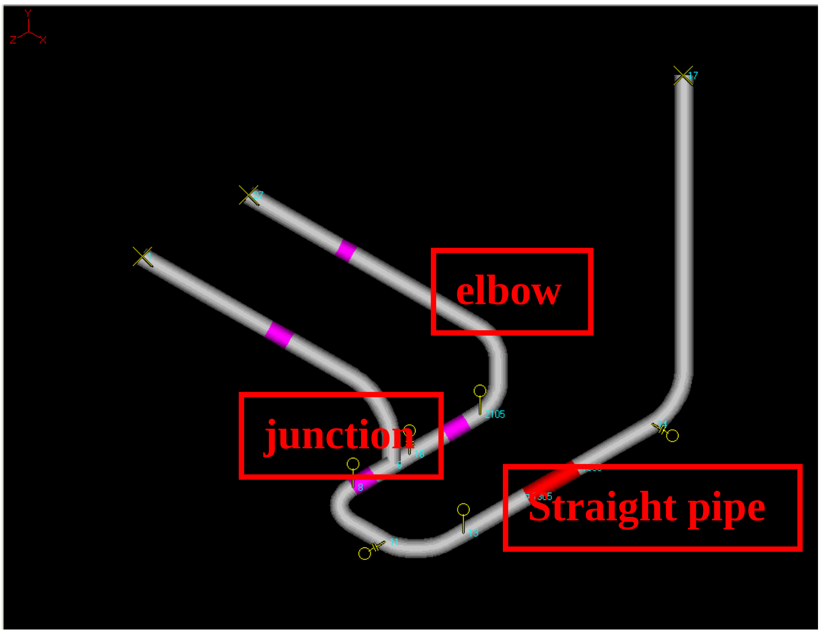

Figure A5: Locations on the pipe system for different K_3 values

Results for the austenitic piping are shown in the Tables A6-A8. A direct comparison between Pipestress computed F_{en} and detailed values is hence enabled.

Table A6: Austenitic - 1.4306. F_{en} values for a straight pipe (K3=1**)**

	PIPESTRESS				Detailed method
	A *(def st, mean T)*	**B** *(ave st, mean T)*	**C** *(def st, max T)*	**D** *(ave st, max T)*	
Trans. 1 (10 s)	3.63	2.69	6.32	3.48	3.72
Trans. 2 (100 s)	1	1	1	1	1
Trans. 3 (30 s)	2.39	2.26	6.32	4.00	3.49

Table A7: Austenitic - 1.4306. F_{en} values at a tee junction (K3=1.87)

	PIPESTRESS				Detailed method
	A *(def st, mean T)*	**B** *(ave st, mean T)*	**C** *(def st, max T)*	**D** *(ave st, max T)*	
Trans. 1 (10 s)	3.63	2.60	6.32	3.25	3.46
Trans. 2 (100 s)	1	1	1	1	1
Trans. 3 (30 s)	2.39	2.24	6.32	3.70	3.27

Table A8: Austenitic - 1.4306. F_{en} values for an elbow (K3=3.3)

	PIPESTRESS				Detailed method
	A *(def st, mean T)*	**B** *(ave st, mean T)*	**C** *(def st, max T)*	**D** *(ave st, max T)*	
Trans. 1 (10 s)	3.63	2.51	6.32	3.02	3.23
Trans. 2 (100 s)	3.63	3.29	6.32	5.18	4.36
Trans. 3 (30 s)	2.39	2.22	6.32	3.42	3.09

The results for the austenitic piping are further summarized in Figure A6. It is shown that combination D, i. e. average strain rate and maximum temperature give overall very good results. This conclusion holds well regardless of transient and component for the austenitic material. Combination C, i. e. minimum strain rate and maximum temperature are well on the conservative side for all cases.

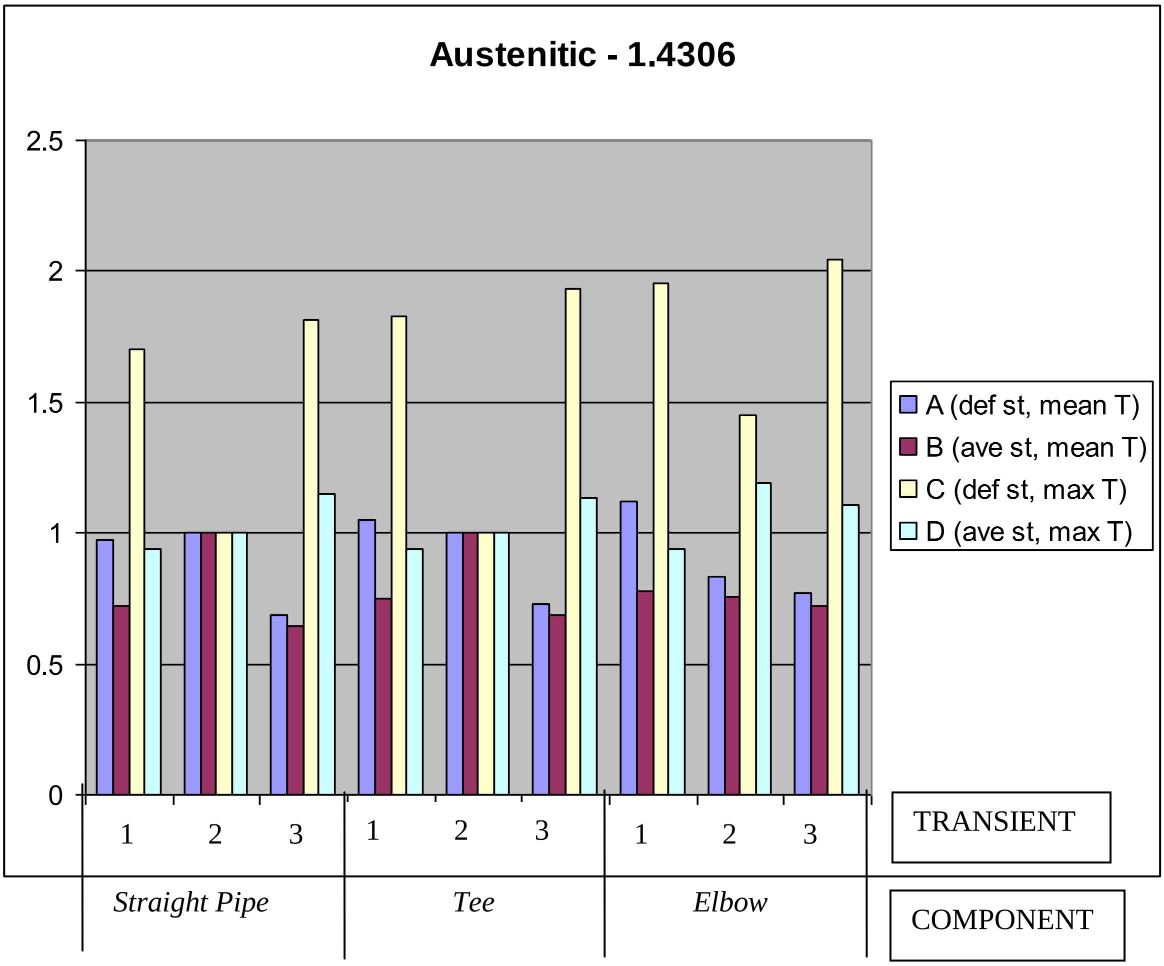

Figure A6: Summary of the results in tables A6 - A8. Pipestress provided F_{en} values compared to the detailed values.

The influence of the type of component in the austenitic piping is further analyzed with the detailed method. These results are presented in Table A9 and Table A10**.** Table A10 shows the F_{en} value relative to the straight pipe F_{en}. The results show that the influence of the type of component is small for the austenitic piping.

Table A9: Austenitic - 1.4306. F_{en} values by the detailed method

	Straight pipe $K_3=1$	*Tee* $K_3=1.87$	*Elbow* $K_3=3.3$
Trans. 1 (10 s)	3.72	3.46	3.23
Trans. 2 (100 s)	1	1	4.36
Trans. 3 (30 s)	3.49	3.27	3.09

Table A10: Austenitic - 1.4306. The influence of the K3 factor is compared for the F_{en} value

	Straight pipe	Tee	Elbow
Trans. 1 (10 s)	1.00	0.93	0.87
Trans. 2 (100 s)	--	--	0.86
Trans. 3 (30 s)	1.00	0.93	0.88

Table A11 is provided as an additional check of computed stress ranges for the austenitic piping. Pipestress and the detailed method are shown to provide similar stress ranges.

Table A11: Austenitic - 1.4306. Stress comparison

	Straight Pipe K_3=1			Tee joint K_3=1.87			Elbow K_3=3.3		
Transient	1	2	3	1	2	3	1	2	3
Stress amplitude (MPa)	305	95	385	462	155	620	729	254	1006
Stress amplitude – det. Meth (MPa)	247	94	350	459	178	644	807	317	1136
Difference	1.23	1.01	1.10	1.01	0.87	0.96	0.90	0.80	0.89

Results for the ferritic piping are given in Tables A12-A14.

Table A12: Ferritic – 15Mo3. F_{en} values for a straight pipe (K3=1)

	PIPESTRESS				Detailed method
	A (def st, mean T)	**B** (ave st, mean T)	**C** (def st, max T)	**D** (ave st, max T)	
Trans. 1 (10 s)	6.28	4.22	20.94	9.45	9.17
Trans. 2 (100 s)	1	1	1	1	1
Trans. 3 (30 s)	2.54	2.42	20.94	14.03	9.05

Table A13: Ferritic – 15Mo3. F_{en} values for a tee junction (K3=1.87)

	PIPESTRESS				Detailed method
	A (def st, mean T)	**B** (ave st, mean T)	**C** (def st, max T)	**D** (ave st, max T)	
Trans. 1 (10 s)	6.28	3.88	20.94	8.02	7.93
Trans. 2 (100 s)	1	1	1	1	1
Trans. 3 (30 s)	2.54	2.37	20.94	11.83	7.83

Table A14: Ferritic – 15Mo3. F_{en} values for an elbow (K3=3.3)

	PIPESTRESS				Detailed method
	A (def st, mean T)	B (ave st, mean T)	C (def st, max T)	D (ave st, max T)	
Trans. 1 (10 s)	6.28	3.57	20.94	6.79	6.88
Trans. 2 (100 s)	1	1	1	1	1
Trans. 3 (30 s)	2.54	2.32	20.94	9.96	6.82

A comparison between Tables A9-A11 and Tables A12-A14 shows that the environmental factors are higher for the ferritic piping than for austenitic piping. The value of F_{en} is higher for the ferritic piping by a factor ranging from 2.1 to 2.6. The results for the ferritic piping are summarized in Figure A7. The Pipestress results relative to the detailed method are shown. It is shown that combination D, i. e. average strain rate and maximum temperature give overall fairly good results. This conclusion holds well regardless of transient and component for the ferritic material. Combination C, i. e. minimum strain rate and maximum temperature are well on the conservative side for all cases.

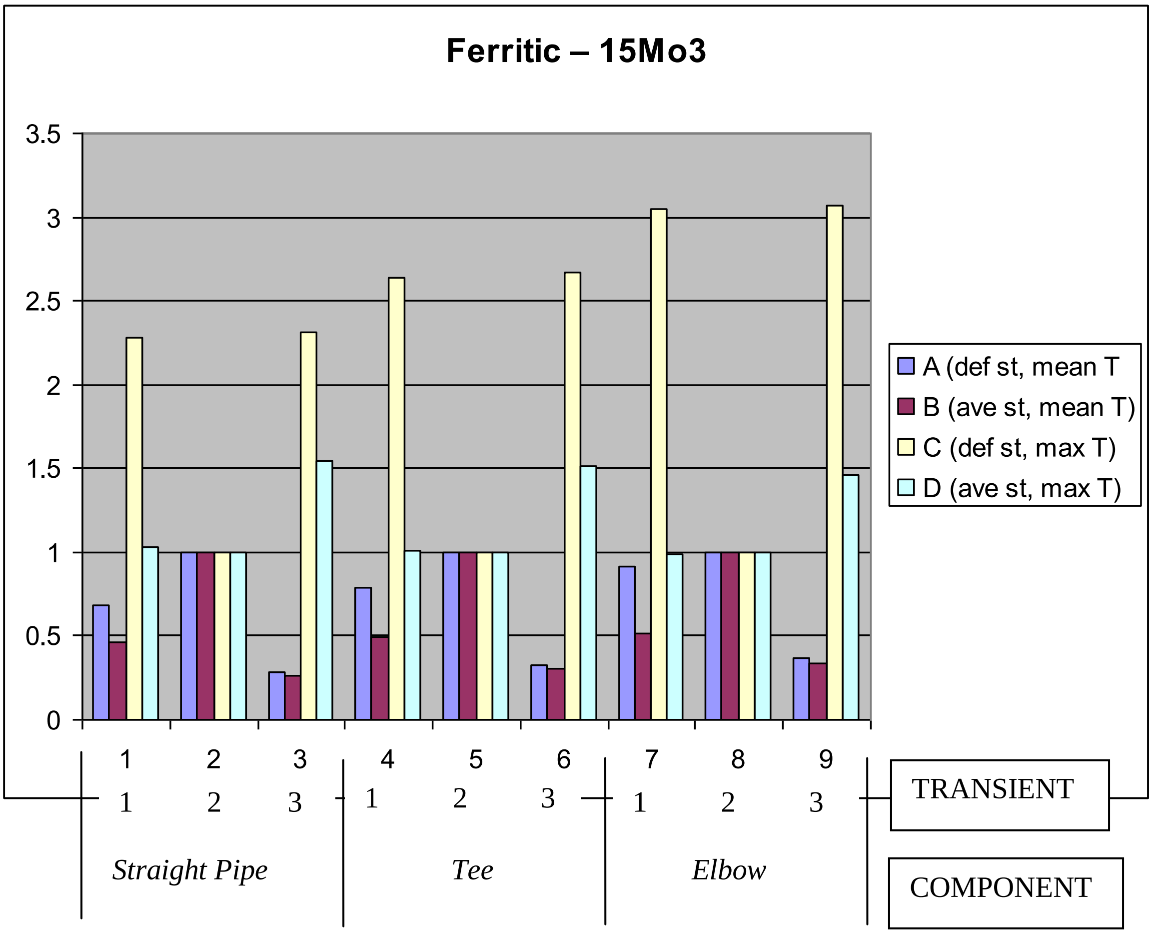

Figure A7: Summary of the results in tables A9 – A11. Pipestress provided F_{en} values compared to the detailed values.

The influence of the type of component is further analyzed with the detailed method. These results are presented in Table A15 and Table A16. Table A16 shows the F_{en} value relative to the straight pipe F_{en}, which is the highest value for all cases. The results show that the influence of the type of component is fairly small for the ferritic piping also.

Table A15: Ferritic – 15Mo3. F_{en} values by the detailed method

	Straight pipe $K_3=1$	*Tee* $K_3=1.87$	*Elbow* $K_3=3.3$
Trans. 1 (10 s)	9.17	7.93	6.88
Trans. 2 (100 s)	--	--	--
Trans. 3 (30 s)	9.05	7.83	6.82

Table A16: Ferritic – 15Mo3. The influence of the K3 factor is compared for the F_{en} value

	Straight pipe	*Tee*	*Elbow*
Trans. 1 (10 s)	1.00	0.86	0.75
Trans. 2 (100 s)	--	--	--
Trans. 3 (30 s)	1.00	0.86	0.76

Table A17 is provided as an additional check of computed stress ranges for the ferritic piping. Pipestress and the detailed method are shown to provide similar stress ranges.

Table A17: Ferritic – 15Mo3. Stress comparison

	Straight Pipe K_3=1			Tee joint K_3=1.87			Elbow K_3=3.3		
Transient	1	2	3	1	2	3	1	2	3
Stress amplitude [MPa]	185	32	179	296	53	292	478	86	477
Stress amplitude – det. Meth [MPa]	156	36	167	290	64	314	510	113	555
Difference	1.19	0.86	1.07	1.02	0.83	0.93	0.94	0.76	0.86

A6. Conclusions

The implementation of a computational procedure for the environmental factor, F_{en}, in Pipestress has been investigated. The investigation has been carried out by analysis with three transients on a model piping system. The Pipestress results were compared with results obtained by a detailed procedure developed by Inspecta Technology, based on the instructions in NUREG/CR-6909 (the ANL-procedure). The comparisons were performed for austenitic and ferritic steels.

- The implementation of the environmental factor computation in Pipestress is simple. No detailed integration with time varying parameters is performed. Instead all parameters remain constant throughout the transients.
- The parameter values are given as default by Pipestress unless other values are provided by the analyst.
- The comparison shows that these constant parameter values for Pipestress must be chosen with care in order to obtain results comparable to those obtained by the detailed calculations.
- Calculations with mean transient temperature values as input should be avoided, since the environmental factors tend to become significantly lower than the values derived by the detailed calculations. Instead maximum transient temperatures should be used as input.
- If maximum temperatures are combined with average strain rates the correlation between Pipestress and the detailed method is surprisingly good. Clear conservatism in relation to the detailed methods is obtained if lower bound strain rates are used as input instead of mean values.
- These model examples show the importance of the temperature values for the computed F_{en} values.
- The strain rate is of less importance, however not negligible.
- The local stress indices K_3, raise the stress ranges up to three times the value for a straight pipe. However, this only results in 15-30 % increase of the F_{en} value. Hence, the computed F_{en} is fairly independent of the component type.
- The environmental factors were larger for the ferritic steel piping than for the austenitic steel piping by a factor to the order of 2-2.5 for identical transients.
- Pipestress with its current implementation for environmental factors should not be used as a research tool for environmental effects. However, Pipestress can be used as effective tool for considering environmental effects in the engineering analysis of piping systems. It is recommended that the maximum transient temperature is always chosen for input.

A7. References

/A1/ Pipestress, DST, version 3.6.2

/A2/ Catalano, J., *Specification for Implementation of US NRC R.G. 1-207 in Pipestress Computer Program Specification No. DST-spec-2008-1 Revision 1,* DST Computer Services, S.A., July 2009.

/A3/ Chopra, O., K, Shack, W.,J., *Effect of LWR Coolant Environments on the Fatigue Life of Reactor Materials*, NUREG/CR-6909, ANL-06/08.

/A4/ Steingrimsdottir, K., Dahlberg, M., *A fatigue analysis including environmental effects for a pipe system in a Swedish BWR* , Technical report no. 50009450-4, Inspecta Tehnology AB, 2010.

/A5/ U.S. Nuclear regulatory commission, *Regulatory Guide 1.207,* Office of Nuclear Regulatory Research, March 2007.

/A6/ ASME Boiler & Pressure Vessel Code, ASME III, Division 1, NB-3000, 2007.

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The Swedish Radiation Safety Authority has a comprehensive responsibility to ensure that society is safe from the effects of radiation. The Authority works to achieve radiation safety in a number of areas: nuclear power, medical care as well as commercial products and services. The Authority also works to achieve protection from natural radiation and to increase the level of radiation safety internationally.

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The Authority reports to the Ministry of the Environment and has around 270 employees with competencies in the fields of engineering, natural and behavioural sciences, law, economics and communications. We have received quality, environmental and working environment certification.

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