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Latest Advances in Fatigue Monitoring Technology Using EPRI's FatiguePro Software

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ABSTRACT

In 1985, EPRI embarked upon the development of an on-line fatigue monitoring system for nuclear power plant components. The resultant system, **FatiguePro**, has been successfully implemented and operated at approximately thirty operating nuclear units world-wide over the past twelve years.

Significant efforts have been expended on the development of the **FatiguePro** software over the past twelve years, and improvements are continuing. These include: (1) enhancements in personal computer capabilities and operating system improvements, (2) lessons learned by the large population of users, and (3) the incorporation of new technical algorithms to address regulatory requirements.

This paper describes the most recent advancements made to the **FatiguePro** software, including: (1) sophisticated thermal hydraulic models to remove the reliance on conservative, design basis, thermal "step" transients, (2) analytical models and extensive field data that address the effects of thermal stratification, (3) advanced thermal stress solutions that accommodate more complex fracture mechanics solutions for fatigue crack growth assessments, (4) environmental fatigue assessments, including those that require difficult strain rate determinations, and (5) a **FatiguePro** User's Group (FPUG) that directs the future enhancement of the software and provides a valuable forum for sharing, solving and responding to industry fatigue-related issues.

INTRODUCTION

The accumulation of fatigue due to plant operation represents a significant aging concern for critical components in operating nuclear power plants. To assure that design safety margins remain adequate throughout the operating life of the plant, varying degrees of comparison are required by the various plant licensing bases to demonstrate that actual operating experience remains bounded by that assumed in the original plant design. Typically, during plant operation, all significant design transient operating cycles are logged and counted in accordance with plant licensing bases to assure that the design fatigue limits are not exceeded. In practice, however, many of the actual plant operating cycles are not well characterized by the design transients. Also, classification of individual plant events into one of the design transient categories is a difficult task, for which plant operators are given relatively little guidance. As a result, some operating plants have approached the limit for allowable design transients early in plant life. In other cases, classification of plant operating cycles may be done incorrectly or inconsistently, resulting in a poor estimate of cumulative usage accumulation. Finally, there have been occurrences of fatigue failures caused by loading not considered in the original design basis (e.g., stratification).

In most cases, the design transients very conservatively bound plant operation. However, in the past, there have been no practical means by which utilities could take credit for this implicit margin, which would extend the useful life of plant components. As a result, new methods of demonstrating adequate design safety margins have been pursued. These methods include cyclic analysis of actual event history and real time computation of cumulative usage factors from actual plant operating data. Modern computers have also made these seemingly complicated tasks easy to implement.

In 1985, EPRI initiated a program to develop a prototype software system for monitoring the cumulative usage factor in nuclear power plant components. A unique methodology was developed which used "Green's Functions" and transfer matrices for accessing plant instrumentation data and converting them directly to peak stress versus time at locations of interest [1]. The methodology was developed into a specialized software system called **FatiguePro. FatiguePro** has been successfully implemented and operated at approximately thirty nuclear units world-wide over the past twelve years. Significant efforts have been expended on the development of the **FatiguePro** software over the past twelve years, and improvements are continuing.

In the following sections, some of the more significant and recent advancements made to the **FatiguePro** software are discussed.

THERMAL HYDRAULIC MODELS

One significant improvement in stress calculations that has been incorporated into the **FatiguePro** software is via the use of thermal hydraulic models that are designed to eliminate the unrealistic "step" temperature changes associated with design transients. These "shower head" models are designed to evaluate the transient temperature response of a component piping/fluid system to varying input temperatures and flow parameters. The shower head model accounts for the upstream temperature instrument, the advance of the fluid flow, and the convective heat loss from the piping (including insulation) between the measured fluid temperature point and the monitored location. The objectives of the shower head model are as follows:

1. To account for the time delay between the plant temperature instruments and the monitored location.
2. To account for heat transfer between the piping, fluid, and ambient air during the transport phenomenon.
3. To account for cooldown of the piping and fluid during stagnant flow conditions.

The analyzed piping system is broken down into multiple segments, as shown for an example BWR feedwater line in Figure 1. Each segment represents a different pipe size. Each element consists of the fluid, piping and insulation in a segment, of piping. The three temperature nodes represent the calculated temperatures in the fluid, piping and ambient air.

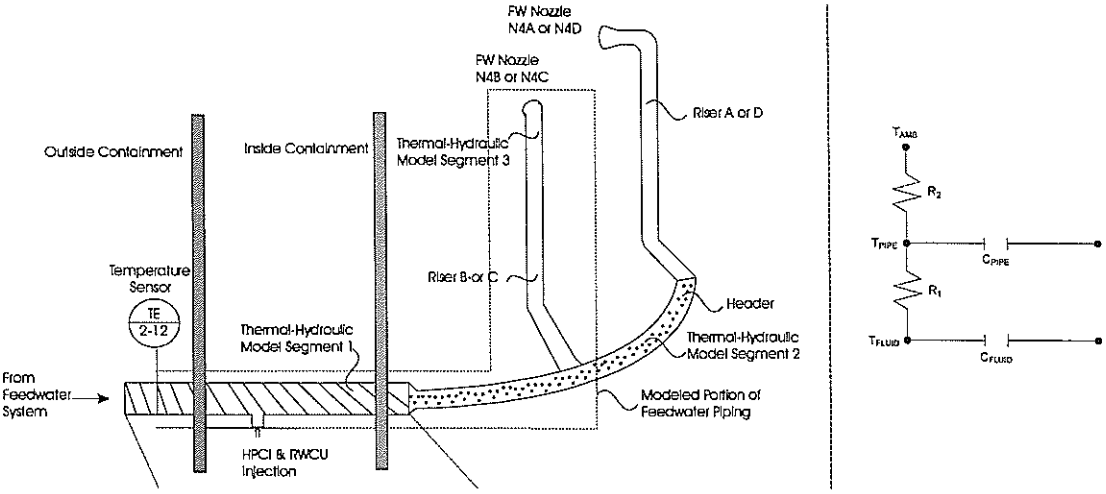

Figure 1: Thermal-Hydraulic Model Segments and Thermal Model of Piping/Fluid System

The following logic is used to compute the temperature at each fluid and piping node:

1. The time period for traversing one element is calculated.
2. For each time step calculated in Step 1:
   a. The temperatures for all elements are transferred to the next element.
   b. The heat transfer to ambient is calculated for each element using the time period calculated in Step 1 above.
3. For stagnant flow conditions, only the heat transfer calculation in Step 2.b above is performed for the integration time period.

If the incoming fluid velocity is high enough that the fluid temperature gradient along the pipe can be neglected, then, for computational ease, all fluid temperature nodes are set to the temperature instrument value, and the heat transfer calculation is performed for the piping temperature nodes.

If there is a time gap in the input data, two cases are considered. If the ending fluid velocity in the previous hour was zero, then it is assumed that the fluid velocity remained zero for the intervening hours and that the fluid and piping nodes were the same temperature. In this case, an exponential cooldown is used. If the ending fluid velocity in the previous hour was non-zero, then it is assumed that the same non-zero velocity existed for the intervening hours and that the steady state temperature distribution is calculated.

The benefits of implementing a shower head model can be a dramatic reduction in calculated stresses and the resulting fatigue usage. Figure 2 depicts these benefits.

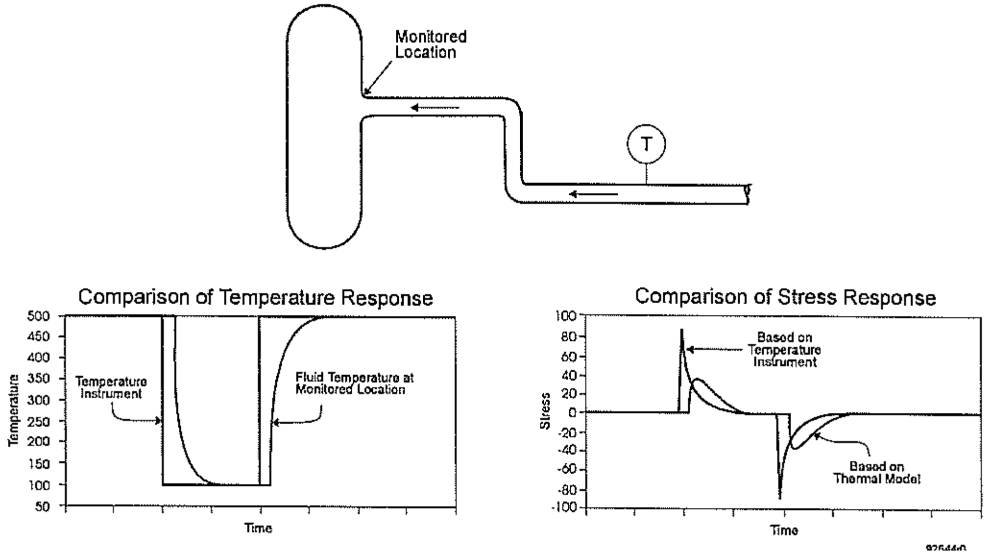

Figure 2: Benefits of Thermal Hydraulic Models

THERMAL STRATIFICATION MODELS

As a result of cracks detected in the vicinity of PWR steam generator feedwater nozzle to pipe welds at several plants [2], analytical models that address the effects of thermal stratification were derived for use in **FatiguePro** based on extensive field data. The cracking has been diagnosed as thermal fatigue due to flow stratification conditions which occur at low, non-constant feedwater flow rates, when plants are in hot standby or at very low power, with feedwater typically being supplied by the auxiliary feedwater (AFW) system, as illustrated in Figure 3.

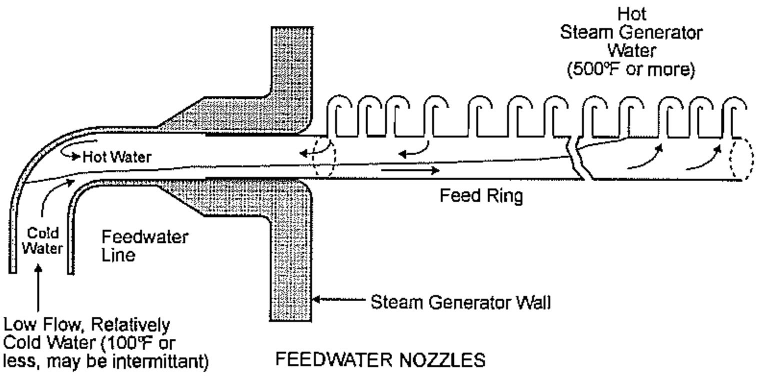

Figure 3: Steam Generator Feedwater Nozzle Stratificaton

In order to develop an improved understanding of the flow stratification phenomenon and its relationship to plant specific AFW temperature and flow cycling, temperature sensors were installed on the outside surface of a feedwater nozzle, in the vicinity of a nozzle-to-pipe weld that exhibited the cracking. The data obtained from these sensors were used to develop a conservative stratification load definition in the feedwater nozzles. The intended uses of the data and resulting correlation were two-fold: (1) to develop an accurate design basis for future improvements to the feedwater nozzle/pipe design aimed at mitigating thermal fatigue/flow stratification concerns, and (2) to improve the stress transfer functions for the feedwater nozzle region in **FatiguePro**.

A two-dimensional model of the feedwater piping was used to parametrically evaluate inside pipe wall boundary conditions to match the measured piping outside diameter steady state temperature response. From these results, a relationship between auxiliary feedwater flow rate and stratification level was developed. The relationship was correlated against data from German HDR-TEMR tests [3].

Several portions of the AFW flow history that exhibited steady state characteristics were used in a parametric study to determine the relationship between the AFW flow and the stratification level in the pipe. However, for the majority of the time, the AFW flow is cycling and therefore in a transient condition. Hence, it was desirable to account for this transient effect in the analytical model. Because of the transient nature of the cycling, the stratification height, and the hot and cold fluid temperatures are all functions of time. Therefore, the transient effect was studied by use of a Green's Function approach.

The following conclusions were reached based on all of the stratification evaluations:

- Parameters were established that very accurately predicted the test temperature data obtained on the outside of the feedwater nozzle.
- Based on the steady state analyses, a relationship was developed between the AFW flow rate and the stratification level in the pipe. This relationship compared very well with those previously determined from the literature.
- A parameter was determined to account for transient response due to AFW flow changes.
- **FatiguePro** provides a valuable tool that can be used to accurately track actual fatigue usage during the complicated thermal hydraulic conditions associated with stratified flow.

FRACTURE MECHANICS MODELS

Fracture mechanics models are used by **FatiguePro** to perform flaw tolerance evaluations for those component locations where fatigue usage limits are projected to be exceeded prior to the end of the evaluation period. These evaluations can be used to help determine reinspection intervals by determining the length of time before the flaw depth reaches allowable levels. The evaluations postulate the existence of a hypothetical initial flaw (thereby eliminating the need for a usage factor), apply crack growth methodology to determine the end-of-period flaw size, and compare the resulting flaw size to the appropriate allowable value.

During initial **FatiguePro** development, the stresses were conservatively assumed to be uniform through the pipe wall thickness (i.e., membrane stresses). This allowed for relatively simple estimates of fatigue crack growth for pipe and nozzle safe end locations. However, as field experience was gained, it became clear that a more rigorous and general fracture mechanics model was needed for more complex geometries. This was particularly true for nozzle corners where the uniform stress approach was overly conservative and not appropriate for use. A more general but complicated model was selected that is composed of separate Green's Functions for the coefficients of a cubic polynomial that describes the thermal stress distribution, $\sigma_T(x,t)$, in a structure due to a unit step change in local temperature:

$$\sigma_T(x,t) = C_0(t) + C_1(t)\,(x/X) + C_2(t)\,(x/X)^2 + C_3(t)\,(x/X)^3$$

where:
$C_i(t)$ = polynomial coefficients as a function of time
x = distance into section from the surface
X = a defined reference dimension
t = time

The cubic polynomial stress distribution in the body due to pressure is similarly defined for a unit pressure increase from zero, but the stress coefficients are not a function of time.

The stress intensity factor for any crack depth, a, is described as follows:

$$K(a,t) = (G_0C_0(t) + G_1C_1(t)\,(a/X) + G_2C_2(t)\,(a/X)^2 + G_3C_3(t)\,(a/X)^3)\,(\pi a)^{1/2}$$

where:
G_i = fracture mechanics mode coefficients defined by the user
C_i = thermal or pressure stress coefficient defined above
a = crack depth

A generic crack growth law formulation is used of the following form:

$$da/dN = C\,(AR + B)\,\Delta K^n$$

where:
da/dN = crack growth per cycle
A,B,C,n = coefficients defined by the user
R = ratio of K_{min}/K_{max}
ΔK = absolute value of stress intensity range between two load sets

Implementation of this model into **FatiguePro** allows for a very convenient solution to a seemingly complex problem. Fracture mechanics analysis of nozzles provides a complement to detailed fatigue usage evaluations, and provides valuable insight into component reinspection intervals or scheduled inspections.

ENVIRONMENTAL FATIGUE MODELS

Environmental fatigue evaluation capabilities have also been added to **FatiguePro** on a plant specific basis in response to recent laboratory test data in simulated reactor water environments [4]. These capabilities resulted from concerns that the effects of the reactor water environment on some components may not be adequately addressed in current design requirements. Some of the laboratory data suggest, under certain combinations of conditions, that existing design fatigue curves may not be adequate.

The evaluation of environmental fatigue is somewhat complicated, as most relationships that have been developed rely on dissolved oxygen (measurements of which are not always available) and strain rate (which can be difficult to calculate). **FatiguePro** has proven to be a powerful and convenient engine for computationally addressing and evaluating this issue.

During the stress calculations routinely performed by **FatiguePro**, the computed stresses are filtered to identify local maxima and minima (peaks and valleys, or P&Vs). These P&Vs are identified by *transients*, where a transient is defined as the period of time where stress is monotonically increasing (culminating in a peak) or decreasing (leading to a valley). P&V reversals with a magnitude less than the endurance limit of the material being monitored are ignored, as they have no effect on computed fatigue.

Various parameters are utilized in the analysis, based on the associated transient: the extreme stress value, the time the peak or valley occurred (**t**), the maximum local temperature (**T**), the maximum concentration of dissolved oxygen (**DO**), and the strain range weighted environmental fatigue factor ($F_{en,PV}$). The values of extreme stress, **t**, and **T**, are extracted and stored with each P&V. The **DO** value can be either utilized as a separate input file or included in the data acquisition system. The $F_{en,PV}$ value is calculated directly within **FatiguePro** once all inputs are available. The methodology used to determine $F_{en,PV}$ was previously developed by EPRI [5].

The $F_{en,PV}$ factor for each peak or valley is computed by integrating real-time F_{en} values:

$$F_{en,PV} = \frac{1}{W}\int(\sigma_t - \sigma_{t-1})F_{en}(\varepsilon', S, DO, T)dt$$

$$W = \int(\sigma_t - \sigma_{t-1})dt$$

$$\varepsilon' = \frac{100(\sigma_t - \sigma_{t-1})}{E \times 10}$$

σ_t = Stress value at time ‘t’
σ_{t-1} = Stress value at the time step prior to ‘t’
$F_{en}(\varepsilon', S, DO, T)$ = environmental factor
ε' = the 10 second strain rate
E = elastic modulus

Once peaks and valleys are identified, a rainflow algorithm is used to pair P&Vs into load pairs. The alternating stress intensity, S_a, is then computed for each load pair, taking into account K_e for large stress ranges. Nominal fatigue usage, U_i, for each load pair is as $U = U_i * F_{en}(\varepsilon', S, DO, T)$. Total usage is computed as the sum for all pairs:

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

FATIGUEPRO USER'S GROUP (FPUG)

At the conclusion of **FatiguePro** development, there was a desire on the part of many utility users of the **FatiguePro** software to form a group that directs the future enhancement of the software and provides a valuable forum for sharing, solving and responding to industry fatigue-related issues. In particular, a way to disseminate all of the lessons learned by the large population of users was desired. To respond to these desires, EPRI formed the **FatiguePro** User's Group (FPUG) in 1998. The FPUG has the following objectives as a part of its mission:

- Management of fatigue margins at member utility nuclear plants through various methods, including the use of EPRI's **FatiguePro** software.
- Providing updated **FatiguePro** software that is compatible with evolving computer infrastructure and environments.
- Enhancing member utility fatigue management capabilities through networking, exchanging of ideas and experiences, and presentation of topics in the area of fatigue.

Membership is composed of one utility representative for each subscribing plant site. The FPUG is initially charted for four years and includes member-directed **FatiguePro** software development and enhancement.

Software development and enhancement will include the implementation of three major architectural changes to **FatiguePro**, thereby "modernizing" the software, and allowing for more efficient code maintenance over subsequent years. These include:

1. Implementation of a 32-bit design which will operate under current computer operating systems and use the improved interface features standard to these operating systems.
2. Implementation of a full-featured database engine for storing configuration data and program results using standard SQL format.
3. Implementation of integrated data review and graphics modules such that reliance on other external software will no longer be needed to perform these functions.

The culmination of this effort will be the next generation of the **FatiguePro** software (Version 3.0). Semi-annual meetings linked with annual fatigue seminars are planned for the duration of the FPUG term to enhance member participation.

CONCLUSIONS

The intent of the **FatiguePro** software is to provide an industry-approved tool that can be used by plant engineers to fulfill plant cyclic duty tracking requirements by using any combination of approaches. All of the approaches used by **FatiguePro** are intended to demonstrate, in an accurate, reliable, and retrievable fashion, that structural design margins for all critical components are maintained during actual plant operation. Therefore, **FatiguePro** provides the technical tools that may be used to assure that structural design margins are maintained.

This paper describes the most recent advancements made to the **FatiguePro** software. Each of these advancements has proven difficult and/or cost prohibitive for utilities to deal with on an individual basis. However, the **FatiguePro** software, combined with the powerful networking and upgrading associated with EPRI and the FPUG, has proven to be a cost effective way for utilities to address fatigue issues and stay current on fatigue-related issues.

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