The Evaluation and Analysis of Stresses in High Temperature Piping

G. Kistenmacher
Rheinisch-Westfälischer Technischer Überwachungs-Verein e.V.,
Postfach 7041, D-4300 Essen 1, Germany

"Abstract"
The first part of this lecture is concerned with the differences which exist between the normal low-temperature piping design and that for high temperatures. In this connection some additional modes of failure will be presented as typical problems of the high-temperature design, as follows:

creep and creep ratchet,
creep relaxation and
elastic follow up.

In the second part of the lecture the possibilities for calculating the influences of the high-temperature effects, in connection with the analysis of stresses and strains in piping systems are discussed. With respect to typical systems in a sodium-cooled reactor and to steam piping in a gas-cooled high-temperature power plant stress categories and strain limits are developed, so that, on the basis of the analysis of low-temperature piping, rules for dealing with high-temperature piping are obtained.

The stress and strain limits are compared with the rules given by ASME for the high-temperature design and also with the limits of the ASME-Code NB.

Thus the paper is intended to help facilitate the design of high-temperature piping, but with the same level of safety as is necessary for class 1 piping in water cooled reactors.

1. Introduction

In the Federal Republic of Germany as in most of the other industrially developed countries of the world the construction of nuclear power plants tends towards high temperature plants, which work at temperatures above 500°C, as fossil plants have done for a long time.

In this way, disregarding other advantages, it is possible to use a turbine with a high pressure part.

For power piping and other high temperature piping in nuclear power-plants the requirements for the design and calculation are much higher than for piping in fossil plants, and there are very different types of piping in different reactor types. For example there are sodium and steam pipes in the sodium-cooled reactor (SNR) and gas or steam pipes in the Thorium High Temperature Reactor (THTR) which contain fluids with temperatures of 535 - 555 °C.

Sodium piping, manufactured from stainless steel X6CrNi 1811 comparable with American SS 304, has nomally low pressures while steam piping, often manufactured from X20CrMoV121, which is a ferritic steel, has to withstand pressures of about 20,0 MPa.

For the future development of coal liquefication plants which will have higher working temperatures of about 900 °C, it will be necessary, to develop the knowledge about high temperature design and the calculation of piping systems in such a way that the same level of safety is reached as is usual in PWR's.

2. Basis for the calculation of stresses and strains in Pipin systems

Normally the evaluation of stresses and strains in piping systems of nuclear power plants follows /1/, /2/, /3/ or /4/. The ASME-Committee published /5/, which contains rules for handling high temperature components, but there are many problems in using this publication for the design and calculation of piping systems.

The creep region, beginning at 375 °C for ferritic and 425 °C for austenitic steel, causes some further modes of failure, which are not mentioned in /1/, /2/, /3/ or /4/. These are

- continous creep, caused by mechanical loads
- creep ratchet, caused by interaction of primary and secondary stresses
- elastic follow up and
- reduction of life by creep relaxation.

2.1 Continous creep

Creep caused by mechanical loads has been a familiar phenomenon for a long time. It is a continuous deformation which leads to rupture after some time. The time to rupture depends on the level of the primary stresses.

2.2 Creep ratchet

Creep ratchet, similar to the thermal ratchet mentioned in /1/, takes place through the interaction of primary and secondary stresses in such a way, that every cycle of secondary stresses which is long enough to cause relaxation produces an incremental step of deformation until collapse strain is reached. This phenomenon appears already when stresses are beyond the yield stress S_y.

Stresses to cause creep and thermal ratchet must have a centre-symmetrical distribution around the shell.

2.3 Elasic follow up

If a piping system has a very inhomogenous distribution of stresses caused by thermal expansion, so that one point is highly stressed while the remaining part of the system has very low stresses, most of the creep deformation (induced) will take place at the highly stressed point after a very short time, while the stresses in the other parts of the system decrease only a little.

Elastic follow up can lead to the following modes of failure:

- large deformations
- failure by increasing primary stresses caused by "creep-hinges"
- The static system can change into a kinematic one by "creep-hinges"
- failure by instability caused by large deformations.

It must be mentioned, that the forces and moments in the anchor points of a piping system can be come much greater in a shut-down period of a plant when creep has occurred in the same system during operation.

Figures 1 and 2 demonstrate two examples of this behavior in piping systems.

2.4 Decrease of life by creep relaxation

This phenomenon is described in the literature /6/ as "influence of hold time", which means that hold times cause a reduction in the number of allowable load cycles.

Normally this influence /5/ is described in the formula shown in Fig.3. The factor D is also given by /5/.

The form of the fatigue curve depends in /5/ on the intensity of the analysis of the component. If stresses and strains were calculated inelastically, it is possible to choose a less conservative curve than with elastically calculated stresses and strains.

3. Limits to modes of failure in the high temperature region

The modes of failure in the high temperature region make it necessary to tie the limit values to allowable values for the operating time and for deformations. The allowable load cycles are included in the allowables for

the life, when stresses and strains alternate in the piping system.

3.1 Limits for primary stresses

The well known equations for primary stresses from /1/, /2/, /3/ and /4/ change for the design of high temperature nuclear piping into the following equations:

$$P_m \leqq S_t \qquad (1)$$

$$P_e + \frac{P_b}{K} \leqq S_t \qquad (2)$$

with

$$S_t = \min \left\{ \begin{matrix} \sigma_{B,t,T}/1,5 \\ \sigma_{1\%,t,T} \end{matrix} \right\} \qquad (3)$$

$\sigma_{B,t,T}$ minimum value of tensile strength at temperature and at time t

$\sigma_{1\%,t,T}$ minimum value of 1% plastic strain at temperature and at time t

Instead of the time-independent value the right hand side of the equation shows time-dependent limits. The faktor K is a time temperature and material dependent quantity and it is also dependent on the cross-sectional behavior of the pipe. This factor is described in /5/.

In the Federal Republic of Germany, with the construction of the SNR and the THTR, the stress limit depending on the transition from secondary to tertiary creep was neglected, because the factor of safety of 1,5 already protects from the tertiary creep region.

For initial conditions of a piping system these limits ensure a conservative design, but with the influences described in chapter 2.3 and Fig. 2 it is necessary to find out the stresses at any point at any time, when "creep-hinges" have changed the initial static model to a different one. This is very important especially for liquid metal piping, because the mechanical loads from weight are normally very high and the stress distribution in piping systems can vary conciderably.

It is also very important, when constant and spring hanges are used, because a variation of these elements combined with the variation of mechanical load can cause failure by overstress and overstrain.

Although a design of high temperature piping with bellows in unusual in unclear piping of class 1, the above explanations show, that these elements would help the designer, because the mentioned modes of failure will disappear.

Besides, the length of a system would be reduced by a factor 2 ÷ 3, and the use of flexible hanger element would also be reduced. This is favourable for earthquake design.

3.2 Limits for primary plus secondary stresses

In /1/ and /4/ there are well defined limits for the sum of primary and secondary stresses to produce "shake down" or to ensure that plastic cycling without ratchet occurs in a piping system.

Because increase in strains in the high temperatur region cannot be prevented, limits given in /5/ for primary and secondary stresses go hand in hand with the creep-fatigue analysis, in which peak stresses are also involved (Fig. 3).

The way to find out the strains, which are limited according to Fig. 3, especially from calculation on an elastic basis, is undefined or - using the simplified methods proposed in /5/ - too conservative.

Especially in high temperature piping systems the direction of stresses and strains, calculated in accordance with /1/ or /4/, are unknown. Furthermore the definition of P_b as a cross-sectional stress caused by a moment must be revised, because a strain of 2 % would produce large deformations, which exclude the use of a linear theory of first order.

The piping design guide for LMFBR piping design /6/ proposes a new definition for "shake down", as shown in Fig. 4. Different methods for ensuring that the system "shakes down" in the high temperature region are compared with the normal shake down conditions of /1/ and /4/.

According to Fig. 4 d shake down occurs, when the elastically calculated stresses are beyond $(S_{r1} + S_{r2})$, where S_r is a stress value for the asymptote of a relaxation-curve (Fig. 5).

This manner of describing shake down has been modified in German high temperature reactor types for easier handling, especially for the piping design.

In place of the limit $(S_{r1} + S_{r2})$ different criteria are used. The easiest way is to define the limit by yield stress S_y (Fig. 4f). This is possible for materials with high yield stress and a low S_t.

Another way of defining shake down, especially when different cyles have different temperatures in and beyond the creep region is with the criterion $(S_t + S_y)$ (see Fig. 4e).

The criterion "3 S_m" given in /1/ or /4/ can never be sufficient as is shown in Fig 4c.

Even if one of the criteria for high temperature piping is used, the strain limits according to Fig. 3 must be met, because continuous increase in strains and creep ratchet occur even if the stress is beyond the yield stress S_y.

Creep effects, which are cyclic in character and produce an incremental increase in strains, must have a centre-symmetrical distribution around the circumference of a pipe.

Thermal and creep ratchet can often be considered in two steps,

because the first effect occurs, when short time transients produce high secondary stresses. The second form of ratchet can already occur at low stresses beyond yield stress S_y, but it requires a hold time. So these two phenomena can be devided in two different analyses without any reduction in safety.

/5/ allows calculating strains on an elastic basis with the Bree test /7/, but ist stipulates the handling or those stresses, which perhaps produce "elastic follow up", as primary. That's why the elastic analyses are normally too conservative for the design of high temperature piping.

3.3 Elastic follow up

By calculating stresses and strains on an inelastic basis one can prevent a high temperature piping system from elastic follow up by meeting the strain-limits of Fig. 3.

If the low secondary stresses, proposed in Fig. 4d,e,f are met and the stress level in a piping system is not very different as regards the whole structure "creep-hinges" would not occur and elastically calculated stresses and strains will be almost as high as in reality.

3.4 Creep-fatigue

Hold times change the behavior of materials considerably when stressed by cyclic loading. Because the use of temperature-dependent curves for the allowable cycles is not sufficient, hold time effects are summarized together with the fatigue according Fig.3.

As demonstrated in /8/, the equation in Fig. 3 does not describe adequately the real behavior in a piping system.

One can show by examples, that the hold time influence is as great, as the increase in the stress range depending on relaxation effects (Fig. 6).

If $(S_{r1} + S_{r2})$ is used as the "shake down"-limit, one can follow the ASME-Code NB 3650 /1/, with the simplified elastic-plastic analysis, in order to obtain results, which are absolutely comparable to the fatigue analysis according to /5/.

Especially in high temperature piping systems nearly every second load cycle goes hand in hand with a decrease in temperature and an increase in S_y. In this way the strain-time relationship looks like Fig. 7.

For this form of load-history $(S_{r1} + S_{r2})$ or $(S_t + S_y)$ can be used as the "shake down" limit.

Meeting these secondary stress limits one can use the fatigue curve while ignoring hold times.

4. Comparison of existing rules and the procedure for evaluating stresses and strains in high temperature piping systems

The existing rules /1/, /4/ enable one to design piping systems on an elastic basis.

This paper shows, that these rules, modified in some points, can also be regarded as sufficient for the design of nuclear high temperature piping. The modifications were discussed in the earlier sections. The basis of stress categories can be used, even if some further modes of failure exist.

References

[1] ASME-Code Section III Subsection NB

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[3] ASME-Code Section III Subsection ND

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[5] ASME-Code Case N47-17

[6] LMFBR Piping design guide
Herausgeber: C.F. Braun u. Co., Report Nr. San-781-1 1971

[7] J. Bree, "Incremental Growth Due to Creep and Plastic Yielding of Thin Tubes Subjected to Internal Pressure and Cyclic Thermal Stresses", Journal of Strain Analysis
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[8] K.IIDA, M. Kitagatawa, K. Taumra, A. Matsushita, M. Fukagawa and Y. Saiga.
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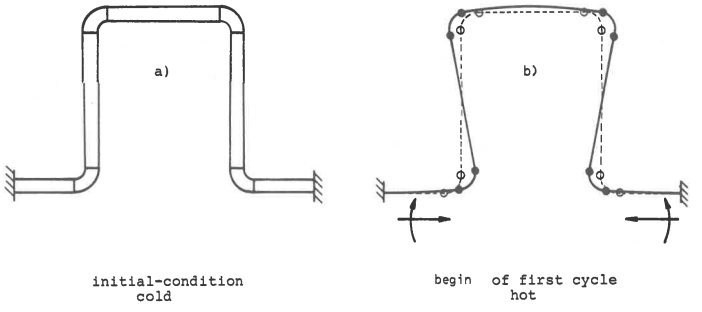

Fig. 1 Typical deflections and support reaction in high temperature piping

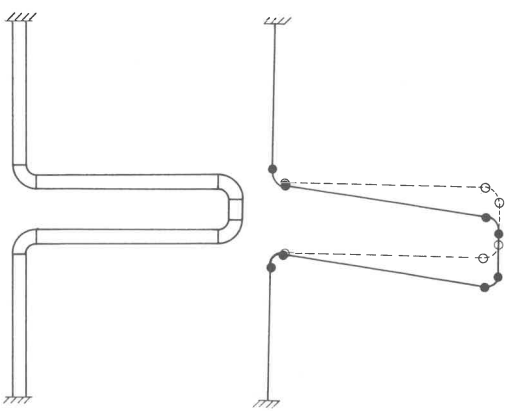

Fig. 2 "Creep-hinges", causing a cinematic system

stress category	limits
$P_l + P_b + Q$	$\varepsilon \leq \begin{cases} 1\ \% \\ 2\ \% \\ 5\ \% \end{cases}$ membran, bending, local
$P_l + P_b + Q + F$	$\sum \frac{t}{T_d} + \sum \frac{n}{N_d} \leq D$

t = hold time $\quad$ n = operating cycles

T_d = allowable hold time $\quad$ N_d = allowable cycles

Fig. 3 Strain limits and creep-fatigue analysis

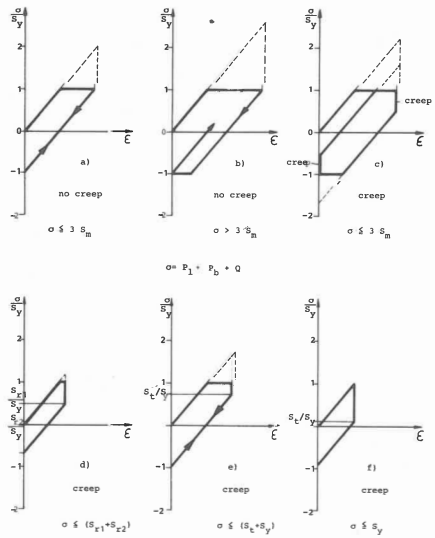

Fig. 4 Comparison of different shake down conditions

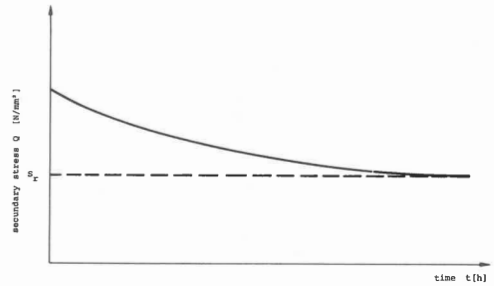

Fig. 5 Evaluation of S_r

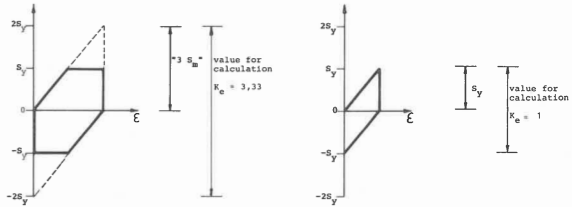

Fig. 6 Examples with total relaxation of secondary stresses

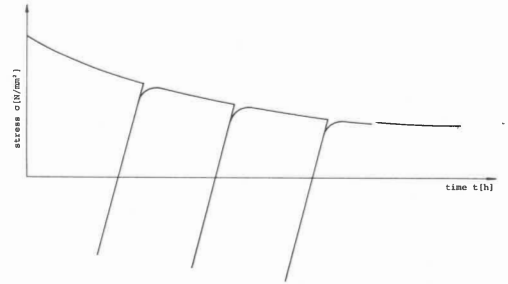

Fig. 7 Typical stress-time relationship with varining temperature conditions