Comparison of the fatigue penalty factors (Ke Methodologies)

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ABSTRACT

For future Class 1 stress analyses, it becomes important to remove unnecessary conservatisms as much as possible. The Ke factor is used to calculate the usage factor for the stress levels exceeding allowable yield stress limit of the component material. In general, the Ke factor is equal to 1.0 for stress ranges less than two times yield and higher than 1.0 for stress ranges above two times yield.

In order to find a uniform methodology to calculate the Ke factor, the currently used and proposed methodologies are being evaluated and compared in this paper. The Ke methodologies from the ASME Section III, the JSME and the RCC-M Codes are compared and evaluated against the newly proposed ASME methodology. This topic is hard to solve, as experts in the general subject of fatigue calculations do not generally agree on what Ke factor should be considered.

Finally, it is shown that the differences in the fatigue results from the various Ke methodologies are small, when compared with the fatigue penalty resulting from the new Rules for the consideration of the environmental effects on fatigue.

INTRODUCTION & GENERAL OVERVIEW OF Ke METHODS

The purpose of this paper is to compare five different methods for the calculation of the usage factor for the cases of high stress levels. For these cases of high stress levels, a correction of the predicted purely elastically calculated alternating stress is required. This is done in general through a so-called Ke factor, which is equal to 1.0 for the smaller stress ranges, but is greater than 1.0 for the larger stress ranges. Below is a general overview of different methods used to calculate the Ke factor:

1.) Current 2004 ASME-Code, Section III, NB-3600 Piping (Ref. 1):

$$Sa = 0.5 * Ke_{(U.S.)} * [\ S_T^{mech.} + K_3 * \Delta T_1 \text{ stress} + \Delta T_2 \text{ stress}\ ] \quad (1)$$

where Sa is the alternating stress, $Ke_{(U.S.)}$ is the current Ke penalty factor from the ASME-Code, $S_T^{mech.}$ is the total stress range from the mechanical loads only, ΔT_1 stress is the stress range from the linear through-wall temperature gradient, K_3 is the corresponding stress index, and ΔT_2 stress is the non-linear contribution from the through-wall temperature distribution.

2.) New Proposed Ke Methodology by Steve Adams, ASME Sub-Group on Design Analysis (SGDA), 2005 (Ref. 6).
The main characteristic of this Ke methodology is the decoupling of the total stress ranges into the mechanical, the thermal through-thickness linear and the thermal peak stress ranges. This methodology was developed for NB-3200 components (Ref. 6). A simplified version of that methodology is given here below and in Table 1 for the design of piping systems (Ref. 7):

$$Sa = 0.5 * [\ Ke_{(U.S.)} * S_T^{mech.} + Kn * Kv * K_3 * \Delta T_1 \text{ stress} + Kv * \Delta T_2 \text{ stress}\ ] \quad (2)$$

where

Kn for the notch effect

Kn = 1.0 if $S_T^* \le 3\ Sm$

Kn = The lesser of $1.0 + [\ (K_3)^{\frac{1-n}{1+n}} - 1.0\ ] * [\ \frac{S_T^* - 3\,Sm}{S_T^*}\ ]$ or Ke / Kv if $S_T^* > 3\ Sm$

[Note: Kn cannot be smaller than 1.0]

Poisson ratio's Kv

Kv = 1.0 if $S_T \leq 3\ Sm$

Kv = 1.4 if $S_T > 3\ Sm$ and $(K_3 * \Delta T_1\ stress + \Delta T_2\ stress) \leq (S_T - 3\ Sm)$

Otherwise: $Kv = 1.0 + 0.4 * [\ (S_T - 3\ Sm) / (K_3 * \Delta T_1\ stress + \Delta T_2\ stress)\ ]$

In the formula for Sa above, Ke is still the same as in the current 2004 Edition of the ASME-Code, except that, as an alternative to the n values given in the ASME-Code, n may be taken from the Cyclic Stress-Strain Curve of the material. Ke is a function of the primary plus secondary stress range Sn, of the material characteristics m and n, and of the 3 Sm value.

3.) 2002 Edition of the JSME-Code (Ref. 4).

$$Sa = 0.5 * Ke_{(Japan)} * [\ S_T^{mech.} + K_3 * \Delta T_1\ stress + \Delta T_2\ stress\ ] \quad (3)$$

where the definitions of the various stress contributions are the same as in item 1 above, except for the fact that the $Ke_{(Japan)}$ factor is - in general - smaller in value than $Ke_{(U.S.)}$. The formulas for $Ke_{(Japan)}$ can be found in Ref. (4).

4.) French RCC-M Code of Construction, dated June 2000 (Ref. 2):

$$Sa = 0.5 * [Ke(mech.) * S_T^{mech.} + Ke(ther.) * S_T^{ther.}\ ] \quad (4)$$

with $Ke(mech.) = Ke_{(U.S.)}$ and $Ke(ther.) = 1.86 * [\ 1 - \frac{1}{1.66 + (\frac{Sn}{Sm})}\ ]$ for austenitic stainless steel only

5.) B31.7 Nuclear Power Piping, from the year 1969 (Ref. 3):

$$Sa = 0.5 * K_{(epsilon)} * Kf * [\ Primary + Secondary\ Stress\ Range\ ] \quad (5)$$

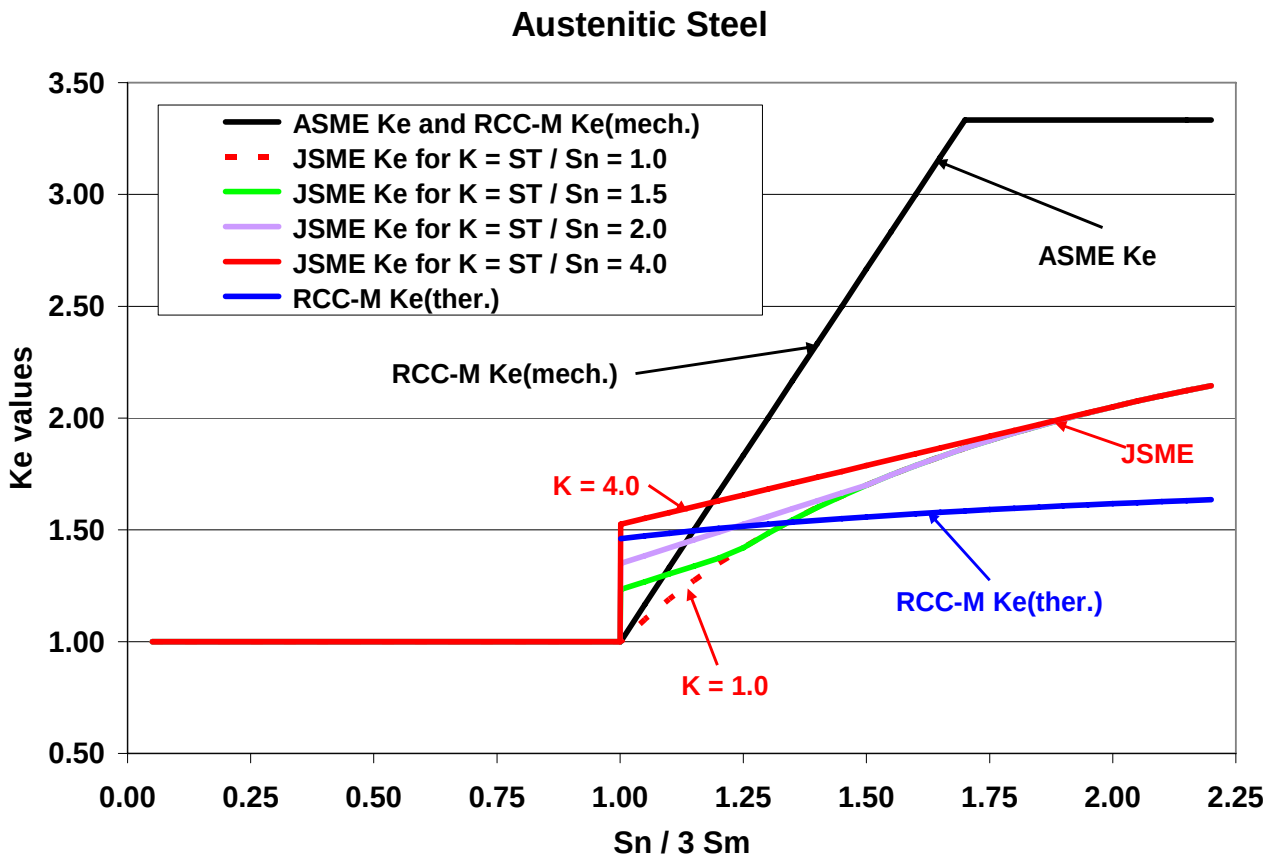
where Kf is the fatigue strength reduction factor and $K_{(epsilon)}$ is the elastic-plastic correction factor. The $K_{(epsilon)}$ correction factor could be large, because it is a function of Sn, where Sn includes the ΔT_1 stress.

Table 1: Piping Stress Equations and Definition of the various stress values

Variables	Descriptions	Formulas
Sn	Primary + Secondary Stress Range, without ΔT_1	$C_1\ \Delta P\ Do / 2\ t + C_2\ \Delta M\ Do / 2\ I + C_3\ Ta / Tb\ stress$
$S_T^{mech.}$	Total mechanical Stress Range	$K_1\ C_1\ \Delta P\ Do / 2\ t + K_2\ C_2\ \Delta M\ Do / 2\ I + C_3\ Ta / Tb\ stress$
S_T^*	Total Stress Range, without the non-linear thermal gradient	$K_1\ C_1\ \Delta P\ Do / 2\ t + K_2\ C_2\ \Delta M\ Do / 2\ I + K_3 * [\ C_3\ Ta / Tb\ stress + \Delta T_1\ stress\ ]$
S_T	Total Stress Range, including all the contributions	$K_1\ C_1\ \Delta P\ Do / 2\ t + K_2\ C_2\ \Delta M\ Do / 2\ I + K_3 * [C_3\ Ta / Tb\ stress + \Delta T_1\ stress\ ] + \Delta T_2\ stress$
Ta / Tb stress		$E_{ab}\ \lvert\ \alpha_a\ T_a - \alpha_b\ T_b \rvert$
ΔT_1 stress		$E\ \alpha\ \Delta T_1 / [2 * (1 - \nu)]$
ΔT_2 stress		$E\ \alpha\ \Delta T_2 / (1 - \nu)$

Figure 1 below shows the various Ke values for the ASME-Code, the JSME-Code and the French Code RCC-M. It is interesting to note that the function used in the French Code RCC-M for the thermal types of stress is similar to the function used in the Japanese Code (from JSME) for both the mechanical types of stress and the thermal types of stress.

Figure 1: Comparison of Ke functions [ASME-Code vs. JSME-Code vs. RCC-M]



Notes:
1.) the RCC-M Ke(ther.) is to be applied on the axial temperature gradient stress range (Ta / Tb stress) and on the radial temperature gradient stress range (DT1 and DT2 stresses)
2.) the B31.7 Methodology is not shown in the Figure above.

FATIGUE CALCULATION EXAMPLE COMPARISON

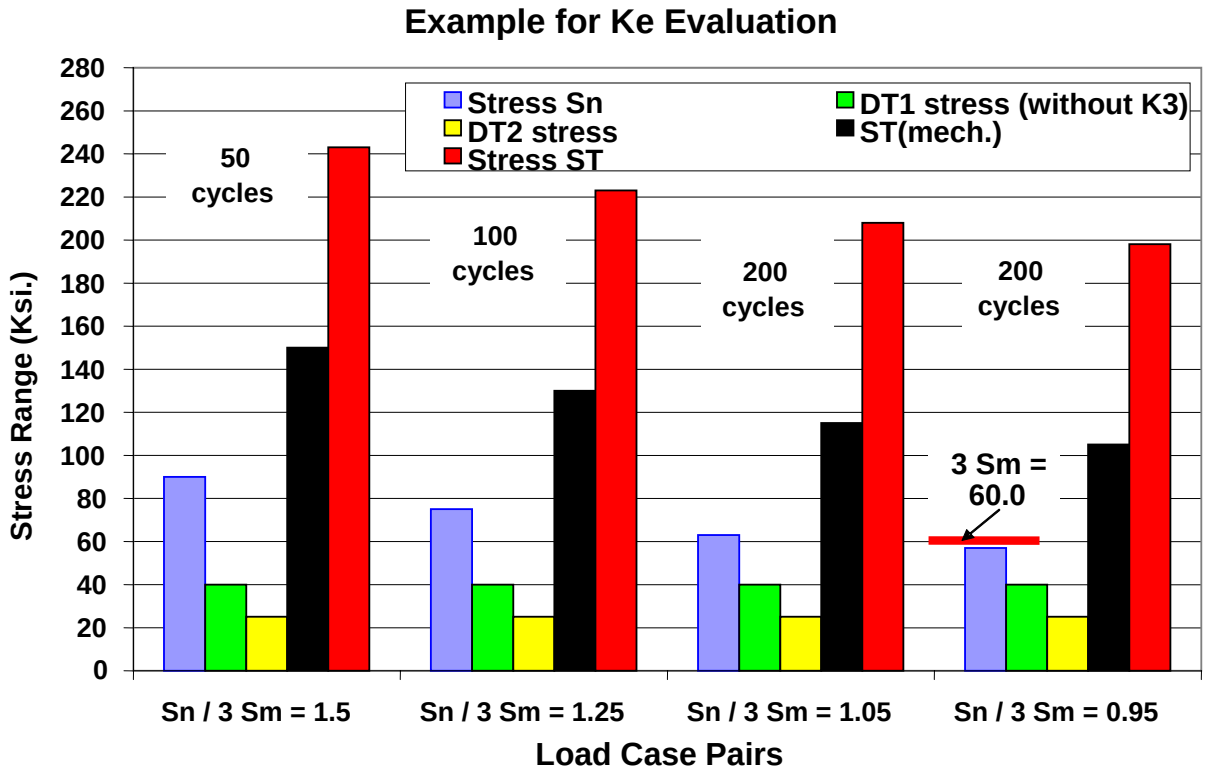
In order to compare the various Ke methodologies, four typical stress ranges that could be found in piping stress calculations are chosen. These four stress ranges are shown in Table 2 and Figure 2. As far as the Sn / 3 Sm ratios are concerned, these four stress ranges are such that they have a wide range of values, starting at 0.95 (no need of a Ke factor) and ending at 1.5. This value of 1.5 for the Sn / 3 Sm ratio is a reasonably high value for that stress ratio.

All the stress calculations performed in this example are exclusively for austenitic stainless steel. The main reason for choosing austenitic stainless steel is because – in the future – the most severe usage factors will be at austenitic stainless steel locations, as the new rules for the consideration of the environmental effects on fatigue are the most severe for that material. In fact, they are much more severe than for carbon steel and low alloy steel.

Table 2: Stress Ranges considered in this example

	Range No. 1	Range No. 2	Range No. 3	Range No. 4
number of cycles =	**50**	**100**	**200**	**200**
3 Sm =	60	60	60	60
n =	0.3	0.3	0.3	0.3
m =	1.7	1.7	1.7	1.7
Sn =	**90**	**75**	**63**	**57**
K3 =	1.7	1.7	1.7	1.7
DT1 stress =	40	40	40	40
DT2 stress =	25	25	25	25
ST(mech.) =	150	130	115	105
ST* =	218	198	183	173
ST =	243	223	208	198
K3 * DT1 stress =	68	68	68	68
Sn / 3 Sm =	1.5	1.25	1.05	0.95
2004 ASME-Code Ke =	2.67	1.83	1.17	1.00

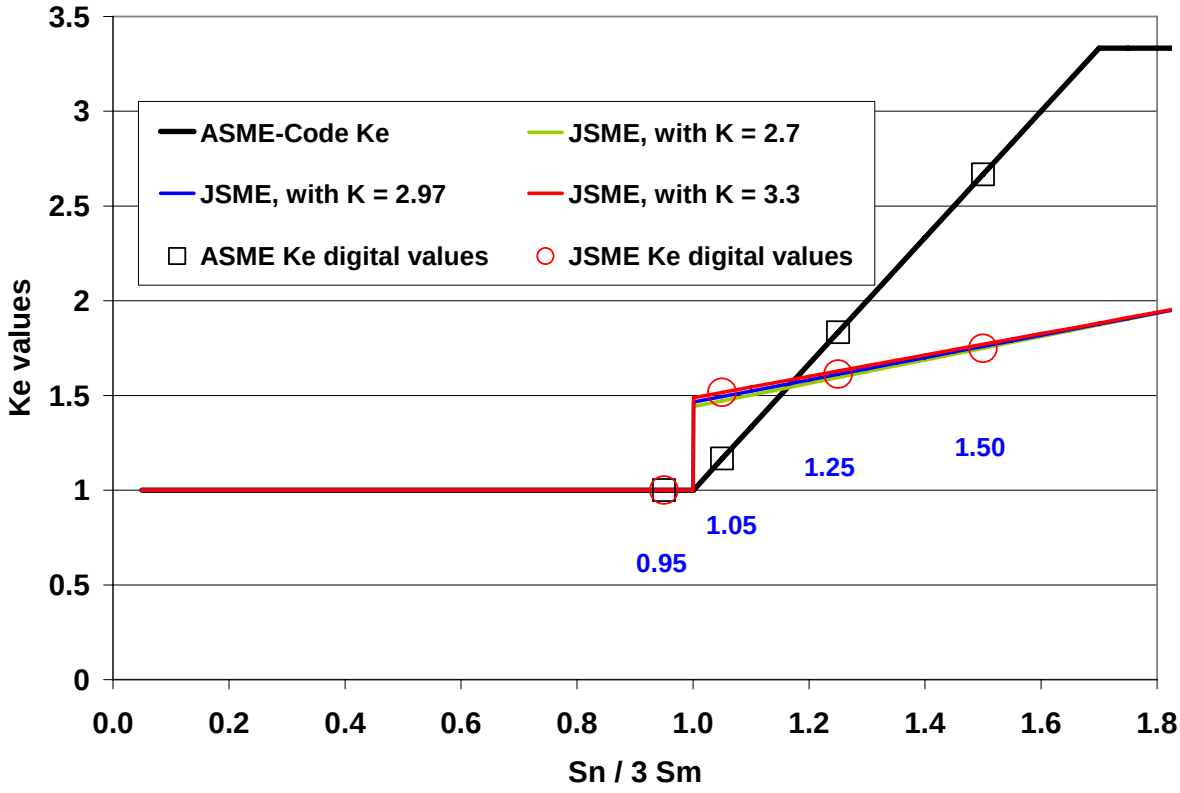
Figure 2: Graphical View of the Input



Based on the four Sn / 3 Sm stress ratios in Figure 2, the Ke values for the current ASME-Code Ke Methodology and for the JSME-Code Ke Methodology can be calculated directly, as shown in Figure 3. Note that the ASME Ke values are independent of the K ratio (ST / Sn), whereas the JSME Ke values are function of the K ratio.

In Figure 3, the Ke factors from the other methodologies are not shown, as these other methodologies do not have a direct calculation of the Ke factor. Note, however, that the RCC-M Ke(mech.) factor is exactly the same as the ASME-Code Ke factor from the 2004 Edition of the ASME-Code (Ref. 1).

Figure 3: Comparison of Ke functions between the current ASME-Code and the JSME-Code



The fatigue calculations have been performed for the stress ranges listed in Table 2. The results from these fatigue calculations are shown in Figure 4 and listed in Table 3 below. These results are given for each stress range considered (Range No. 1 through Range No. 4) and for the total cumulative usage factor, considering the four stress ranges.

For the newly proposed ASME-Code methodology, two cases have been evaluated: the case with the formulas given earlier in the paper, and the case that considers a factor of 1.0 for Kn (for the notch effect). This is because there have been discussions whether the Kn factor is really required for piping stress calculations.

From Figure 4, it can be seen that the newly Proposed ASME Ke-Methodology and the June 2000 RCC-M Ke-Methodology lead to usage factors that are very close to each other for all load pairs (meaning, for all stress ranges). This is due to the fact that both of these methods have recognized that different Ke values need to be applied to the:

a.) mechanically-induced stresses, including the stresses from the thermal expansion moments.
b.) thermally-induced stresses (from the through-wall temperature gradients).

In general, the differences between the cumulative usage factors, using the five methods considered in this paper, are not very different. As expected, the current ASME-Code methodology (Ref. 1) leads to the highest cumulative usage factor as shown in Figure 4 and Table 3.

Figure 4: Comparison of the Usage Factors for the various methods and for the various stress ranges (Sn / 3 Sm)

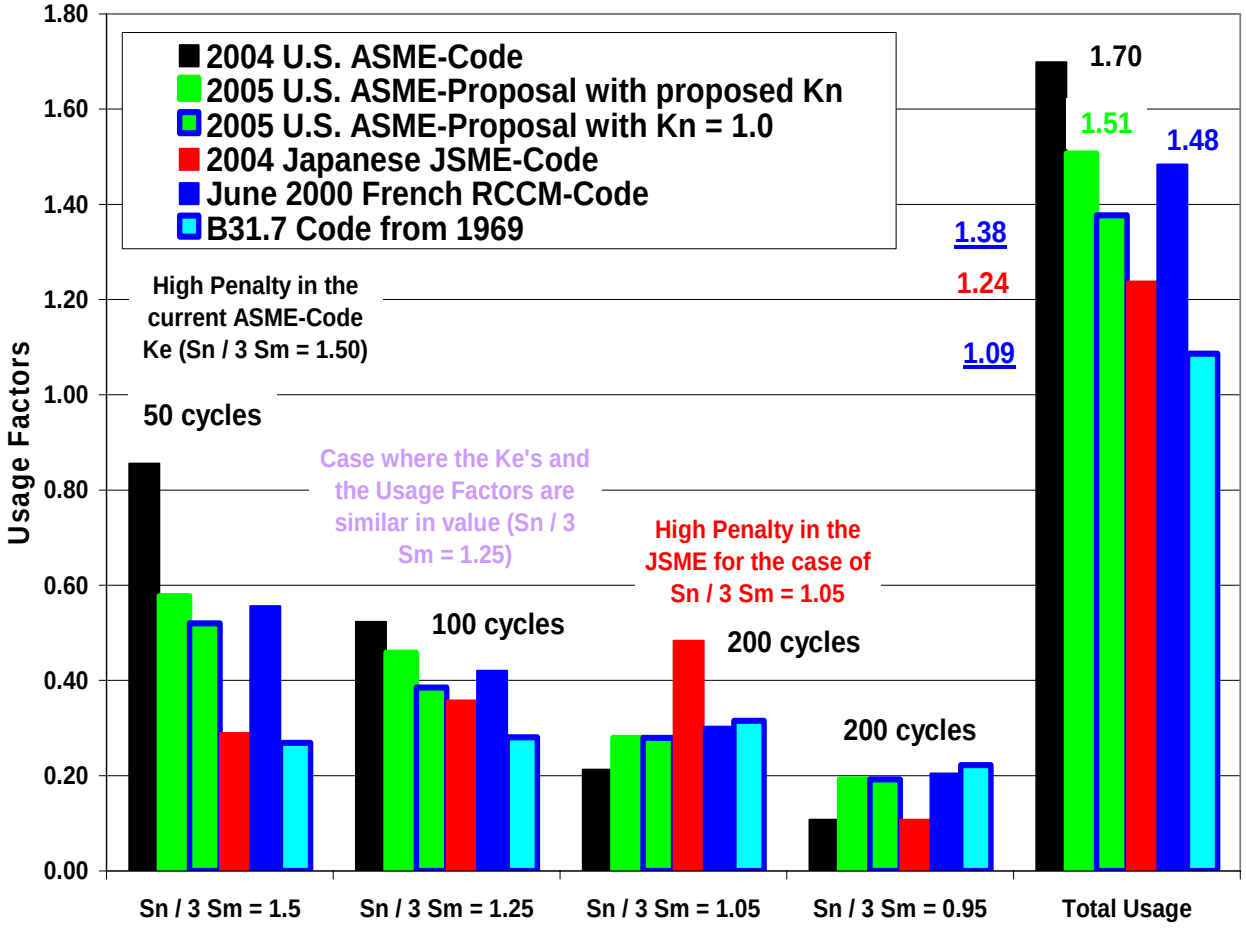


Table 3: Results / Cumulative Usage Factors

Methods	Range No. 1	Range No. 2	Range No. 3	Range No. 4	Total C.U.F.
Sn / 3 Sm →	1.50	1.25	1.05	0.95	
Cycles →	50	100	200	200	
1. Current 2004 ASME-Code, in NB-3600	**0.86**	**0.52**	0.21	0.11	**1.70**
2. New Proposed Ke Methodology (2005)	0.58	**0.46**	0.28	0.19	1.51
3. Current 2004 JSME-Code (from Japan)	0.29	0.36	**0.48**	0.11	1.24
4. RCC-M Code from France (June 2000)	0.56	**0.42**	0.30	0.20	1.48
5. B31.7 Nuclear Power Piping (year 1969)	0.27	0.28	0.32	0.22	1.09

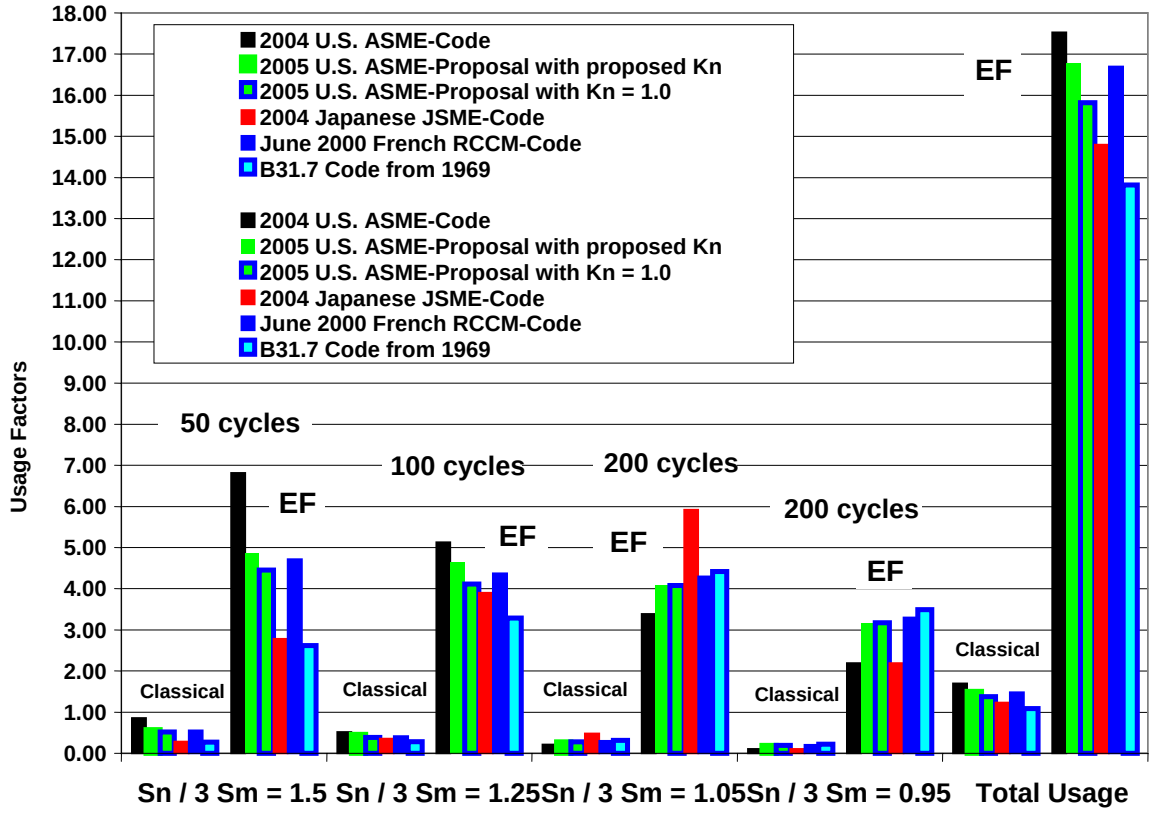
The bold underlines numbers indicate the higher usage factors for each Range, as well as for the Total C.U.F.

CONSIDERATION OF THE ENVIRONMENTAL EFFECTS ON FATIGUE

The next phase of this study was to evaluate the influence of considering the newly proposed austenitic steel Fatigue Curves from O'Donnell (Ref. 5). For the same Sa values calculated using the stress ranges – also called load set pairs - of Table 2, the reduced numbers of allowable cycles have been calculated based on the revised design fatigue curves that consider the most severe environmental effects. Then, the resulting increased usage factors and cumulative usage factors have been calculated. These increased usage factors and cumulative usage factors are shown in Figure 5, where EF means that the most severe environmental effects have been considered, including the high temperature at saturation and the low strain rate at saturation. In Figure 5, Total Usage indicates the cumulative usage factors considering the sum of the four load set pairs (or stress ranges).

In general, it can be seen from Figure 5 that the usage factors, with the consideration of the most severe environmental effects on fatigue, are approximately 10 times greater than using the current ASME-Code Methodology (Ref. 1). This conclusion is of course a function of the methodology chosen to consider the environmental effects on fatigue. In this case, the methodology with the revised design fatigue curves has been chosen (Ref. 5), but it must be pointed out that the F(en) methodology is probably the methodology that will be used in the future. The F(en) factor is the penalty factor to be applied to each number of allowable cycles resulting from the current ASME-Code Design Fatigue Curves. Once F(en) has been determined through one of the currently proposed F(en) methodology, the formula is simply for each load set pair: N(EAF) = N(current Design) / F(en), where EAF means "Environmentally Assisted Fatigue" and F(en) is the environmental penalty factor always equal to or greater than 1.0.

Figure 5: Usage Factors using the current Design Fatigue curves and using the revised Design Fatigue Curves considering the Environmental Effects on Fatigue [EF]



CONCLUSIONS

1.) It cannot be said that a certain Ke methodology would lead to less severe or more severe results than the other methodologies. The main reason for this is that the Ke values are not only a function of the ratio Sn / 3 Sm, but also of the stress concentration factor K = ST / Sn.

2.) In general, the current ASME-Code methodology leads to higher usage factors than the other methodologies. However, it has been found that the reductions in usage factors - when using the other methodologies - are not significant at all.

3.) This paper only presents one example. It would be premature to draw general conclusions without evaluating other cases.

4.) It is easy to see in Figure 5 that the gain from using a more correct Ke methodology is not at all sufficient to make up for the severity of the currently proposed methodologies to take into account the environmental effects on fatigue.

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(7) ASME Working Group on Piping Design (WGPD), Developments by Paul Hirschberg, 2005 (Discussions on Piping Ke still going on at the time of preparing this paper)