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STEAM GENERATOR FEEDWATER NOZZLE STRATIFICATION MODEL DRIVEN BY PLANT FLOW MEASUREMENTS FOR FATIGUE MONITORING

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ABSTRACT

Thermal stratification can occur in the steam generator feedwater nozzles of Pressurized Water Reactors (PWR). The stratification is due to cooler feedwater entering the steam generator, which is at a flow rate low enough to not completely sweep the inlet piping and nozzle with cooler water, but instead flow under the layer of hotter water heated by the steam generator inventory. Stratification can occur when the steam generators are receiving water inventory from either the auxiliary feedwater or the main feedwater system, as long as the incoming water is sufficiently cooler than the bulk steam generator temperature and not flowing at a high rate. The stratification temperature difference (ΔT) and cyclic action severities are most prevalent during the hot standby and startup power modes of a PWR. This paper describes the computer simulation of thermal stratification loading in a steam generator feedwater nozzle. The simulation was used in a model to account for thermal stratification effects in the transient and fatigue evaluation performed in the online monitoring system. A detailed application of the existing nozzle analysis-of-record provided the basis for developing the online fatigue computer simulation. The analysis correlated the thermal stratification loading to auxiliary feedwater flow rate, since the prevalent stratification fatigue damage was shown to occur during times when the plant was operating primarily from auxiliary feedwater flow. When driven by auxiliary feedwater flow rate, a series of higher order polynomials, coupled with simplified heat transfer calculations, were developed in the online fatigue monitoring software to simulate the thermal stratification loadings in the feedwater nozzle. The simulated loadings were then input to another module of the online monitoring software to calculate ASME Code fatigue usage factors. This development combined arithmetical modeling of the system with a detailed stress model to enable the fatigue usage factor calculation from plant computer data in the plant's online transient and fatigue monitoring system.

INTRODUCTION

The steam generators of a PWR receive their inventory water from the feedwater system. The feedwater enters the steam generators through the horizontal feedwater nozzles. Thermal stratification in PWR feedwater nozzles and inlet piping has been detected and evaluated. During normal full power operations, feedwater flow is very high, on the order of 10000-15000 gpm, which precludes stratification in the feedwater nozzle region. However, stratification can occur from relatively low flow conditions in conjunction with a large temperature difference between the incoming water and the bulk steam generator temperature. These conditions are most prevalent during plant heatup and cooldown periods, but may also occur during hot standby mode, such as may occur when a plant temporarily goes offline to a no-load condition. As a result of these observed stratification events, many plants are now using various methods of monitoring for the feedwater nozzle regions, to track the thermal conditions and transients.

Feedwater nozzles typically exhibit higher fatigue usage than an upstream piping run, due to the combination of severe thermal stratification loadings and the structural discontinuities in the nozzle geometry. The most severe stratification loadings occur during hot standby and startup modes of the plant. During these times, the incoming feedwater flow rate is significantly lower such that the nozzle is not swept completely; rather, incoming cooler water flows under the layer of hotter water causing stratification in the nozzle. The flow may come from either the main feedwater system or the auxiliary feedwater system. In the event of the latter, the temperatures of the incoming flow may be as low as 40°F. Under these conditions, the nozzle is subjected to stresses from local thermal stratification; it can also experience large bending moments, particularly in the event that the inlet piping run is horizontal for a significant length as it approaches the steam generator.

One particular plant had an ASME Section III fatigue analysis performed for the feedwater nozzles to show that the nozzles were capable of enduring stress cycles associated with a certain number of hours under low flow, stratification-susceptible conditions from the auxiliary feedwater system. As a result, the monitoring method employed by the responsible engineer at the plant was to manually track the quantity of hours that the steam generators were receiving feedwater inventory from the auxiliary feedwater system. The plant was already using the automated WESTEMS™ plant monitoring software[1] to monitor many other locations in the plant, and it was decided that the cumbersome manual method could be replaced with automated monitoring in the plant's existing system.

The analysis-of-record (AOR) was reviewed to determine that the low flow auxiliary feedwater was the controlling condition contributing to fatigue. The detailed analysis provided a direct correlation between the auxiliary feedwater flow rate and stratification height in the nozzle. Detailed FEA then related the stratification height to stresses at various locations throughout the nozzle. This supported development of a 4-stage process (Figure 1) in the software to emulate the AOR and perform online fatigue monitoring at the feedwater nozzles based on input flow data from the auxiliary feedwater system.

The monitoring software provided an integrated modeling capability [1, 2] that was used to perform the necessary transformations in a staged process, from the initial input to the final fatigue result. This capability allows several software models to be processed in a defined order, such that the output of one model is the input to the next. For the work herein, stage 1 consisted of polynomial-type functions in the software; stage 2 consisted of modified heat transfer models; stage 3 consisted of more polynomial-type functions; stage 4 consisted of modified simplified stress models.

For stage 1, the AOR data was used to curve fit the flow-versus-height data with 6th order polynomials. The curve fit equations were then programmed into the polynomial model configuration. The equations were configured to accept auxiliary feedwater flow data from the plant computer to calculate the stratification height in the nozzle. Once the stratification height had been determined in the software algorithm, the height data was input to stage 2, a modified heat transfer calculation in another module of the software. The heat transfer module would typically be used to calculate a changing temperature distribution through a given material thickness. However, the module was not used in this manner for this work; namely, it was not developed to alter the height data in any manner. Rather, the heat transfer module was developed to only densify the stratification height data time history. Once the height data time history had been densified, it was able to be input to stage 3, a second set of 6th order polynomials. These polynomials were curve fitted from the AOR to correlate the stratification height-versus-stress. Finally, the stress data was able to be input to stage 4, another module of the software to calculate fatigue values.

Ultimately, the auxiliary feedwater flow rate is input to the online monitoring software and fatigue is calculated automatically. This is summarized in Figure 1. The details of the model development are discussed in this paper.

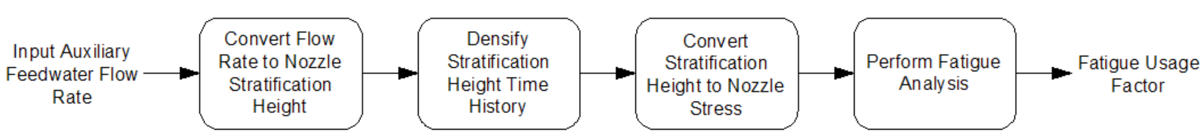

Figure 1: 4-Stage Model Simulation

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APPLICATION OF ANALYSIS-OF-RECORD

The design AOR was the result of a replacement steam generator (RSG) program at the plant. The new steam generators were designed to have an enhanced feedwater (FW) nozzle transition piece, which would mitigate and/or preclude erosion-corrosion problems experienced by the original steam generator FW nozzles. The AOR analyzed 15 stress locations along the axis of the nozzle region; each of 15 locations was analyzed at 13 circumferential locations spanning 180° of the geometry (top to bottom in 15° increments). The AOR indicates that a stress path at the junction of the nozzle and its transition piece was the limiting location, having the highest fatigue usage. The AOR showed that approximately 95% of the design usage was due to thermal stratification loading at this stress path, which was labeled as stress path 4. Specifically, the 180° (bottom) circumferential location was the most limiting at stress path 4 (Figure **2**). Thermal stratification loading was determined to be primarily a function of AFW flow. As a result, the fatigue monitoring models discussed herein were configured to track fatigue usage as a function of AFW flow as opposed to typical fatigue monitoring based on detailed transient inputs such as typical bending moments, pressure, and explicit local thermal effects. Since these other transient loadings contributed approximately 5% of the AOR fatigue usage, their effects were conservatively incorporated into the baseline fatigue usage calculations.

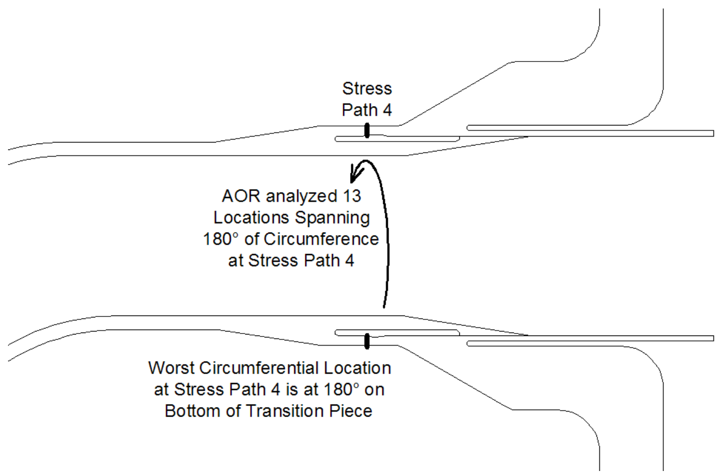

Figure 2: Location of Stress Path 4 from AOR

MONITORING MODEL DEVELOPMENT STRATEGY

The development in the AOR was based upon approximately 95 sample hours of AFW flow obtained from the plant. The data was obtained for the purposes of benchmarking the fatigue monitoring models. Since stress path 4 was the limiting path, the objective was to develop 13 monitoring models (1 model for each circumferential location at path 4) in the software. Using the sample AFW flow data, the 13 models were then benchmarked against the fatigue results given in the AOR.

Upon concluding that the monitoring models benchmarked adequately in the software, the model for the 180° circumferential location was recreated 3 more times for use in online monitoring, 1 model for each steam generator FW nozzle. The models were configured in the plant's latest monitoring software database. The final 4 models were benchmarked against the AOR using the 95 hours of sample data with the software configured for an online monitoring setting.

The developments of the models comprising the 4 stages are discussed in the following sections. The benchmarking as well as the method used to develop the models' baseline fatigue usage is also discussed.

STAGE 1—FLOW VS. LEVEL CORRELATION

The AOR concluded that the stratification produced the most dominant stresses in the axial direction; as a result, the focus therein was on the axial stratification stresses produced for a given flow rate. Using this basis, stage 1 polynomial functions were developed in the monitoring software, which would track AFW flow and could reproduce the axial stresses tabulated in the AOR. The axial stress is a function of stratification level; the stratification level is a function of FW flow. Power Modes 2 and 3, startup and hot standby respectively, are when the FW nozzles usually stratify due to low flow. If low flow occurs, the models will detect it and model the stratification.

The AOR documented a study of the flow-versus-stratification level and tabulated the correlation (Table 1). A polynomial least squares curve fit was derived from the flow-versus-level correlation and used to produce a representative polynomial function. The polynomial function was input to the module of the monitoring software designed for this purpose. Additional if/then logic functions available in the software were also configured to monitor the output of the flow-versus-level polynomial and correct spurious outputs. The logic functions were configured to force the polynomial's output to be 180° in the event that the plant flow sensor erroneously gave a negative flow value; conversely, the logic functions forced the polynomial's output to be 0° in the event the plant flow sensor gave a higher flow value than 127.58 gpm. These limits were based on the AOR data shown in Table 1, where stratification extremes are defined for given flow values.

Table 1: FW Flow vs. Stratification Water Level

Flow (gpm)	Stratification Level (deg)	Flow (gpm)	Stratification Level (deg)	Flow (gpm)	Stratification Level (deg)
0.00	180.0	17.11	110.0	74.84	50.0
1.43	170.0	26.37	100.0	84.81	40.0
2.43	160.0	36.35	90.0	95.50	30.0
3.45	150.0	45.61	80.0	106.19	20.0
4.72	140.0	54.88	70.0	117.60	10.0
6.41	130.0	64.86	60.0	127.58	0.0
9.98	120.0				

The combined process of polynomial and if/then logic check functions was input to the monitoring software. The polynomial curve fit equation is shown below in Equation 1. The resulting output of the process is a time history data point of the stratification level in the FW nozzle, for input to stage 2.

$$\begin{aligned} Level &= 2.0432\text{E-}9x^6 - 8.6975\text{E-}7x^5 + 1.4358\text{E-}4x^4 \\ &\quad -1.1539\text{E-}2x^3 + 4.6364\text{E-}1x^2 - 9.5225\text{x} + 179.21 \\ where\ x &= flow\ rate\ in\ gpm \end{aligned} \tag{1}$$

STAGE 2—DENSIFY THE STAGE 1 OUTPUT

After processing the stage 1 models, the output stratification level data points were processed through the monitoring software's Heat Transfer Models (HTM's). Typically the HTM module of the software is used to calculate 1-dimensional heat transfer through a constant wall thickness, while accounting for an interior and/or exterior film coefficient. The HTM's were not used for heat transfer purposes here; rather, they were used to heavily populate (densify) the stage 1 output data. They were uniquely configured in a different manner since the stage 1 models would only calculate stratification level at an instance of time where the incoming flow data changed. The subsequent stage 3 models would then only calculate stress at those instances of time. This was inadequate since flow could change from one extreme to another from one instant of time to the next and cause the stage 1 models to calculate nozzle statification level only at the flow extremes. As a result, the stage 1 models would inadvertently miss the stratification level change in between, which oftentimes produces a more severe stress state. For example, Figure 7 shows the most severe stress states occurring at 45° and 150° stratification levels, which could be missed by the models if the stage 1 output data shows flow changing from ~120 gpm to ~1 gpm, with no intermediate data points captured. Therefore, the calculated stress range for the flow change event would be smaller than what actually occurred. To fix this, HTM's were used in the monitoring software since they could follow the full time history of the stage 1 model outputs and create many data points (densify) along that timeline. Subsequently, the stage 3 models would calculate stratification stress values at each time point created by the HTM's and not miss the critical stress states.

An illustration of the HTM configuration is shown in Figure 3. The stage 1 output data point acted as the stage 2 input "bulk temperature." The HTM was then configured to output the interior wall "temperature." The most critical setting in the HTM's was the h_{inside} film coefficient. Setting it to 1 Btu/s/in^2/°F (extremely high film coefficient) forced the heat transfer model to track the input stage 1 data point exactly and not deviate from the input time history curve as a heat transfer model having a much lower film coefficient would. In other words, $T_{bulk}=T_{interior\ wall}$ at all instances of time. Configuring the HTM's this way densified the time history without altering the stage 1 output, stratification level.

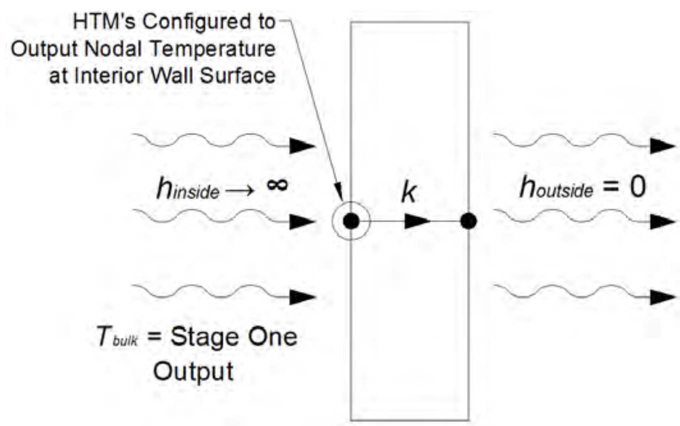

Figure 3: Heat Transfer Model Illustration

STAGE 3—CALCULATE AXIAL STRESS

Stage 2 HTM's created many stratification level data points (densified) along the time history. Stage 3 processed the stage 2 output through another polynomial equation to calculate axial stratification stress for each loop, noting that stratification stress is derived directly from nozzle stratification level. The AOR concluded that the stratification produced the most dominant stresses in the axial direction; as a result, the focus therein was on the axial stratification stresses produced for a given flow rate. The AOR was able to conservatively account for the other 5 stress components; axial stress was directly included though. Following suit, the focus here was also on axial stratification stresses. The stratification stress matrix for stress path 4 was obtained from the AOR (Table 2). Axial stresses were given for each circumferential location at every 15°. A polynomial least squares curve fit relationship was derived from the level-versus-stress correlation at all circumferential locations (0°, 15°,…, 180°). With these curve fit equations, 13 individual polynomials were programmed into the monitoring software, which were used to benchmark all circumferential locations at stress path 4 in a test project database. Discussion regarding this initial testing follows later. Several example curve fits are shown in Figure 4through Figure 7.

Table 2: Path 4 Stratification Stress Matrix

Circumferential Position (deg)	**Stratification Level (deg) Axial Stresses (ksi)**						
	0	**15**	**30**	**45**	**60**	**75**	**90**
0	0.00	-53.65	-71.15	-65.17	-44.52	-20.27	-0.62
15	0.00	-36.30	-57.78	-58.14	-42.16	-20.87	-2.93
30	0.00	-5.87	-20.42	-34.98	-33.48	-21.64	-9.04
45	0.00	15.61	18.22	4.62	-13.70	-19.08	-16.36
60	0.00	26.63	39.45	39.60	19.28	-6.72	-20.08
75	0.00	29.25	45.13	53.36	45.78	18.50	-12.88
90	0.00	25.45	39.82	50.07	50.85	37.36	8.32
105	0.00	17.24	27.40	36.08	40.28	36.82	24.28
120	0.00	6.79	11.43	16.67	21.52	24.02	23.13
135	0.00	-3.80	-4.79	-3.63	0.47	6.60	12.85
150	0.00	-12.73	-18.49	-21.04	-18.18	-9.86	0.87
165	0.00	-18.63	-27.55	-32.67	-30.87	-21.40	-8.10
180	0.00	-20.69	-30.72	-36.75	-35.35	-25.52	-11.39
Circumferential Position (deg)	**Stratification Level (deg) Axial Stresses (ksi)**						
	105	**120**	**135**	**150**	**165**	**180**	
0	17.27	27.17	28.77	24.04	15.44	0.00	
15	13.80	23.41	25.42	21.49	13.85	0.00	
30	4.15	12.77	15.84	14.14	9.27	0.00	
45	-9.47	-2.91	1.40	2.93	2.22	0.00	
60	-23.32	-20.64	-15.66	-10.63	-6.41	0.00	
75	-31.74	-36.28	-32.29	-24.44	-15.35	0.00	
90	-26.83	-44.04	-44.58	-35.88	-23.04	0.00	
105	-5.34	-36.10	-47.19	-41.69	-27.59	0.00	
120	13.76	-9.48	-32.87	-37.37	-26.73	0.00	
135	18.37	16.48	0.67	-16.74	-17.33	0.00	
150	15.65	28.67	33.04	21.38	4.81	0.00	
165	11.88	32.90	49.57	54.74	38.11	0.00	
180	10.29	33.85	54.30	65.79	56.19	0.00	

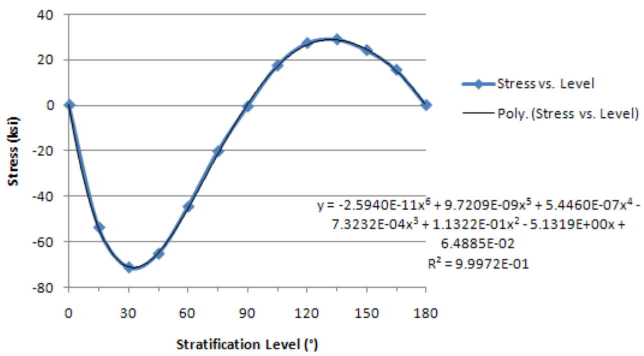

Figure 4: Least Squares Curve Fit
Stress Path 4 at 0°

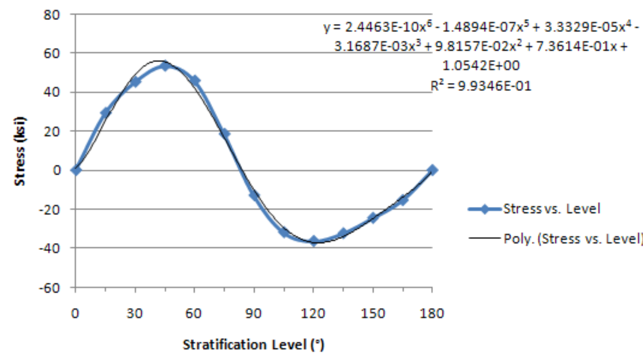

Figure 5: Least Squares Curve Fit
Stress Path 4 at 75°

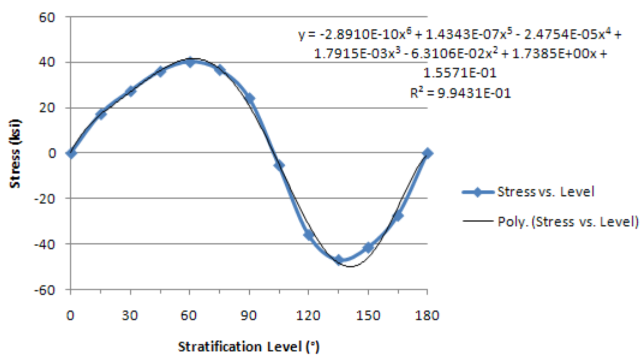

Figure 6: Least Squares Curve Fit
Stress Path 4 at 105°

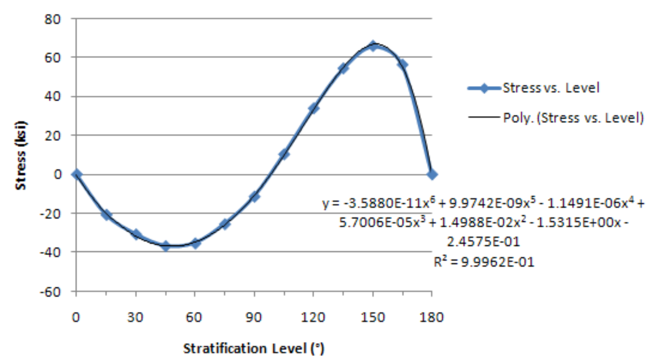

Figure 7: Least Squares Curve Fit
Stress Path 4 at 180°

The curve fit polynomial for the 180° location is shown below in Equation 2.

$$\begin{aligned} Stress &= -3.5880\text{E-}11x^6 + 9.9742\text{E-}9x^5 - 1.1491\text{E-}6x^4 \\ &\quad +5.7006\text{E-}5x^3 + 1.4988\text{E-}2x^2 - 1.5315\text{x} - 2.4575\text{E-}1 \\ &where\ x = strat\ level\ in\ degrees \end{aligned} \tag{2}$$

STAGE 4—1-DIMENSIONAL STRESS MODELS

The stage 3 polynomial models create monitoring data points for the axial stratification stress time history for the steam generator FW nozzle. Simplified stress models were then configured to process those stress time histories and ultimately calculate fatigue usage. Similar to that discussed in the previous section, 13 individual stress models were initially developed to benchmark all circumferential locations at stress path 4 in a test database. Discussion regarding this initial testing is in discussed later in Post-Model Development Work.

As with the stage 2 models, the stress model was not used in its conventional manner. Typically, a simplified stress model would be configured to read pressure, moment, force, and 1D through-wall temperature loading conditions. With these input loading conditions, the model would calculate stress components and ultimately, ASME Code fatigue usage. However, as discussed already, the axial stresses have already been calculated by the stage 1, 2, and 3 models, as derived from the AOR stress analysis. Note that the AOR was able to conservatively account for the other 5 stress components; axial stress was directly calculated though since it was the dominating component. Therefore, the simplified stress model inputs were manipulated such that the model would perform a "passive" role to only read in axial stresses from the stage 3 models, and ultimately calculate ASME Code fatigue usage from those stresses. With that, the pressure input was zeroed out, which forced the model to assume no pressure activity was taking place; likewise for piping forces and moments. Since approximately 95% of the fatigue usage in the AOR was due to thermal stratification, usage effects from these other events were calculated into the model's baseline fatigue usage, which is discussed later in Post-Model Development Work.

The simplified stress model is unable to operate without thermal loading inputs. Therefore, the model was configured to read a constant input temperature (100°F) and a constant film coefficient (100 Btu/s/in^2/°F), together forcing the model to assume no thermal variations ever take place.

To read in the axial stress calculated by the stage 3 models, the simplified stress model was configured to read 1 mechanical load case. Note that a "load case" is simply a mechanical loading on the component, such as a moment or force. Typically, this portion of the simplified stress model would be configured to read a force or bending moment, from which it would calculate stresses from classic equations such as F/A or MC/I, having other parameters correctly set for the model. However, the model inputs were manipulated such that the model would read in the axial stress data point from the stage 3 model, forgoing direct stress calculations within the simplified stress model.

The analysis methods in the AOR conservatively accounted for effects from K_e, and Poisson's correction (NB-3227.6); however, K_y effects were directly included in the fatigue usage calculations. Specifically, K_y was set at a constant value as shown below. Alternating stress range was calculated in the AOR as shown below in Equation 3.

$$\begin{gathered}\frac{S_{range}}{2} * K_y = S_a \\ where\ K_y = a\ constant\ value, \frac{30\text{E6 psi}}{28\text{E6 psi}}\end{gathered} \tag{3}$$

With the above equation, the fatigue usage from the AOR was able to be reproduced with hand calculations. The software model's material properties were input so as to compute a constant K_y, as was the case in the supporting AOR. Also, the material properties were altered in the software such that S_m was set at 100 ksi for the entire operating temperature range. This would force the NB-3228.5(b) calculation of K_e to always be 1.0.

As mentioned, the simplified stress model was configured to read 1 mechanical input load only. The input axial stress from the stage 3 model was assigned to the simplified stress model's Y axis. Selecting the Y axis was arbitrary so long as 1 of the 3 principal axes was selected. Considering how the model is supposed to be configured under normal conditions, the model was detecting an input load assigned only to the Y axis. When the model runs, it would then perform the needed range pairing, principal stress calculations, and fatigue calculations with only 1 axis having a stress input; this mimics the process used in the AOR to calculate stratification stress usage.

POST-MODEL DEVELOPMENT WORK

Two remaining items needed addressing to complete the aforementioned models: benchmark the models and calculate a baseline fatigue usage number. Upon completion of both of these items, the models were ready for installation to the plant's online monitoring system.

The models were benchmarked against the AOR stratification fatigue usage results. Three tests were run. The initial test was executed for stress path 4 at all 13 circumferential locations. Thirteen sets of models were established in the database, each containing unique stage 3 axial stress curve fit polynomials. The software was run using the standard ASME NB-3200 process and the results were very favorable. They are shown below in Table 3.

Table 3: Fatigue Model Benchmark for Path 4 at All Circumferential Locations

Index	Circumferential Position	Fatigue from Monitoring Software	AOR Fatigue	Percent Difference[1]		Index	Circumferential Position	Fatigue from Monitoring Software	AOR Fatigue	Percent Difference[1]
1	0°	0.02240	0.01003	1.2370%		8	105°	0.01530	0.00753	0.7770%
2	15°	0.01310	0.00602	0.7080%		9	120°	0.00520	0.00247	0.2730%
3	30°	0.00240	0.00127	0.1130%		10	135°	0.00080	0.00035	0.0450%
4	45°	0.00070	0.00031	0.0390%		11	150°	0.00250	0.00159	0.0910%
5	60°	0.00610	0.00230	0.3800%		12	165°	0.01270	0.00742	0.5280%
6	75°	0.01730	0.00740	0.9900%		13	180°	0.02260	0.01228	1.0320%
7	90°	0.02250	0.00956	1.2940%						

1) Fatigue values from the software and the AOR were normalized to 1, which is the maximum allowable usage, and the difference between them was calculated in this column. For example, the index 1 result from the software was 2.24% of 1 and the result from the AOR was 1.003% of 1. Percent difference was therefore calculated as 2.24 – 1.003.

The second benchmark test was run for stress path 4, but only at the 180° circumferential location. The only difference in this test versus the first test, was that 4 sets of models were made, 1 for each steam generator at the plant. The test was to simply ensure that all 4 sets of models produced identical results to each other for the same input data and to the 180° results shown in Table 3 from the first test (usage = 0.02260). The results were as expected, identical.

The third benchmark test was very similar to the second test, except the software was setup as if in an online monitoring setting. It was expected that the third test should produce a higher fatigue usage at the 180° circumferential location than the previous 2 tests, because of the more conservative computational methods while in an online monitoring setting. The 4 sets of models produced identical results one to another, and larger than tests 1 and 2, with a fatigue usage factor of 0.04502.

The final item needing attention before the models could "go live" is to program the 1D simplified stress models with a baseline fatigue usage number. This number consists of the AFW hours experienced to-date as well as other transient usage (pressure, piping loads, thermal excursions other than stratification) shown in the AOR since the usage from these other transient loadings had a very small contribution to the overall usage and could be omitted from online monitoring. It was conservative to add them into the baseline usage, as if the transients have already occurred in their entirety.

Upon determining the "go live" date and simply calculating/programming the baseline fatigue usage for each of the 4 sets of models, the plant will begin automated monitoring of their FW nozzles using the monitoring software.

CONCLUSIONS

The model development outlined herein demonstrates the ability to take stress data from an existing AOR and produce an online monitoring model for online monitoring of a component at a plant. The development was able to be accomplished using 4 stages in the plant's existing monitoring software. In several cases, the software's hardcoded models proved useful outside of their intended design and use. The software produced favorable benchmark results that yielded conservative and reliable online monitoring for the FW nozzle. The models were input data from one existing plant sensor, FW flow rate, which greatly simplified the model integration into the plant's existing software monitoring system. This yielded a very effective and economical monitoring solution for the plant.

NOMENCLATURE

1D—One Dimensional
A—Area
AFW—Auxiliary Feedwater
AOR—Analysis of Record
C—Distance from Neutral Axis to the Point of Interest
F—Force
FEA—Finite Element Analysis
FW—Feedwater
HTM—Heat Transfer Model
I—Second Area Moment of Inertia
K_e—ASME Elastic-Plastic Penalty Factor
K_y—Elastic Modulus Correction Factor
M—Moment
PWR—Pressurized Water Reactor
RSG—Replacement Steam Generator
S_a—Alternating Stress
S_m—Allowable Membrane Stress
S_{range}—Stress Intensity Range Formed From 2 Stress States
ΔT—Temperature Difference

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