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Environmentally-Assisted Fatigue Screening

Process and Technical Basis for Identifying Environmentally-Assisted Fatigue Limiting Locations

(pending EPRI technical report)

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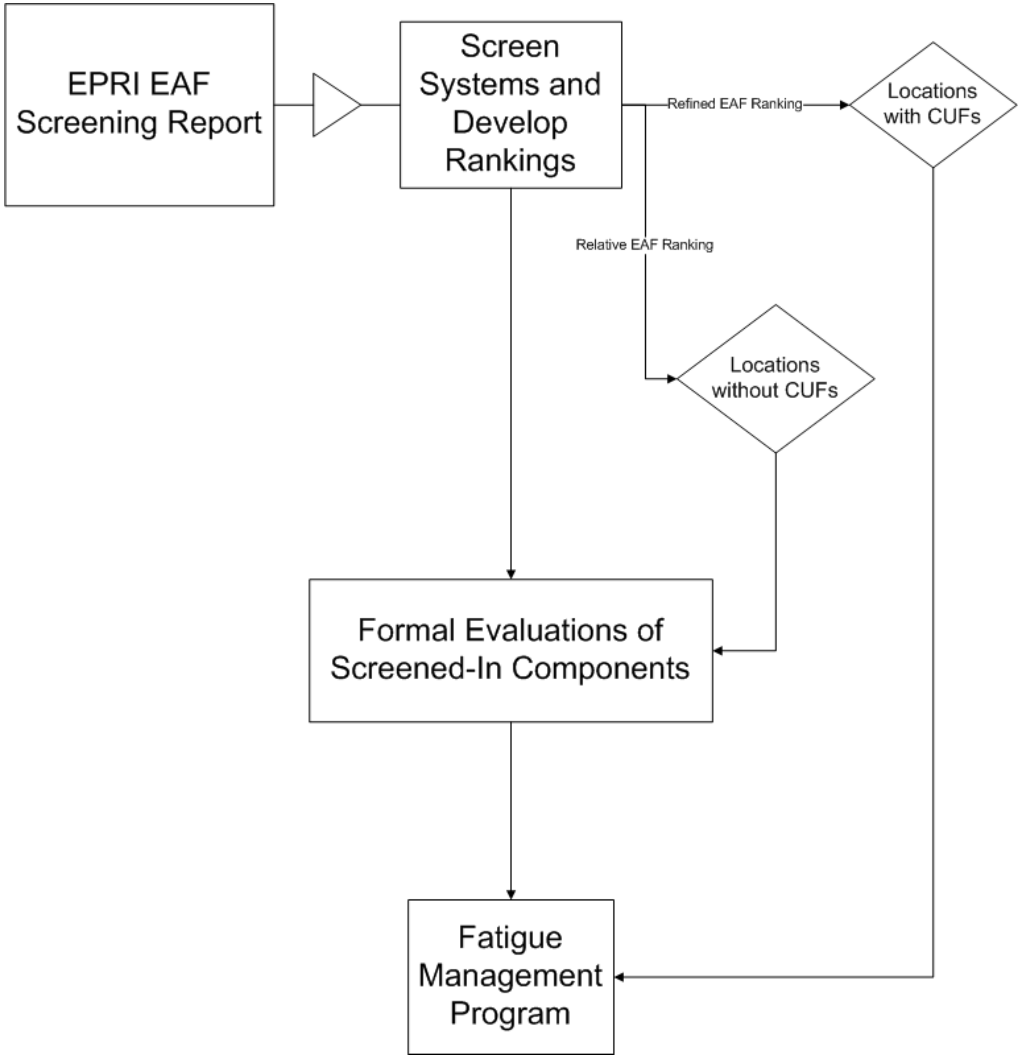
Presentation Objective

- Present EPRI-sponsored proposed technical basis and process for environmentally-assisted fatigue screening.
- Show that approach described meets the need of GALL Rev. 2 for EAF screening.

Where Report Fits Into Overall Program



EPRI EAF Screening Report

Screen Systems and Develop Rankings

Refined EAF Ranking

Locations with CUFs

Relative EAF Ranking

Locations without CUFs

Formal Evaluations of Screened-In Components

Fatigue Management Program

General Objectives of EPRI Report

- Define a process for environmentally-assisted fatigue screening and ranking of components in nuclear power plant Class 1 systems.
- Describe the technical basis for the process
- This process:
  - must be effective for PWRs and BWRs, both with ASME Section III / B31.7 piping and B31.1 piping.
  - can be used to screen plant locations in order to rank them on the basis of environmentally-assisted fatigue. These ranked locations can then be compared to the NUREG/CR-6260 sample locations and may augment a plant's Fatigue Management Program (FMP).
- The desired outcome of this process is to determine plant locations which can be demonstrated to bound other locations of like materials and can serve as limiting environmentally-assisted fatigue locations for the plant.

Challenge

- License Renewal rules require that applicants demonstrate fatigue management including environmentally-assisted fatigue effects.
- The NUREG/CR-6260 locations were identified as a sample of locations to evaluate for environmentally-assisted fatigue and to include in the plant Fatigue Management Program.
- The challenge is to know if the NUREG/CR-6260 locations bound the plant for environmentally-assisted fatigue effects.
- If the NUREG/CR-6260 locations do not so bound, add bounding locations to FMP.

Criteria for Process

- The screening and ranking procedure developed has the following properties:
  - No requirement for new formal stress or fatigue analysis.
  - Includes procedures that are practical to use, with readily available design input.
  - Provides appropriate *relative* environmentally-assisted fatigue rankings of components.
  - Allows the use of either NUREG/CR-5704 (stainless steel)/6583 (carbon and low alloy steel)/6909 (Ni-Cr-Fe) or just NUREG/CR-6909 for all materials.

Benefits

License Renewal

- This process will enable plant owners to demonstrate knowledge of the locations in their plant that can serve as limiting locations for environmentally-assisted fatigue evaluations.
- This process provides the rationale for selecting these bounding locations.
- Plant owners will minimize the necessity of formal fatigue analysis, while meeting the regulatory requirements for determining the bounding environmentally-assisted fatigue locations in the plant.
- NRC staff can examine one possible uniform approach to determination of limiting locations for EAF evaluations for license renewal applications.

Approach

- Need relative measure for comparison.
- Not resorting to simplifications to identify locations with complex loading.
- Estimate of CUF and F_{en} necessary without requiring formal stress/fatigue analysis.
- Some complicating features are present.

More Challenges - CUFs are Not Equal

- Determination of this list of bounding locations is not as straight forward as multiplying each design CUF value by a factor or factors. Examples of the complicating factors are:
- Not all CUF values represent the same degree of analytical rigor.
  - Analysis of design severity plant transients produces different CUF values for a component than analysis of actual severity plant transients.
  - Analysis using “bundled transients”(1) yield significantly higher CUF values than analyses of the same component with “un-bundled” transients.
- For a given plant transient, F_{en} factors often will trend counter to the computed CUF values, thus potentially complicating the ranking of the CUF_{en} (CUF considering environmental influence on fatigue) values for a component.
  - Faster rise times for a thermal transient will tend to produce lower F_{en} factors, but larger CUF values. Since $U_{en} = F_{en} \times U$, the product of the two is not known a priori without further analysis.
- Analysis of design numbers of plant transients can yield different rankings of CUF and CUF_{en} values than analyses of projected numbers of plant transients.
  - The two different mixes of plant transients, each with their unique transient characteristics, can cause the weighted F_{en} factors and CUF_{en} values to vary significantly.

(1) *Bundled Transients*: Enveloping of multiple plant transients by one conservative plant transient.

CUF_{en}'s Vary by Material and DO

- Different materials of construction exhibit different environmentally-assisted fatigue characteristics, even in the same component.
  - The same plant transients applied to one component will produce different U_{en} values for different material of construction.
  - DO content affects materials of construction differently and varies by NUREG rule.

More Differences

- Further factors that influence the evaluations are:
  - Use of the alternate rules of NUREG/CR-5704 (stainless steel) and NUREG/CR-6583 (carbon and low alloy steel) will produce somewhat different values of F_{en} than the newer rules of NUREG/CR-6909 for those materials.
  - Components in similar plants will likely have similar estimated CUF_{en} characteristics, although some may have computed CUF values and others may not. This conclusion is based on an EPRI review of piping fatigue [1] where it was determined that:
    - Although ANSI B31.1 and ASME Code, Section III, Class 1 piping rules are fundamentally different, experience in operating plants has shown that piping systems designed to B31.1 are adequate.
    - The operation of B31.1 plants is also not different from that of plants designed to ASME Code, Section III, Class 1.

[1] EPRI Report "Fatigue Comparison of Piping Designed to ANSI B31.1 and ASME Section III, Class 1 Rules," TR-102901, EPRI, Palo Alto, CA, December 1993.

Solution and New Terms

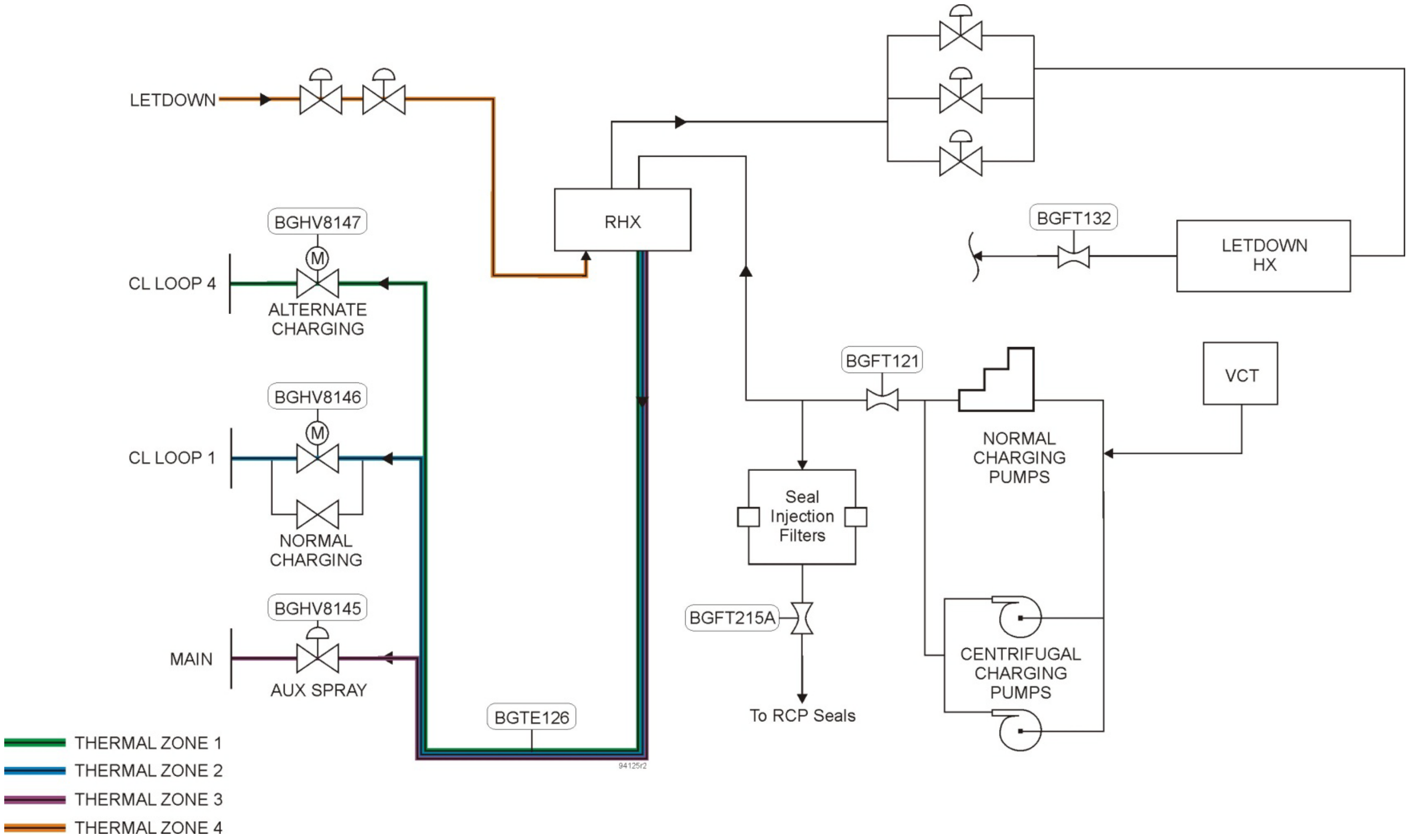
- Provide a robust solution without necessarily requiring a complete reanalysis. EPRI has developed a process for screening all the fatigue-sensitive components in a plant by ranking them in terms of CUF_{en} and then determining a set of *Sentinel Locations* such that each plant component is covered by one or more sentinel locations.
  - A *Sentinel Location* is a specific location in a piping system or vessel that serves as a leading indicator for environmentally-assisted fatigue damage accumulation. Sentinel locations are expected to accumulate more CUF_{en} than other locations and remain bounding as plant transients occur in plant life.
  - A *Thermal Zone* is defined as a collection of piping and/or vessel components which undergo essentially the same group of thermal and pressure transients during plant operations.

Sentinel Locations

- The sentinel locations in a thermal zone may be thought of as a Peloton, which refers to a densely packed group of bicycle racers. A leader is established, but over time a new leader may emerge as the transient mix accumulates.

Peloton

Thermal Zones



Process Basis

- For the reasons discussed, it is necessary to evaluate components and/or locations in a component on a *uniform common basis* to accomplish valid ranking and identification of sentinel locations in each thermal zone. Plants with explicit fatigue design bases (have CUF values) can have:
  - Sets of components evaluated to a reduced, “bundled” set of plant transients and/or a mixture of bundled and unbundled transients.
  - Components or locations in components evaluated to additional refined analyses (e.g., elastic-plastic analysis) while other components or locations are not.
- To assure uniform determination of relative fatigue accumulation, these differences must be accounted for or eliminated. The screening processes are designed to make this common basis determination.

Process Basis

- The screening process is used to review all Class 1 plant components susceptible to environmentally-assisted fatigue, categorize them into thermal groups, and identify one or more sentinel locations for each thermal group that can be analyzed and monitored for environmentally-assisted fatigue usage.
- The idea of sentinel location extends the basic approach that was used in NUREG/CR-6260 of analyzing a few challenging locations to represent the entire plant, but adds a semi-quantitative ranking system to demonstrate that each plant component is represented by at least one sentinel location.
- The idea of a thermal zone has been used for many years in piping analysis to both group and differentiate locations based on operating transient conditions.

Process Flow

- Make F_{en} estimation
  - Qualitative estimate of strain rate
  - Develop expected F_{en} (F_{en}*) as the average of the Best Estimate F_{en} for leading transient and the Maximum F_{en}
  - Compute U_{en}* for locations
- Compute estimated CUF (U*) and estimated CUF_{en}(U_{en}*)
  - Select leading transients
  - Compute thermal through-wall stresses
  - Extract bending moment and seismic stresses from DSR
  - Evaluate leading load pairs and determine estimated U* and U_{en}* Rank locations by U_{en}*, material type, thermal zone and compare to 6260 locations

Outline of Process Steps

This screening process consists of four stages:

1. Data Collection
    - Component geometry and material properties, plant transient characteristics and projections of plant transients for the licensed operating period.
2. Determination of Thermal Zones
    - Components are assigned to appropriate thermal zones and evaluated as a group. This allows definitive rankings to be determined.

Outline of Process Steps

3. Evaluation of Locations
   - Establish *relative* stress, CUF and CUF_{en} values.
   - Common basis approach.
   - Mitigates skewing effects of refined analyses (such as elastic-plastic analysis) for selected components.
   - Ranking on a common basis assures most highly stressed and cycled locations in each thermal zone are identified as leading indicators of fatigue damage for the thermal zone.
4. Ranking and Identification of Sentinel Locations
   - An estimated U_{en}* is determined.
   - Locations within each group with the highest estimated U_{en}* are reviewed to determine one or more sentinel locations.

Process Development Assumptions and Characteristics

- Thermal zones are employed to provide consistency in development of estimated F_{en} values and common basis stress approximations.
- Common analytical basis (un-bundled transients) is used to put all analyses in a thermal zone on the same transient basis.
- Calculated plant piping loads and stresses are used instead of piping attachment point umbrella loads.
- Design severity transients (can use actual severity, if available and consistently applied) are used.
- Geometric factors are applied to stress terms.
- Materials of construction are evaluated together as a group in each thermal zone.

Process Development Assumptions and Characteristics

- Several assumptions are inherent in the process:
  - An estimated F_{en} method is sufficient for a screening process; this process is not intended to provide an ASME qualification of components.
  - Several characteristics of the process are important.
    - Linear elastic stress analysis and superposition of stress contributions are used.
    - The F_{en} factor is applied only for increasingly tensile portions of transients, based on the guidance of MRP-47 [1].
    - The K_e factor is included in both the determination of strain range and estimated strain rate (consistent with proposed ASME-Code Case N-792-1).

[1] Materials Reliability Program: Guidelines for Addressing Fatigue Environmental Effects in a License Renewal Application, MRP-47, Revision 1, September 2005.

Result of Screening Process

- The result of this screening process is a listing of fatigue-sensitive reactor coolant pressure boundary components, organized into groups, ranked by CUF_{en} severity, with at least one sentinel location identified for each group of components.

Evaluation of Locations

- Two analytical evaluation procedures are developed to aid in the evaluation process:
  - one to perform F_{en} *Estimation Evaluations*
    - For plants with explicit fatigue design basis (CUFs) (e.g., Section III or B31.7 piping)
  - one to perform *Common Basis Stress Evaluations*
    - For plants with explicit fatigue design basis but non-uniform transient bundling
    - For plants without explicit fatigue design basis (e.g., B31.1 piping)

F_{en} Estimation Evaluation Procedure

F_{en} Estimation Evaluation Procedure

- Used to estimate F_{en} for locations in plant components on the basis of the relevant parameters – dissolved oxygen, maximum temperature and estimated tensile strain rate – of the leading transient(s).
- The procedure is developed to use:
  - For plants with and without explicit fatigue design analyses available.
  - With design transients or actual transients (consistently applied).
  - With design numbers of transients or licensed operating period (e.g., 60-year) projected numbers of transients.

Technical Basis for F_{en} Estimation Evaluation

- For screening, the rules for calculating F_{en} values may either be taken from NUREG/CR-5704 for stainless steel material, NUREG/CR-6583 for carbon/low alloy steel material and NUREG/CR-6909 for Ni-Cr-Fe material, or from NUREG/CR-6909 for all materials.
- These rules allow calculation of F_{en} factors based on the material at the postulated failure location (SS, CS, LAS and Ni-Cr-Fe) and the following environmental parameters:
  - Estimated strain rate ($\dot{\varepsilon}$), during the transients, in [%/sec].
  - Concentration of dissolved oxygen (DO) in the water, in [ppm].
  - Maximum fluid/metal temperature (T) during the transients, in [°C].
  - (Note: sulfur content of the metal (S) is also a factor for CS and LAS. However, this procedure will conservatively assume all CS/LAS components have the worst possible sulfur content.)

Technical Basis for F_{en} Estimation Evaluation

- Since the procedure is an aid to a screening evaluation for relative ranking, exact values of these parameters are not calculated from qualified design input. Instead, estimated values are determined based on familiarity with operation of the various plant systems and components during both normal operation and the transient conditions as defined in the plant design specifications. Specifically:
  - Any components which have no exposure to the “environment” (i.e., heated primary/secondary coolant water) are assigned an F_{en} value of 1.0.
  - Any transients associated with fast transients (e.g., seismic) may be assigned an F_{en} value of 1.0.
  - A qualitative estimate of the strain rate ($\dot{\varepsilon}$) for the controlling fatigue transient(s) will be determined, based on knowledge of the corresponding plant system. Each component will be identified with one of eight possible categories shown in Table 3-1.

Technical Basis for F_{en} Estimation Evaluation

Table 3-1
Strain Rate Categories

	Strain Rate Category	Estimated $\dot{\varepsilon}$ [%/sec]
	Extreme	≥ 5.0
	V.High	~ 1.3
	High	~ 0.33
	Mid-High	~ 0.087
	Medium	~ 0.023
	Low-Mid	~ 0.0059
	Slow	~ 0.0015
	V.Slow	≤ 0.0004

Technical Basis for F_{en} Estimation Evaluation

- An estimated DO value of “Low” (≤ 0.04 ppm) will be applied for all components exposed to reactor water for PWRs. This determination is based on the observation that for the entire history of most PWRs, the concentration of dissolved oxygen is maintained below 0.04 ppm at all times when water temperature is ≥ 150°C (302°F) (with rare exceptions). (Note: when water temperature is below 150°C, DO is no longer a factor in the value of F_{en} for any of the materials considered in this procedure.) For BWRs, the DO values must be determined based on the procedural policies of the plant for water chemistry control.
- An estimated upper-bound T value will be determined based on the collected design transients for the respective plant systems (for NUREG/CR-6909 evaluations, an average T value is used).

Technical Basis for F_{en} Estimation Evaluation

- For each component, this evaluation computes two hypothetical F_{en} values, one using the estimated parameter values described above, and the second using the same estimated values for DO and T, but using the worst possible (i.e. most conservative) value for strain rate.
- These two computed values are averaged to produce an expected F_{en} for each component. This two-part expected F_{en} is based on experience with performing detailed F_{en} analyses; in general, the estimated F_{en} from a detailed analysis is close to the F_{en} value computed for just the controlling transient pairs, but slightly higher due to contributions from the less-significant fatigue pairs.
- A simple average is judged to magnify the contributions of the less-significant transient pairs to yield a reasonably conservative value suitable for ranking without performing a detailed analysis.

Common Basis Stress Evaluation Procedure

Common Basis Stress Evaluation Procedure

- Procedure based on the rules of ASME NB-3600 modified to address a screening evaluation for relative ranking of locations. Rationales for this approach are that:
  - Majority of the components in the screening population are piping components for which the rules of NB-3600 are appropriate.
  - NB-3600 equations are explicitly defined and require minimal analyst interpretation so that they can be easily included in a spreadsheet.
  - NB-3600 rules are representative of the more general rules of ASME NB-3200 design by analysis, which are appropriate for Class 1 plant components.

Common Basis Stress Evaluation Procedure

- Used for components where:
  - no explicit design fatigue analysis is available, or
  - where is it desired to put components with a fatigue analysis on a common basis
- The user will estimate a common basis CUF.
- The Common Basis Stress Evaluation Procedure is used to perform the following stress computations to determine the common basis CUF:
    - Through-wall transient thermal stresses are computed for leading transients. Transients with thermal shocks are found to be the leading fatigue usage contributor in piping and vessel stress analyses.
    - Piping moment range stresses and pressure stresses are extracted from the plant piping Class 1 stress report. Use of actual piping results avoids the use of piping umbrella loads and helps differentiate moment loadings for locations within a piping system.
    - Peak stresses at discontinuities are accounted for using SCF/FSRFs taken from the ASME Code.

Rationale for the Common Basis Stress Evaluation Procedure

- Taking guidance from the EPRI Fatigue Management Handbook [1], formulas have been developed to compute stresses arising from maximum transient through-wall temperature distributions, axial temperature differences, thermal and mechanical bending stresses and geometric characteristics for piping and vessel components. These formulas ensure a common level of analysis so that the computed stresses are directly comparable between locations.
- These formulas assume that the stresses are linear elastic, and so may be combined using linear superposition. Non-linear plasticity effects are accounted for using elastic-plastic penalty factors (K_e) in accordance with ASME Code Subarticles NB-3200 and NB-3600. Use of linear elastic rules for computing CUF retains technical parity among the components in a thermal zone. By contrast, using elastic-plastic non-linear techniques in a fatigue analysis may significantly reduce the computed CUF for that component, which would give it a much lower CUF than other locations with comparable fatigue duty.

[1] Materials Reliability Program: Fatigue Management Handbook, MRP-235, Revision 1 (with corrections)

Rationale for the Common Basis Stress Evaluation Procedure

- The linear elastic stress state for a location may be computed as the linear summation of the individual stresses caused by various types of loads. Most pressure vessels and piping system components include stresses due to internal pressure, thermal (due to temperature distribution in the component), and boundary interface loads, such as forces and moments caused by thermal expansion, thermal stratification, anchor displacement, seismic movement, etc. Deadweight and residual stresses may be ignored, because they do not vary with time and therefore do not impact the computed stress range.
- For a linear elastic stress analysis, stress contributions may be classified as one of two types:
  - Stresses due to loads, such as pressure, piping thermal expansion, etc. that are directly scalable to pertinent parameters (pressure, temperature, etc.), and
  - Time-dependent thermal stresses, which depend on the axial and radial temperature distributions in the component rather than any single instantaneous parameter.

Rationale for the Common Basis Stress Evaluation Procedure

- Stress contributions of the second type depend on the temperature history and are typically calculated by a time integration of the product of a predetermined Green's function, or influence function, and the transient temperature data. Performing this integration is more complex than is desired for this screening process. Instead, an estimate of the maximum stress range during each significant thermal transient is computed, as described below. This estimate applies a uniform level of conservatism, and is sufficiently precise to determine a relative ranking among the components in a thermal zone.
- The stress computation combines stresses from the following terms:
  - Through-wall transient thermal stresses are computed using the graph shown in Figure 3-1. For each transient, two non-dimensional factors ($k/(hL)$ and $(kt_0)/(\rho c_p L^2)$) are computed as entry into the curve for the determination of the normalized thermal peak stress.
  - Piping moment range and pressure stresses are extracted from the plant piping Class 1 stress report. Umbrella loads (conservative loads assigned to the system to facilitate design of adjoining systems) are not recommended, as they don't inform the relative severity at different locations.
  - Thermal stratification moment stresses are assumed to be negligible or included in the computed piping moment stress range.
  - Seismic stresses.
  - Peak Stresses at discontinuities are accounted for using appropriate SCFs.

Rationale for the Common Basis Stress Evaluation Procedure

- The *Common Basis Stress Evaluation Procedure* is used to determine approximate stress ranges arising from pairs of selected significant transients, compute alternating stress values including simplified elastic-plastic (K_e) effects, and produce incremental CUF (U_{incr}) for input numbers of plant transients (either design numbers or projected numbers).
- These incremental CUF values are added to produce the common basis CUF (U*). Estimated F_{en} values are computed (using either the older or newer environmentally-assisted fatigue rules), along with an incremental U_{en} for each transient pair.
- These are summed over the significant transients to yield an estimated U_{en}* for that location.

Limitations and Assumptions of the Process

- Stresses caused by complex loading, such as thermal stratification, are not used in the Common Basis Stress Evaluation process. It is typically not practical to compute stratification stresses using this methodology. However, for components subjected to this type of loading, fatigue calculations are expected to have been performed already. Such is the case, for example, with PWR surge lines.
- Likewise, axial thermal gradient stresses produced by geometry or material transitions are also not considered in this process. Branch nozzles without thermal sleeves are commonly subject to stresses caused by axial thermal gradients. Such loading may be attributed to the injection of colder fluid into a hot header, giving rise to significant thermal stresses of a steady state nature near the nozzle corner. Sophisticated fatigue analyses are typically employed to disposition these types of components, and many of them, such as the charging and safety injection nozzles, are the NUREG/CR-6260 locations (the GALL report requires evaluation of the NUREG/CR-6260 locations at a minimum).
- The Common Basis Stress Evaluation process is valid for cylindrical or flat plate components being based on NB-3600 concepts.
- The process does not produce new formal stress results, but uses those results that are available in plant design reports.

Screening Process

1. Gather Required Inputs for Class 1 Vessels and Piping Systems.
2. Determine Thermal Zones for Each System.
3. Identify Materials and Candidate Locations.
4. Calculate U_{en}* Rankings for Each Candidate Location.
   A. F_{en} Estimation Evaluation Procedure
   B. Common Basis Stress Evaluation Procedure
5. For Each Material in Each Thermal Zone perform ranking and sentinel location identification.
6. Evaluate Next Candidate Location.
7. Evaluate Next Thermal Zone.
8. Evaluate Next System.
9. Compile Final List of Sentinel Locations.

Conclusions

- Report provides technical basis of the screening process used to evaluate a plant to determine EAF limiting locations for fatigue monitoring. Procedures for this screening evaluation are described and applied to a pilot PWR plant.
- Process designed to equip license renewal applicants with a consistent method to identify EAF limiting locations additional to the sample locations evaluated in NUREG/CR-6260 for their reactor type and vintage.
- Guiding principles for the screening and ranking process included:
  - Consistent technical basis.
  - Analytical method using readily available design input from P&IDs, piping isometric drawings and piping stress reports.
  - Only basic stress or fatigue analysis required.
- The following are the basic areas of new technology developed by this project:
  - Procedure for Estimating F_{en} Factors.
  - Procedure for Estimating U_{en}.
- An example of the process is provided.

Questions and Comments