COMPARISON OF FATIGUE ASSESSMENT TECHNIQUES FOR HEAT RECOVERY STEAM GENERATORS

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ABSTRACT

In the past several years the cyclic nature of Heat Recovery Steam Generators, HRSG's, has increased dramatically. There are many methods for evaluating cyclic service. Several methods for evaluating cycle life are compared for their use on HRSG's. A discussion of strengths and weaknesses of each method is presented.

INTRODUCTION

ASME Section I [1] and Section VIII, Division 1 [2], do not provide specific rules for to evaluate the cyclic nature of HRSG's. It is, however, the general philosophy of ASME Section I as stated in the Forward, "to afford reasonable protection of life and property and to provide a margin for deterioration in service so as to give a reasonably long safe period of usefulness." Therefore, it is the opinion of many in the industry that the use of ASME Section I has shown through experience, to provide an adequate margin of usefulness without performing a formal fatigue or creep-fatigue evaluation. This general philosophy has come under question in recent years since the nature of the operation of most HRSG's has changed from a normally base loaded operation to a cyclic one. The lack of any specific rules in ASME Section I to evaluate the cyclic nature of operations has required designers to go elsewhere to find methods to address the industry concerns.

Other recognized boiler and pressure vessel codes and standards provide methods and rules that can be used to evaluate the fatigue life of HRSG's. Annex I of the Pressure Equipment Directive 97/23/EC (PED) [3] requires that the design must take appropriate account of all foreseeable degradation mechanisms such as fatigue. For other degradation mechanisms, such as creep interaction with fatigue there are very few methods available. The methods used to evaluate fatigue vary from exemption calculations, to simplified methods, to detailed methods. A comparison of several recognized codes and standards for evaluating cycle life of HRSG components are presented.

GENERAL

The HRSG user provides the manufacturer with the cyclic service information required to evaluate fatigue. This information includes the type and number of startup, shutdown and load change cycles, see Figure 1 for a typical pressure and temperature startup curve for an HP Steam Drum downcomer nozzle. The HRSG manufacturer takes the number and severity of the cycles into consideration when choosing the details used in the design of the HRSG. See Table 1 for an example of cyclic operation for an HP Steam Drum**.** Depending on the number and severity of cycles, a fatigue evaluation may be based on exemption rules. Using the proposed details, the components are normally designed using design-by-rule procedures, and then evaluated for fatigue. If the component does not meet the intended cycle life, then the operating conditions, design details or both are modified such that the anticipated service is met. Fatigue evaluations are normally performed on components having excessive thermal gradients and pressure cycling. These components include, but are not limited to:

- HP Superheater Outlet Header Attachments
- HP Remote Steam Drum Nozzles
- Header Inlet Nozzles of Feedwater Heaters
- Division Plates in Common Headers

FATIGUE EXEMPTIONS

Many boiler and pressure vessel codes and standards provide provisions to exempt fatigue evaluations. Exemptions are based on the components meeting the code design rules and details. Limitations are also placed on the number of full range pressure cycles, partial range pressure cycles, magnitude of thermal gradients within startups and shutdowns cycles, and the magnitude of cyclic mechanical loads such as piping loads. For the most part, exemption provisions are based on conservative evaluations using allowable membrane stresses and fatigue design curves (S-N curves). Fatigue exemption rules are also a function of construction details. Described below are several fatigue exemption procedures.

ASME Section VIII Division 2 (ASME VIII-2) [4]

Clause AD-160, ASME VIII-2 provides several methods for exempting fatigue evaluations. The method most likely to be used in exempting an HRSG component from fatigue is Condition B. This method individually checks the adequacy of the startup/shutdown full range pressure cycles, operating pressure cycles, startup/shutdown thermal gradients, operating thermal gradients, and full range piping/mechanical loads. Allowable startup/shutdown thermal gradients can be determined from the Condition B exemptions; therefore allowable startup and shutdown rates can be determined [5].

British Standard, PD 5500 [6]

Annex C of PD 5500 presents exemptions from fatigue evaluation that are similar to ASME VIII-2 clause AD-160 Conditions A and B. Using PD 5500, the method most likely to be used in exempting an HRSG component from fatigue would be clause C.2.3. This clause is similar to ASME VIII-2 Condition B and considers pressure, thermal and piping load changes.

German Technical Rules for Steam Boilers, TRD [7]

Like ASME VIII-2, TRD offers several methods for exempting fatigue evaluations. TRD 301, Clause 6.1 exempts internal pressure and temperature changes for up to 10,000 startups from ambient condition provided the material is carbon or low alloy steels and the maximum allowable working pressures does not exceeding 460 psig (3.2MPa) or the membrane stress due to design pressure does not exceed 22 ksi (150 MPa). This criterion would exempt most remote steam drums made from SA-516 Gr. 70 material and most headers made from SA-106 Grades B or C. It should be noted that there are no limitations on thermal gradients and there is no mention of exempting the effects of piping load changes. The TRD 301 rules are for openings in cylindrical shells and TRD 303 contain the rules for openings in dished heads.

European Standard for Water-Tube Boilers, EN 12952-3 [8]

EN 12952-3 clause 13.3.1 basically exempts fatigue evaluation of components made of carbon or ferritic alloy steels (Cr < 3%), high-chromium steels, and austenitic stainless steels provided all welded connections are made between materials with similar coefficients of thermal expansion and external loads are negligible. If the external loads are not negligible, clause 13.3.4 provides exemptions based on full range pressure cycles, part range pressure cycles, thermal gradients and mechanical loads on branches (nozzles). Clause 13.3.4 limits full range pressure cycles to 3000 and partial range pressure cycles (not exceeding 50% of the full pressure) to 10,000. Clause 13.3.4 also limits thermal gradients based on the interaction with piping loads and construction details such as partial penetration versus full penetration welds.

European Standard for Unfired Pressure Vessels, EN 13345 [9]

EN 13345 does not have much in regards to fatigue exemptions, but allows exemptions for full range pressure not exceeding 500 cycles and small pressure fluctuations can basically be ignored.

Discussion of Fatigue Exemption Rules

A wide range of permitted fatigue exemptions exist in different codes and standards. Thermal gradients exist in HRSG's, and these gradients need to be quantified in order to use fatigue exemptions. Through thickness thermal gradients, caused by transients, can be determined by equations or analytical methods such as finite difference or finite element methods. The determination of the thermal gradients adds to the degree of difficulty in fatigue exemption methods. See Figure 2 for an example of thermal gradients in a HP Drum downcomer nozzle during a cold startup.

Not mentioned above are the ASME VIII-2 and PD 5500 exemption based on previous and satisfactory experience on comparable equipment and operations. The experience exemption is not widely used by manufacturers, but TRD 301 and EN 12952-3 probably use experience in the exemptions permitted in their rules. The TRD and EN 12952-3 exemptions seem to agree with EPERC Report No. 10391001-1 [10], which states "relatively few defects have been reported in water tube boilers and piping." Also fatigue failures of steam drums are virtually non-existent.

If fatigue evaluations cannot be exempted, the next step would be to use simplified fatigue evaluation methods.

SIMPLIFIED FATIGUE EVALUATION METHODS

Many boiler and pressure vessel codes and standards provide simplified fatigue evaluation methods. Once again these methods are based on the components meeting the code design rules and details. For the most part, stress ranges are determined by the use of stress indices or stress concentration factors. See Figure 3 for an example of stress concentration at a nozzle due to internal pressure. For many component configurations these factors are provided, or the designer may determine them. Stress concentration factors can be found in the literature or determined by analytical or experimental methods. See Figure 4 for an example for stress concentration at a nozzle due to thermal gradients. Once the stress ranges are determined, fatigue curves are used to determine the associated number of allowable cycles. For multiple conditions, such as Cold, Warm, and Hot startups and shutdowns, Miner's rule is used for life fractions and cumulative damage. Described below are several simplified fatigue evaluation methods.

ASME Section VIII Division 2(ASME VIII-2) [4]

Article 4-6 of ASME VIII-2 provides stress indices for the determination of stresses due to pressure for openings (nozzles) in heads and shells. Once stresses due to pressure are known, their effect on fatigue life can be determined using the fatigue evaluation procedures in Appendix 5. Use of these indices requires the nozzle attachment to meet certain dimensional restrictions, including shell thickness-to-diameter ratios, nozzle-to-shell diameter ratios, and specialized details. Since most HRSG components do not require these types of details for the intended cyclic service, the ASME VIII-2 simplified method is not normally used. Also, the ASME VIII-2 simplified methods do not provide a procedure for determining thermal stresses at nozzles or openings. Another restriction with ASME VIII-2 is that the fatigue curves are limited to 700°F (370°C) for carbon and low alloy steels and 800°F (430°C) for austenitic stainless steels. Many components operate in temperature ranges above these limits rendering these rules inadequate for HRSG's.

British Standard, PD 5500 [6]

The simplified stress and fatigue evaluation procedures in PD 5500 are located in various sections of PD 5500. This standard provides simplified methods to calculate stresses at nozzles due to internal pressure, thermal gradients and piping loads based on using stress concentration factors and "cookbook" methods. The use of computer software based on these methods can greatly improve the use of these rigorous manual calculations. The simplified methods for determining stresses due to pressure are located in clauses G.2.3.5.2 and G.2.5.2 of Annex G. For simplified transient thermal gradients and stresses due to these thermal gradients, section G.4 of Annex G can be used. As for stresses due to piping loads, sections G.2.3 and G.2.5 of Annex G are used. Fatigue evaluation procedures in PD 5500 require the determination of the maximum principal stress range for each individual cycle. Once the principal stresses are known, the fatigue evaluation is done in accordance to Annex C. Useful examples to illustrate the assessment of vessels subject to fatigue are given in Enquiry Case 5500/106. A limitation of PD 5500 is that the fatigue curves are limited to 660°F (350°C) for ferritic steels and 800°F (430°C) for austenitic stainless steels. Again for many components, these temperature limitations render the PD 5500 inadequate for HRSG applications.

German Technical Rules for Steam Boilers, TRD [7]

The simplified fatigue rules in TRD are provided in TRD 301 Annex 1 for branches in cylindrical shells and TRD 303 Annex 1 for branches in dished heads. Stresses due to internal pressure and thermal gradients are determined by the use of stress concentration factors. For stresses due to internal pressure, the stress concentration factors are based on the type and weld of the branch attachment detail. If full penetration welds are not used, a residual weld gap exists and an additional stress concentration factor is added to the stresses due to pressure. Also, due to the out-of-roundness of the shell an additional stress concentration factor is added to the stresses due to pressure. For stresses due to thermal gradients, a stress concentration factor of 2 is used. Stress concentration factors other than those provided may be used as long as they can be shown to be acceptable. An effective stress range that includes the influence of mean stress is determined (Gerber rule). Using the fatigue curves, the allowable number of design cycles can be determined from the effective stress range. Miner's equation is used to determine life fractions and cumulative damage due to multiple types of cycles. TRD requires the cumulative damage fraction to be less than or equal to 0.50.

An advantage of the simplified TRD rules is that they are easy to use. Another advantage is that the fatigue curves are provided up to 1100°F (600°C). Also, TRD rules can easily be used to determine allowable thermal gradients (delta-T's) based a on given number of cycles. See Figure 5 for an example allowable delta-T curves for startup and shutdown of a HP Superheater outlet header. Allowable startup and shutdown rates can be calculated based on the delta-T's. These rates are very conservative and misleading since they are based on a quasi-stationary temperature pattern, which is not the case for a thermal transient. These calculated rates have been known to be conservative by a factor of 2. The rate calculation is actually not needed since the delta-T is used to determine stress. A disadvantage of the simplified TRD fatigue rules is that there are no provisions of piping loads. However, many times piping loads reduce the maximum stress due pressure and thermal gradients and can be ignored. Another disadvantage with the TRD rules is that the stress concentration factors do not cover all details used in HRSG construction; determination of these are left to the designer. A major conservatism with TRD rules is that the cumulative damage cannot exceed 0.50. ASME VIII-2, EN 12952-3, and PD 5500 would allow cumulative damage fractions to be 1.0.

European Standard for Water-Tube Boilers, EN 12952-3 [8]

The simplified fatigue evaluation methods in EN 12952-3 are very similar to those in TRD, with a few exceptions. One of the prominent exceptions is EN 12952-3 takes out a few of the conservatisms built into the simplified TRD fatigue method. For example, TRD uses set stress concentration factors based on details used in construction without consideration of size (diameters and thickness); whereas EN 12952-3 provides curves for stress concentration based on opening to shell diameter ratios and opening to shell thickness ratios. Another difference is that EN 12952-3 allows cumulative damage fraction up to 1.0, as compared to 0.50 in TRD.

Advantages with EN 12952-3 are improved stress concentration factors and the allowance of cumulative damage factors as large as 1.0. Also, EN 12952-3 provides an Annex with material properties needed to perform simplified fatigue evaluations. Like TRD, EN 12952-3 does not provide stress concentration factors for all details used in HRSG construction; determinations of these are left to the designer. Even though simplified rules for determining stresses due to piping loads are not provided in EN 12952-3, an explanation is given that stresses due to piping loads in general occur on the outside of the branch and are usually insignificant at the inside bore where stresses due to pressure and thermal stresses are maximum. Therefore, these can be ignored without significant impact on fatigue life.

European Standard for Unfired Pressure Vessels, EN 13345 [9]

EN 13345 provides simplified fatigue evaluation rules in clause 17. The EN 13345 simplified fatigue evaluation rules are similar to those in ASME VIII-2. Both are based on using stress indices (stress concentration factors) due to pressure cycling only.

EN 13345 provides stress concentration factors for a wide range of construction details, whereas ASME VIII-2 only provides stress concentration factors for specialized branch connections. The fatigue curves in EN 13345 are based on classifications of construction details and this concept is similar to PD 5500. Once stress ranges are determined in EN 13345 clause 17, correction factors based on thickness, temperature and notch effect are used to determine effective stress ranges. With the use of the fatigue curves and effective stress ranges, the associated number of allowable cycles and Miner's rule are used to determine life fractions and cumulative damage.

An advantage with the simplified fatigue evaluation rules EN 13345 is that it provides stress concentration factors for a wide variety of construction details. A disadvantage with these rules is that the stress concentration factors are for the determination of stresses due to pressure only. Another disadvantage is that the EN 13345 simplified fatigue rules do not apply to components operating in the creep range. This is similar to ASME VIII-2 and PD 5500.

Discussion of Simplified Fatigue Rules

The TRD and EN 12952-3 simplified fatigue rules are focused on water tube boilers and provide useful and practical methods to determine fatigue life due to stresses caused by pressure and thermal gradients. Also TRD and EN 12952-3 do not restrict the use of their rules to components outside the creep range. EN 12952-3 provides more flexibility in the determination of stress concentration factors. PD 5500 offers methods to calculate stresses due to pressure, thermal gradients and piping loads but these methods are more complex than EN 12952-3 or TRD. It should be noted that the PD 5500 stress calculation methods could be used in conjunction with any of the fatigue evaluation methods. This can prove to be useful if a more detailed approach is needed. The simplified fatigue evaluations in ASME VIII-2 and EN 13345 are limited to stresses due to pressure, but both of these codes offer more complex methods for fatigue evaluation.

Simplified fatigue analysis rules may be conservative with respect to determining stresses used in fatigue life evaluations. More detailed methods for determining stresses such as finite element analysis may be used to obtain more exact fatigue evaluation.

DETAILED FATIGUE EVALUATION METHODS

For detailed fatigue evaluations, detailed stress analyses are normally used, but not always necessary. These stress analyses are all based on determining stresses using pseudo elastic properties and involve either classical plate and shell theory or finite element analysis. Codes and standards evaluate calculated stresses differently in their fatigue assessment procedures. The rainflow cycle counting method [11] or reservoir cycle counting method [9] are normally used to determine stress ranges and cycles. Also the fatigue curves in codes and standards are different. There are two dominant approaches to fatigue evaluations, the "classical" approach and "welded joint" approach [12]. The classical approach is the basis the ASME VIII-2 method and the welded joint approach is the method used in EN 13345 and PD 5500. Miner's rule is used for life fractions and cumulative damage in both methods.

ASME Section VIII Division 2 (ASME VIII-2) [4]

For the classical approach that ASME VIII-2 pioneered, stress intensity ranges (Tresca) are calculated based on component stress ranges. These stresses are multiplied by fatigue strength reduction factors as appropriate. If stress concentrations are included in the determination of stresses, fatigue strength reduction factors may not be needed. The ASME VIII-2 fatigue curves are derived from strain-controlled fatigue tests of unnotched polished samples without welds. The ASME fatigue curves were based on best-fit curves by applying a factor of two on stress or a factor of twenty on cycles, whichever was more conservative [13]. The ASME fatigue curves also incorporate a tensile mean stress correction. When using the ASME fatigue curves, the effective stress range does not get corrected for mean stress. ASME VIII-2 fatigue curves are limited to 700°F (370°C) for carbon and low alloy steels and 800°F (430°C) for austenitic stainless steels.

British Standard, PD 5500 [6]

The welded joint approached was first used as a pressure vessel fatigue evaluation technique by PD 5500 (formerly BS 5500). Unlike ASME VIII-2, PD 5500 does not use stress intensity ranges. Instead, PD 5500 uses component stress ranges to determine principal stress ranges and these are used to determine fatigue life based on the fatigue curves. The fatigue curves are associated with figures of welded joints and the direction and location of the principal stress is used to determine which of the seven fatigue curve is to be applied. The fatigue curves in PD 5500 are derived from welded samples tested under load-controlled or for applied strains exceeding yield, strain-controlled fatigue tests. The PD 5500 fatigue curves are based on the mean minus two standard deviations of the S-N curves corresponding to 97.7% probability of survival. These fatigue curves basically incorporate mean stress, so the effective stress ranges are not corrected due to mean stress. A limitation of PD 5500 is that the fatigue curves are limited to 660°F (350°C) for ferritic steels and 800°F (430°C) for austenitic stainless steels.

German Technical Rules for Steam Boilers, TRD [7]

Even though TRD does not provide a detailed method for fatigue evaluation it allows the designer to determine effective stress concentration factors due to internal pressure and thermal gradients, and states that significant external loads shall be calculated separately. Detailed stress analysis can be used to determine stress concentrations or the stresses themselves. Once the stresses are known the fatigue rules in TRD can be used to determine cycle life. TRD uses the classical approach in fatigue evaluation and the fatigue curves are based on unnotched samples. Like ASME, the design margins are built into the fatigue curves. These design margins are believed to be the same as AD-Merkblatt S2 (1988 edition) [14], which are 1.5 on the stresses and 10 on the number of cycles applied to the fatigue failure curves based on the onset of an observable crack. The fatigue curves are adjusted for temperature and are provided up to 1100°F (600°C). An effective stress range is calculated using the mean stress (Gerber rule), since the TRD fatigue curves are not adjusted for mean stress.

European Standard for Water-Tube Boilers, EN 12952-3 [8]

EN 12952-3 uses the classical approach for detailed fatigue evaluations and is very similar to ASME VIII-2. The basic difference between EN 12952-3 and ASME VIII-2 is that the fatigue curves in EN 12952-3 are not corrected for mean stress. The effective stress range calculated in EN 12952-3 incorporates mean stress correction, temperature and notch correction factors before using the fatigue curves. The fatigue curves used in EN 12952-3 do not include any design margins, so the designer is required to apply factors of 1.5 on stress and 10 on cycles. The fatigue curves appear to originate from AD-Merkblatt S2 (1990 edition) [15], and are based on unnotched samples. These fatigue curves are based on room temperature tensile stresses and a temperature correction factor is applied to the effective stress range. The temperature correction factor allows the fatigue curves to be used up to 1100°F (600°C).

European Standard for Unfired Pressure Vessels, EN 13345 [9]

EN 13345 provides two different detailed fatigue evaluation procedures, one for welded zones and one for unwelded zones. The welded joint approach used in EN 13345 is very similar to that in PD 5500. Linearized stresses due to gross structural discontinuities are determined and these are termed “structural stresses.” Structural stresses do not include notch effects of local structural discontinuities as those that give rise to non-linear stress distributions across the thickness (e.g. weld toe). Structural principal stress ranges are determined for each loading case. If structural principal stresses change direction during cycles, equivalent structural stresses are determine from the linearized component stress ranges based on Tresca theory. Effective structural stress ranges are determined by incorporating correction factors for thickness and temperature. The notch effects at the welds are picked up by classification of the ten different fatigue curves. The fatigue curve classifications are determined by associating weld attachment construction details, direction of stresses, and the degree weld joint examinations with “class of weld details.” Like PD 5500, the fatigue curves are derived from welded samples tested under load-controlled or for applied strains exceeding yield, strain-controlled fatigue tests. The fatigue curves are approximately three standard deviations of log base 10 of the cycles [log(N)] below the mean curve and represent a probability of failure of about 0.14%. The fatigue curves basically incorporate mean stress, so the effective stress ranges are not corrected due to mean stress. A limitation of EN 13345 is that the fatigue curves are limited to 720°F (380°C) for ferritic steels and 930°F (500°C) for austenitic stainless steels.

For unwelded zones, a variation of the classical approach is used. The total stress that includes both gross and local structural discontinuities and the structural stress are determined. With the total stress and structural stress an effective stress concentration factor is determined along with equivalent stress range. Correction factors for thickness and temperature are applied to the equivalent stress ranges, and then mean stress correction is applied. The fatigue curves are derived from load-controlled or, for applied strains exceeding yield of strain-controlled fatigue tests on unnotched polished samples with the failure mode being crack initiation. The curves incorporate design margins of 10 on cycles and 1.5 on stress. Unwelded zones include the inside crotch of integral “set-in” self-reinforced nozzles, since the weld does not influence this area.

Fatigue evaluations in EN 13345 are very similar to those in German pressure vessel standard AD Merkblatt S 2 (1995 edition) [16]. One difference is that the temperature correction in AD Merkblatt S 2 allows, the fatigue curves to be used to 1110°F (600°C).

Discussion of Detailed Fatigue Evaluation Methods

From the descriptions provided above it is obvious that detailed fatigue evaluation methods vary greatly in the approach. Any of the methods are acceptable, but the results differ due to design margins and basis of fatigue curves. See Table 2 for example of the variation in allowable cycles of various codes/standards. With the welded joint approaches used by PD 5500 and EN 13345, the effects of welding are directly considered in the fatigue curves. The difficult part of the weld joint approach in EN 13345 is the determination of the structural stress, which requires an extrapolation procedure. The detailed fatigue evaluation methods in EN 12952-3 focus on water boilers and are considered very useful for HRSG’s.

CREEP AND FATIGUE INTERACTION METHODS

Creep occurs in components that are stressed at elevated temperatures for long periods of time, such as HP Superheaters and Reheaters. The creep damage is based on the length of time the component is stressed at a particular magnitude and temperature. Therefore, the creep damage at a particular stress and temperature is the ratio of time of operation to allowable time for creep. The total creep usage fraction is the summation of the individual creep damage ratios. For fatigue, the cumulative damage based on Miner’s rule is used. In TRD 508 [17] and EN 12952-4 [18], the summation of the cumulative creep damage and the cumulative fatigue damage is kept less than one. As stated previously, TRD requires the cumulative fatigue damage factor to be less than or equal to 0.5, therefore the cumulative creep damage factor is required to be less than or equal to 0.5; these restrictions are not part of EN 12952 Parts 3 and 4. In TRD 508 and EN 12952-4 the stress level used in individual creep damage ratios is the calculated membrane stress. The allowable time for creep is based on the time it takes for this membrane stress to reach a theoretical lifetime based on 80% of the average creep rupture strength at the specified temperature. The TRD 508 and EN 12952-4 method for creep life determination is simplified but an effective method for creep consideration and for creep-fatigue interaction. Using the membrane stress is practical for creep since secondary and peak stresses relax during creep conditions. Maximum and minimum stresses in HRSG components normally occur during very short time periods in startups and shutdowns and at temperatures where creep is not a consideration. So fatigue is not considered to occur at the same time as creep.

For detailed creep and creep-fatigue evaluation ASME Section III, Subsection NH [19] can be used. Subsection NH was written for nuclear component design and is very complicated, time consuming, and is not considered useful for every day designs of HRSG components. The TRD 508 rules have proven to be satisfactory for HRSG creep and creep-fatigue design, and the EN 12952-4 rules are essentially the same as the TRD rules. The TRD 508 and EN 12952-4 rules are for in-service monitoring of creep and creep fatigue life of water tube boilers, but are used for creep and creep-fatigue evaluations. ASME Section I design rules are based on allowable stress criteria of 100,000 hours in creep, but most HRSG design requirements are for 200,000 to 250,000 hours. TRD and EN 12952, both provide allowable stress values based on creep as high as 250,000 hours. So TRD and EN 12952 consider long term creep in the basic design. For ASME Section I designs, HRSG manufacturers' can consider creep by using the creep data in API 530 [20], BS 1113 [21] or EN 10216-2 [22].

MAGNETITE LAYER CRACKING

A magnetite (Fe_3O_4) layer develops on the inside surfaces of HRSG components and this layer protects these components from dissolved oxygen corrosion. A belief of some in the HRSG industry is that the magnetite layer attached to the steel can crack due to high surfaces stresses in the steel. Others in the HRSG industry feel that magnetite layer issues are not associated with stress at all and setting arbitrary allowable stresses values due to magnetite layer protection should not be done. Despite this disagreement, some standards require a stress check to prevent magnetite layer cracking. For HRSG components in water or water and steam mixtures made from ferritic and martensitic steels, TRD 301, EN 12952 and EN 13345 restrict internal surface stress levels to prevent the protective magnetite layer from cracking. The magnetite layer is assumed to form at operating conditions, so no stress is considered in the layer at operating conditions. Stresses in the layer are considered to be in compression after shutdown and during startup the layer stress can go into tension. The surface stress range allowed is 116 ksi (800 MPa), but the permitted tensile stress is limited to the stress at operation plus 29 ksi (200 MPa). These stresses include the stress concentration effects, and the magnetite layer requirements can govern startup or shutdown rates in HP Remote Steam Drums.

SUMMARY

Many boiler and pressure vessel codes and standards provide fatigue evaluation methods that can be used to assess the life of HRSG's. Most of these codes and standard provide several methods ranging from exemption from fatigue evaluation to detailed fatigue evaluations. There are other codes and standards and other methods such as fracture mechanics, which can be used to evaluate fatigue as well. The results vary from method to method and this is mainly due to the basis of the fatigue design curves (S-N curves) and design margins. See Table 3 for a comparison of various codes for a HP Steam Drum Downcomer Nozzle**.** HRSG manufacturers use fatigue evaluation methods most suited for the components they provide. Many manufacturers use the TRD or EN 12952-3 rules, since these rules specifically focus on water tube boiler fatigue. Also, TRD has many years of proven use. Fatigue evaluations using EN 12952-3, which are similar to TRD, are beginning to be the accepted practice in Europe and are being more widely recognized in North America. The fatigue evaluation methods presented in this paper can be used to supplement HRSG designs to ASME Section I and ASME Section VIII, Division 1.

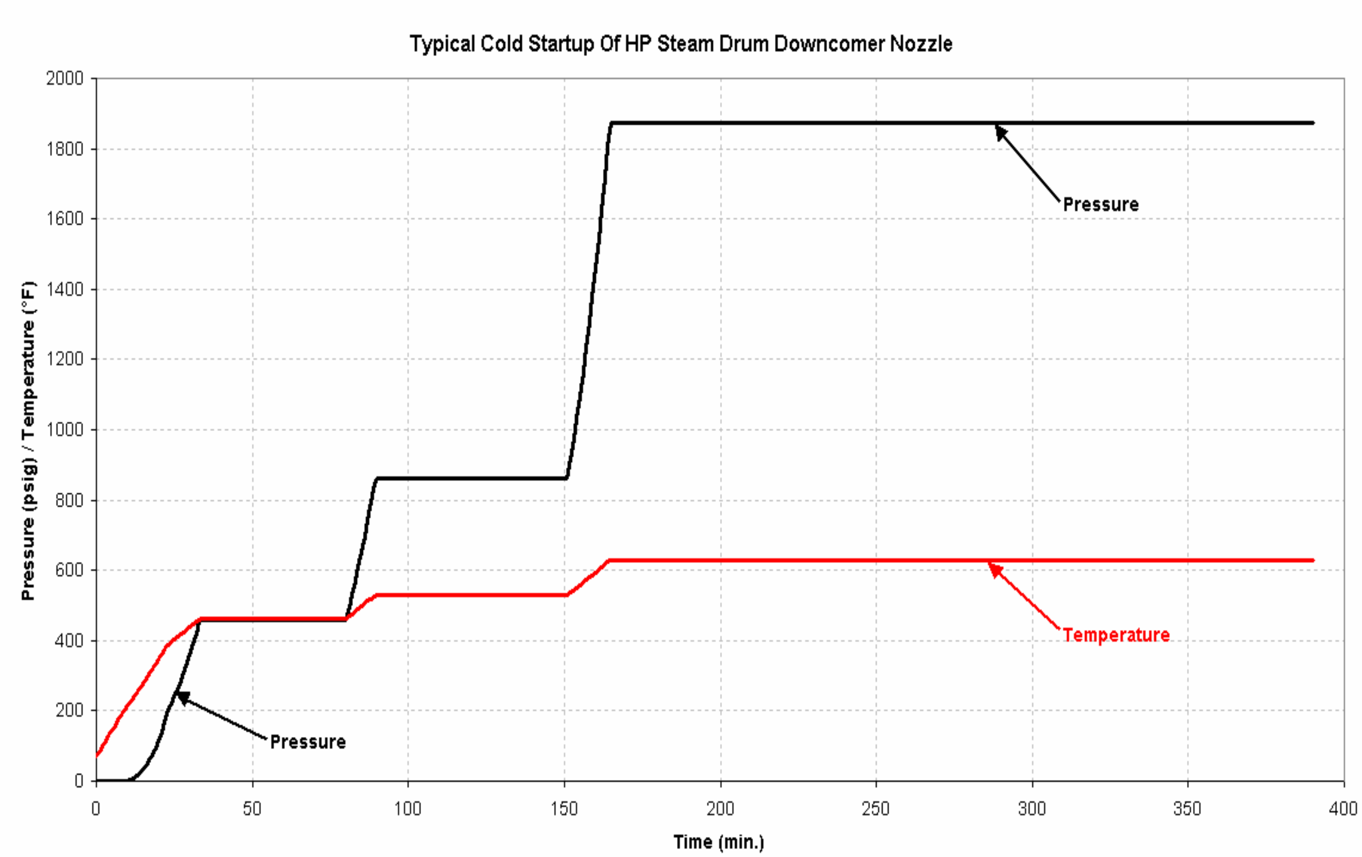

Figure 1: Typical Cold Startup Curve For HP Steam Drum Downcomer Nozzle

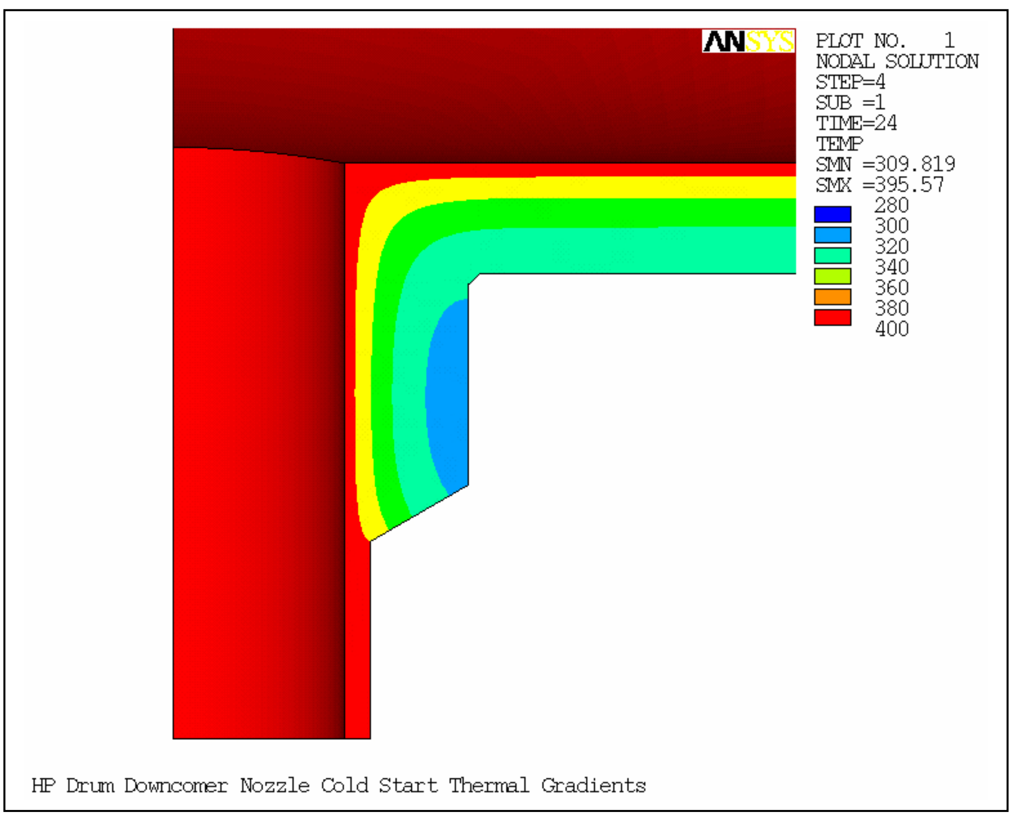

Figure 2: Example Of Thermal Gradients From Finite Element Analysis Of A Downcomer Nozzle In A HP Drum During Cold Startup

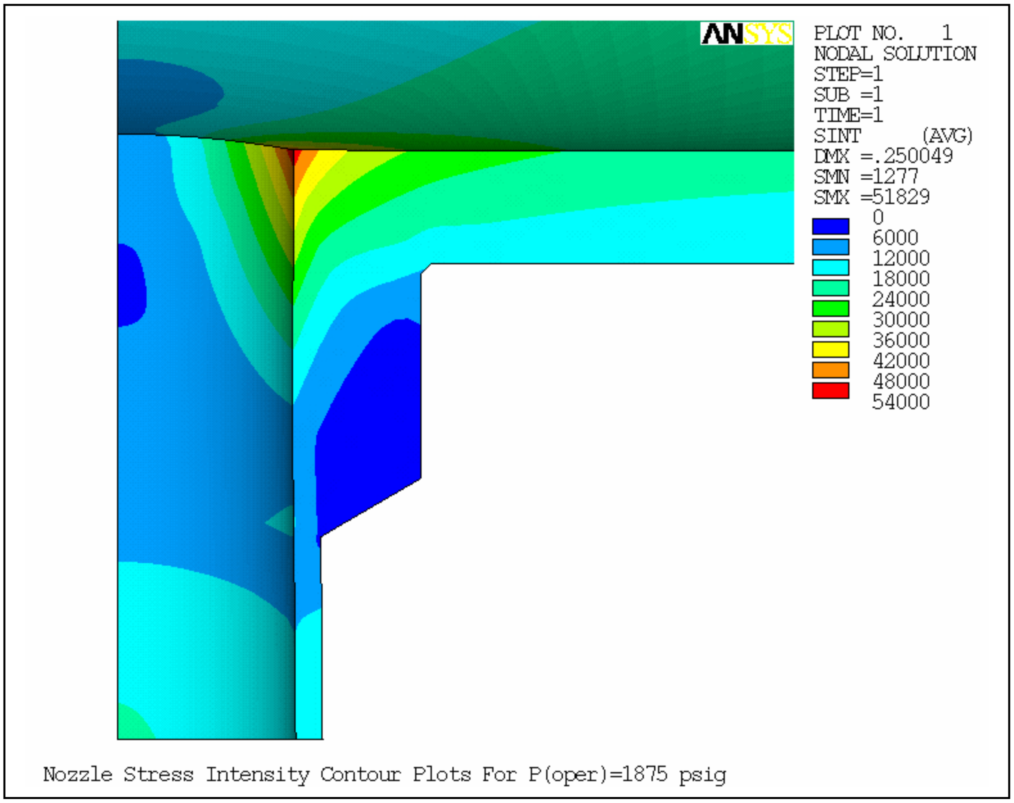

Figure 3: Example Of Stress Intensities From Finite Element Analysis Of Downcomer Nozzle In HP Drum Due To Operating Pressure

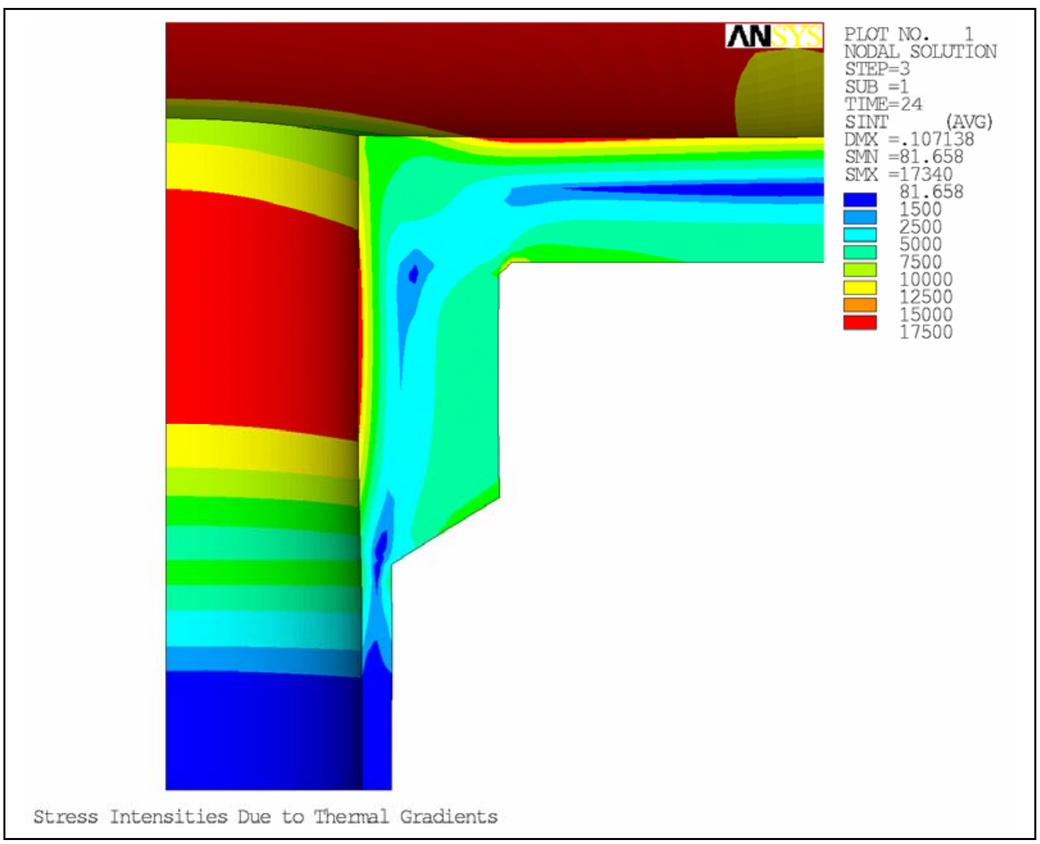

Figure 4: Example Of Stress Intensities From Finite Element Analysis Of Downcomer Nozzle In HP Drum Due To Thermal Gradients At Cold Startup

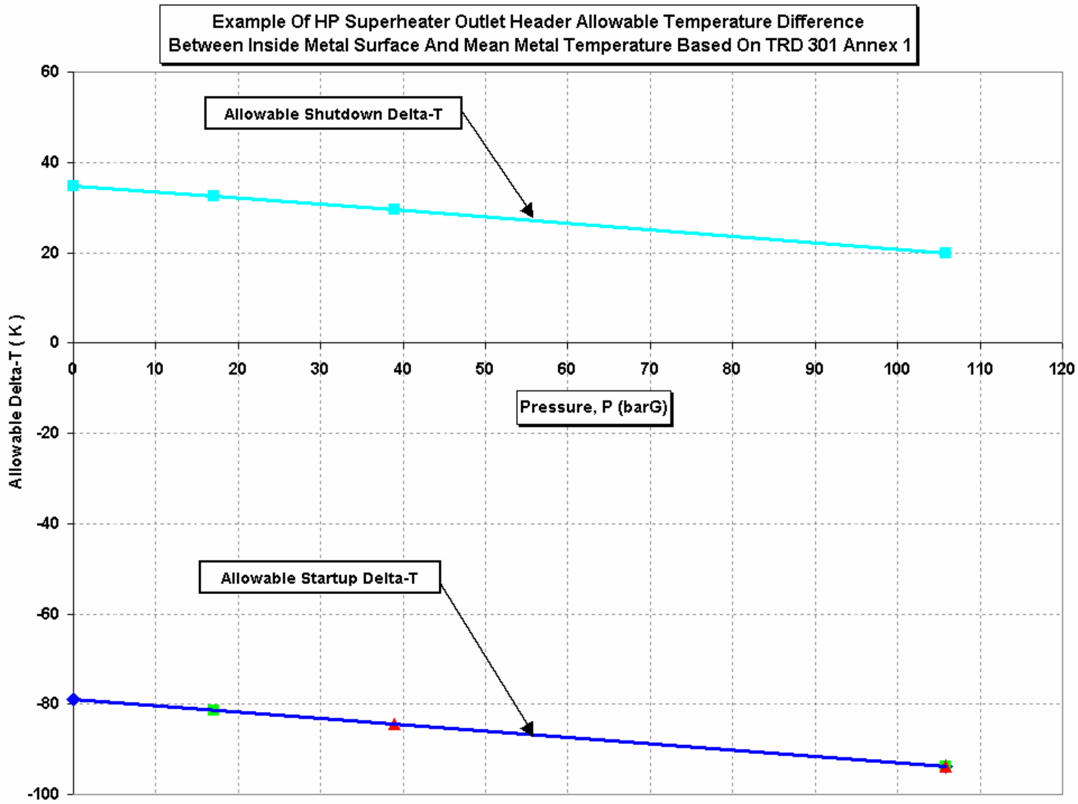

Figure 5: Example Allowable Delta-T Curves For Startup And Shutdown Of A HP Superheater Outlet Header.

Cycle Designation	Time of Standstill	HP Pressure psig	HP Drum Temperature (°F)	Number of Cycles
Cold Starts	time ≥ 60h	0	Temp. ≤ 240	250
Warm Starts	60h < time ≤ 12h	10	480 ≤ Temp. < 240	400
Hot Starts	12h < time ≤ 2h	1585	Temp. > 600	1600
Normal Operation	250,000 h (Total)	1875	625	-
30% Load Changes	Not Applicable	Ramp 72 psig/min	Not Applicable	4000
20% Load Changes	Not Applicable	Ramp 72 psig/min	Not Applicable	4000
10% Load Changes	Not Applicable	Ramp 72 psig/min	Not Applicable	5000
Shutdown	-	-	5°F/Min.	After Each Start

Table 1: Example of Cyclic Operation For HP Steam Drum

Code/Standard	Allowable Cycles for Stress Range of 60 ksi (414 MPa) (1)
ASME VIII-2	16630
EN 12952-3 (2)	174640
PD 5500:2000 (3)	4990
TRD 301 Annex 1 (2)	158000

Notes:

(1) Based on SA-516 Grade 70 material at 400 °F (204°C)
(2) Mean stress correction required.
(3) Based on Curve Classification C.

Table 2: Example of the Variation in Allowable Cycles of Various Codes/Standards

Comparison Of Fatigue Results Based On Various Codes For HP Drum Downcomer Nozzle Using The Cycles Defined In Table 1			
Code/Standard	Fatigue Exempt	Life Fraction Based On Simplified Fatigue Methods (6)	Life Fraction Based On Detailed Fatigue Methods (6)
ASME VIII-2	YES (1)	Not Applicable (5)	0.030
EN 12952	YES (2)	0.044	0.004 (7)
PD 5500	YES (3)	Not Applicable (5)	0.080
TRD 301	YES (4)	0.405	0.004 (7)

Notes:

(1) Both Conditions A and B of AD-160
(2) Based on Clauses 13.3.2 and 13.3.3
(3) Based on Clause C.2.3. Was not exempt per Clause C2.2.
(4) Based on Clause 6.1
(5) No simplified method for calculating stresses due to thermal gradients used.
(6) Based on stresses at the inside corner nozzle bore.
(7) Fatigue curves in EN 12952-3 and TRD 301 Annex 1 are not as conservative as those in ASME VIII-2, see Table 2.

Table 3: Comparison of Fatigue Results of Various Codes for a HP Steam Drum Downcomer Nozzle

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