COMPARISON OF ASME CODE NB–3200 AND NB–3600 RESULTS FOR FATIGUE ANALYSIS OF B31.1 BRANCH NOZZLES[1]

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ABSTRACT

Fatigue analyses were conducted on two reactor coolant system branch nozzles in an operating pressurized water reactor (PWR) that were designed to the B31.1 Code, for which no explicit fatigue analysis was required by the licensing basis. These analyses were performed as part of resolving issues connected with the Nuclear Regulatory Commission's Fatigue Action Plan to determine if the cumulative usage factor (CUF) for these nozzles, using the 1992 ASME Code and representative PWR transients, were comparable to nozzles designed and analyzed to the ASME Code. Both NB–3200 and NB–3600 ASME Code methods were used in performing the analyses. The NB–3200 analyses included the development of finite element models for each nozzle. Although detailed thermal transients were not available for the plant analyzed, representative transients from similar PWRs were applied in each of the analysis methods. The CUFs calculated using NB–3200 methods were significantly less than using NB–3600 analyses. The paper points out the differences in analysis methods and highlights the difficulties and unknowns in performing more detailed analyses to reduce conservative assumptions.

INTRODUCTION

Recent test data indicate that the effects of the light water reactor (LWR) environment could significantly reduce the fatigue resistance of materials used in the reactor coolant pressure boundary components of operating nuclear power plants. The American Society of Mechanical Engineers (ASME) Boiler & Pressure Vessel Code fatigue curves (ASME, 1992) used for the design of these components were based primarily on strain-controlled fatigue tests of small, polished specimens at room temperature in air. Although adjustment factors were applied to the best-fit curves to account for effects such as size, surface finish, environment, and data scatter, some of the recent test data indicate that these adjustment factors may not have been sufficiently conservative to account for environmental effects. In addition, there are older vintage plants where components of the reactor coolant pressure boundary were designed to codes, such as United States of America Standard (USAS) B31.1 (ASME, 1967), that did not require an explicit fatigue analysis of the components.

Since the Code of Federal Regulations currently references the ASME Code, which includes a fatigue evaluation of the components of the reactor coolant pressure boundary (unless certain exemption requirements are met), a concern developed within the United States Nuclear Regulatory Commission (NRC) staff regarding the adequacy of the fatigue resistance of these older vintage plants. To address this concern, a multi–part program, termed the Fatigue Action Plan (FAP), was initiated by the NRC. The Argonne National Laboratory (ANL) has developed interim fatigue curves based on test data of small, polished specimens cycled to failure in water simulating LWR conditions, and published them in NUREG/CR–5999 (Majumdar, Chopra, and Shack, 1993). Another portion of the FAP consisted of the assessment of the fatigue resistance of selected components from a representative sampling of operating plants designed by each of the four U. S. vendors of nuclear steam supply systems (NSSSs). This assessment was performed by the Idaho National Engineering Laboratory (INEL) and the results were reported in NUREG/CR–6260 (Ware, Morton, and Nitzel, 1995). The NUREG/CR–6260 sample included both newer vintage and older vintage plants. During the assessment, it was confirmed that some of the systems and components for the older vintage plants did not have existing fatigue analyses. Representative fatigue analyses were conducted for the portions of these systems that would be classified as Class 1 systems by today's standards.

This paper describes the fatigue analyses that were performed on two reactor coolant system (RCS) components from an older vintage plant with a Westinghouse NSSS. During the NUREG/CR–6260 study the charging system nozzle and the safety injection (SI) nozzles attached to the RCS piping were identified as not having existing fatigue analyses. These components (as well as the NSSS in general for the subject plant) were designed to the

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B31.1 Code. While Table 102.3.2(c) in the B31.1 Code included stress range reduction factors to account for component fatigue, no explicit fatigue analysis was required by the licensing basis. Both three-dimensional and axisymmetric finite element models of both nozzles were developed and fatigue evaluations using the 1992 Edition of the ASME Code were performed. Since some components similar to these have also been evaluated by others using the piping component rules in NB-3600, both NB-3200 and NB-3600 evaluation methods were applied. No detailed thermal transient data were available for these components. Representative transients based on similar components at similarly designed (but generally later vintage) plants were constructed and used in the analyses.

The object of these analyses was to obtain an assessment of what the cumulative usage factors for these components might be if based upon current Code rules. Therefore, the assumptions and approximations used were deemed appropriate to achieve this result. An additional goal for this work was to obtain comparison data for the differences in results that would be obtained when different analysis approaches (NB-3200 versus NB-3600) were used. The analyses and results described herein are not intended to represent or replace licensing basis calculations for the plant.

COMPONENT DESCRIPTIONS

Both the charging and SI nozzles are attached to segments of the RCS cold leg piping. The RCS cold leg piping for this particular plant has an outside diameter of 32.25 inches with a 2.38-inch wall thickness and is constructed of A376 TP316 stainless steel.

The charging nozzle has an overall length of 5.68 inches with a maximum outside diameter of 5.0 inches. The upstream weld end is configured to match 3-inch schedule 80 (nominal pipe size) piping. The nozzle is constructed of A182 F316 stainless steel and includes a thermal sleeve constructed of 304 stainless steel.

The subject plant has three identical SI nozzles. Each nozzle has an overall length of 11.25 inches with a maximum outside diameter of 13.75 inches. The upstream weld end is configured to match 10-inch schedule 140 (nominal pipe size) piping. The nozzles are constructed of A182 F316 stainless steel and include a thermal sleeve constructed of 304 stainless steel.

The interior surface of the nozzles contains no reentrant corners, so areas of stress concentration are minimized. In both cases, the weld between the nozzle and the main coolant piping is made in the shop; thus, no fatigue strength reduction factors are typically applied to this type weld in the subsequent fatigue evaluation. Similarly, in both cases, the nozzle-to-piping weld is a field weld. This weld is not typically included in nozzle analyses, but is usually considered the terminal end of NB-3600 analysis models of the adjoining piping.

MODEL DEVELOPMENT

Historically, the methods used to model complex components have changed as the available computational capability has grown. Simple two-dimensional (2D) models have evolved to very complex three-dimensional (3D) models for the most recent designs. To obtain necessary data for the NB-3200 calculations performed for this assessment, two finite element models were developed for each of the nozzles. A small axisymmetric finite element model was used to model each nozzle in the region of the connection to the branch piping where the geometry is truly axisymmetric while a larger 3D model (with a larger mesh size) was used to examine the knuckle region (nozzle to RCS transition region) where the geometry is not axisymmetric. A quarter section of the nozzle-to-pipe joint region was used for the 3D finite element models of both nozzles. This provided acceptable detail for determining transient thermal load response while helping to minimize computational time. Other appropriate nozzle loads (e.g., dead weight and seismic piping moments) were included in the fatigue evaluations; but, were not included in the finite element models. The 3D model of the charging nozzle/RCS piping area contains 19,346 solid parabolic tetrahedral elements and is shown in Figure 1. The axisymmetric model developed for the charging nozzle contains 264 axisymmetric solid elements and is shown in Figure 2. Since the plant's three SI nozzles are identical, only one model of each type (2D and 3D) was needed. The 3D model of the SI nozzle/RCS piping area contains 5,506 solid parabolic tetrahedral elements and is shown in Figure 3. The axisymmetric model developed for the SI nozzle contains 311 axisymmetric solid elements and is shown in Figure 4. The models were developed using the I-DEAS (version 6.i) solid modeling software. Heat transfer and stress calculations were subsequently made for the models using the ABAQUS (version 5.2) finite element analysis software.

The geometry of the thermal sleeve-to-nozzle wall weld was not shown on the fabrication drawings obtained for these nozzles. A review of numerous nozzle calculations performed by others indicates that no stress concentration factor or fatigue strength reduction factor is typically applied to account for this type of weld (the ASME Code does not list stress indices for this case). Also, the configuration of the thermal sleeve in these nozzles would tend to stagnate the coolant in the annulus between the thermal sleeve and the nozzle wall. Assuming stagnant conditions in the annulus is also consistent with the modeling approach used in all of the other nozzle calculations that were reviewed during the NUREG/CR-6260 assessment effort. The assumption of stagnant conditions in the annulus allowed us to simplify the finite element models by omitting the physical modeling of the thermal sleeve and representing it by the use of different heat transfer coefficients for the nozzle areas, depending on their relation to the thermal sleeve.

It was recognized that there may be conditions where varying turbulent penetration from the coolant in the main loop into the annulus region is possible during thermal transients. Such a phenomenon could alternately heat and cool the annular region; however, there is no physical evidence that such a phenomenon occurs in these nozzles. The sleeves in branch lines of several plants have become separated over the years, but the root cause has generally been attributed to flow induced vibrations rather than thermal fatigue. Based upon the available information, we believe the modeling approach is appropriate to the objectives of the analysis effort.

The NUPIPE-II computer code[2] was used to automatically calculate the usage factors using the NB-3600 Code rules. Thus, two separate finite element piping models were used for these calculations. Moments applied to the charging nozzle by the connected piping were supplied by the plant's licensee, so these moments were

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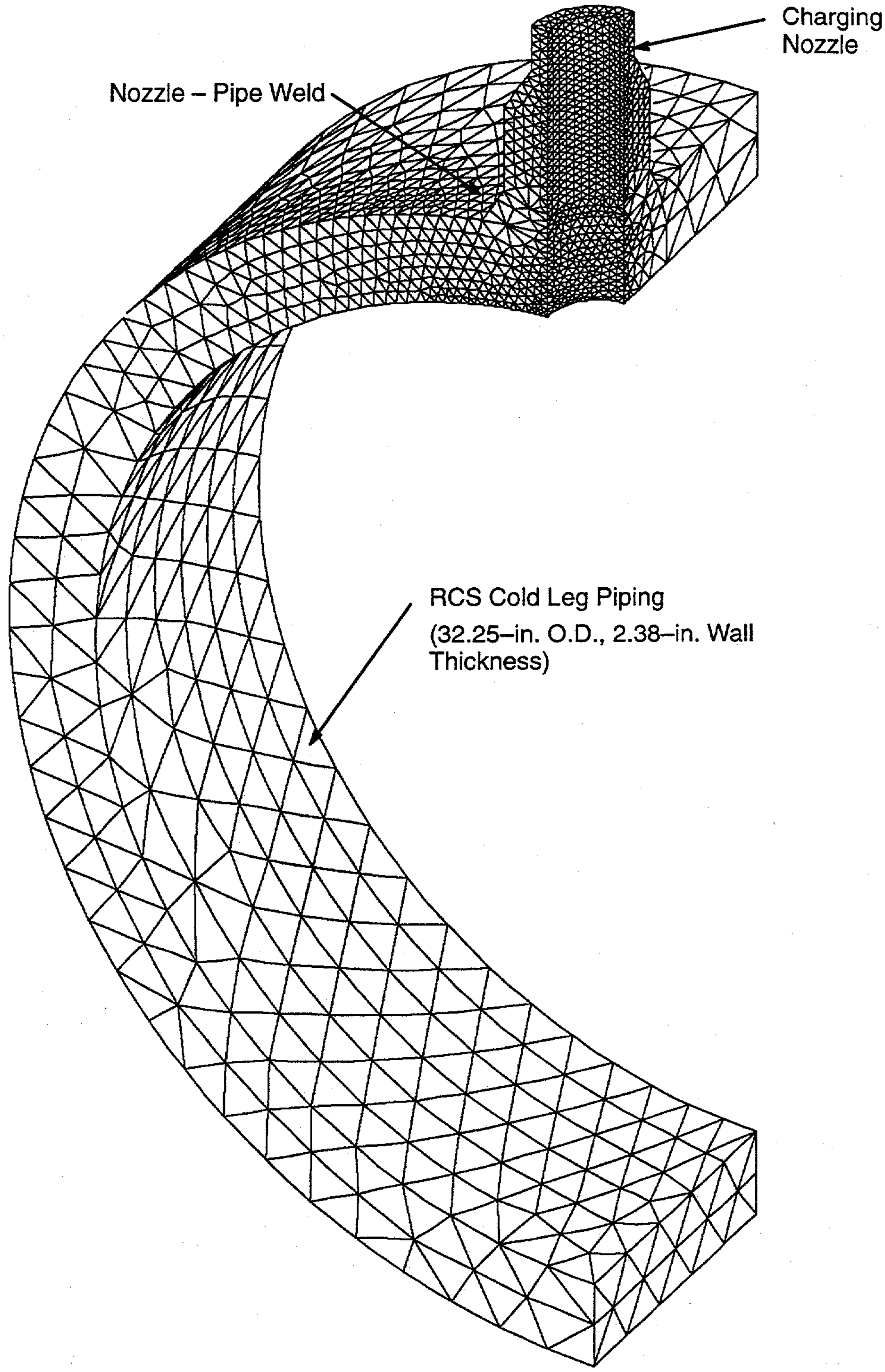

FIGURE 1. THREE–DIMENSIONAL CHARGING SYSTEM FINITE ELEMENT MODEL.

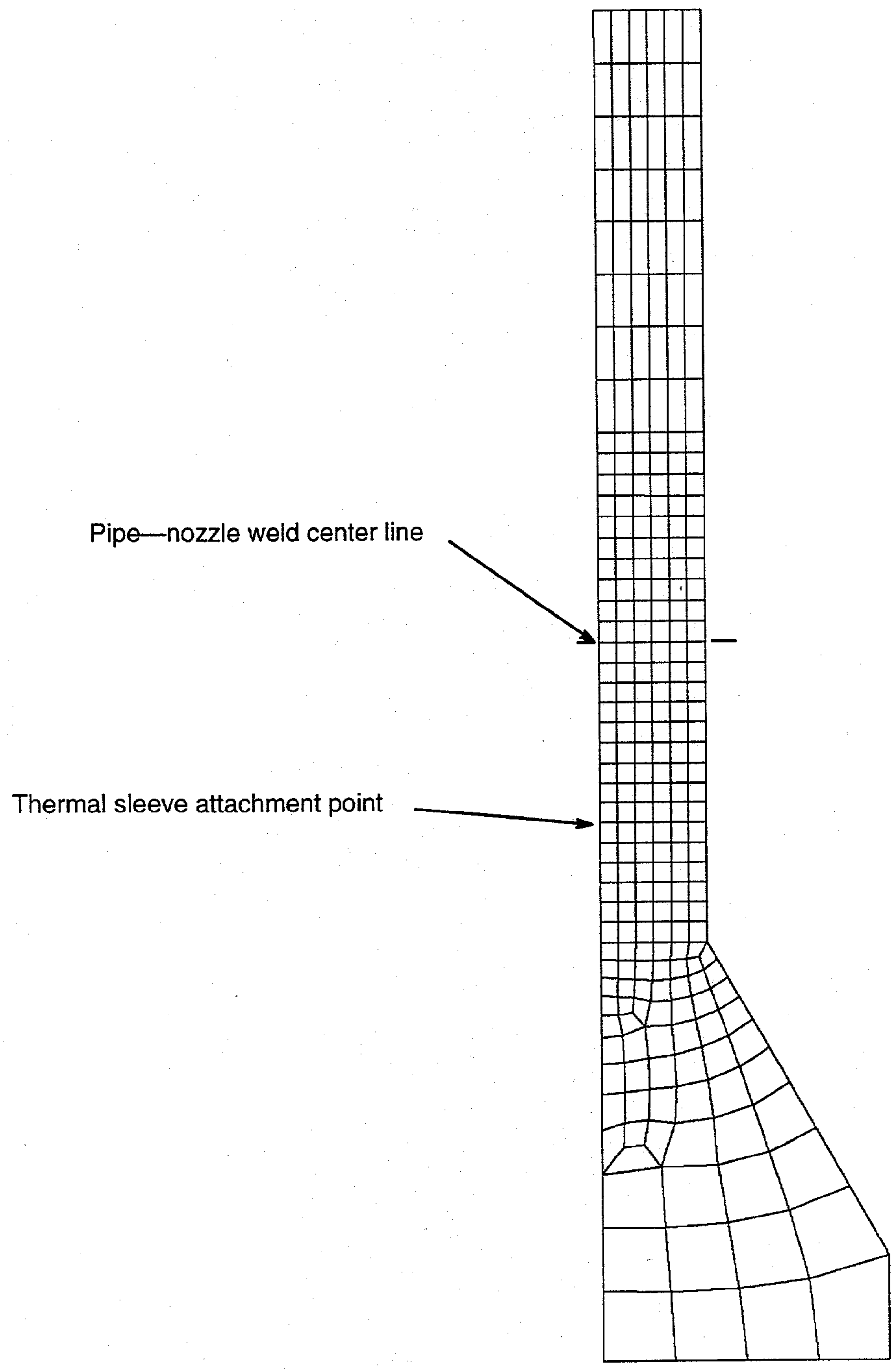

FIGURE 2. CHARGING NOZZLE AXISYMMETRIC FINITE ELEMENT MODEL.

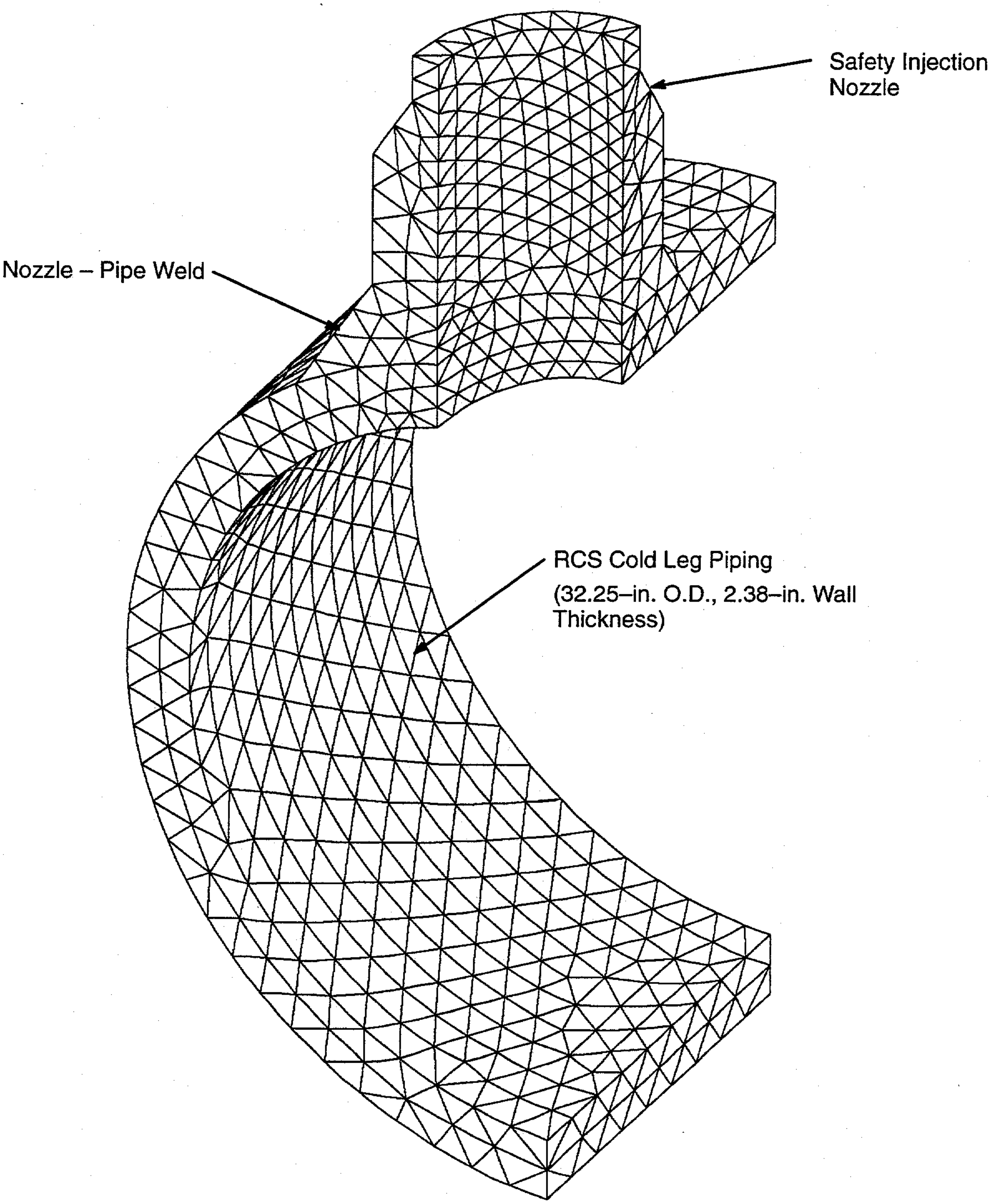

FIGURE 3. THREE–DIMENSIONAL FINITE ELEMENT MODEL OF SAFETY INJECTION NOZZLE.

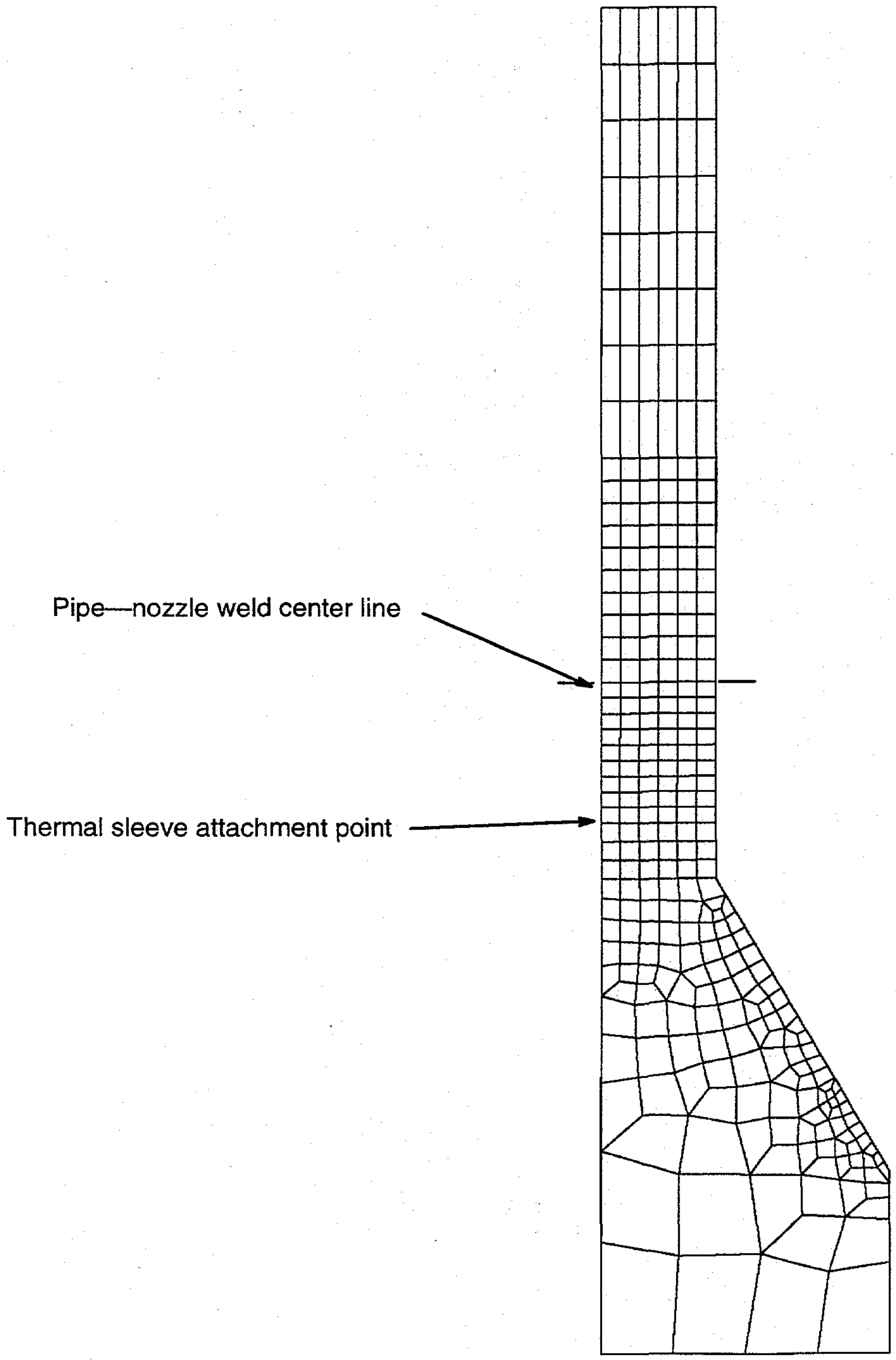

FIGURE 4. SAFETY INJECTION AXISYMMETRIC FINITE ELEMENT NOZZLE MODEL.

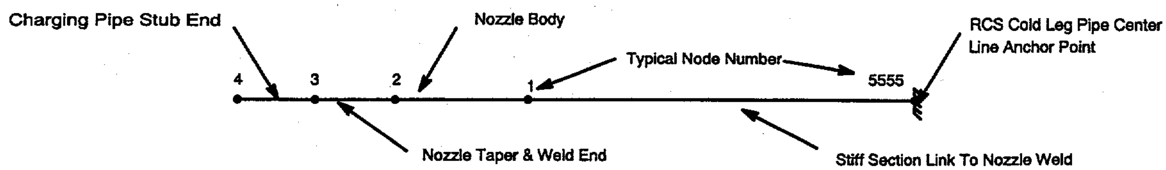

FIGURE 5. NUPIPE–II MODEL USED FOR CHARGING NOZZLE NB–3600 CALCULATIONS.

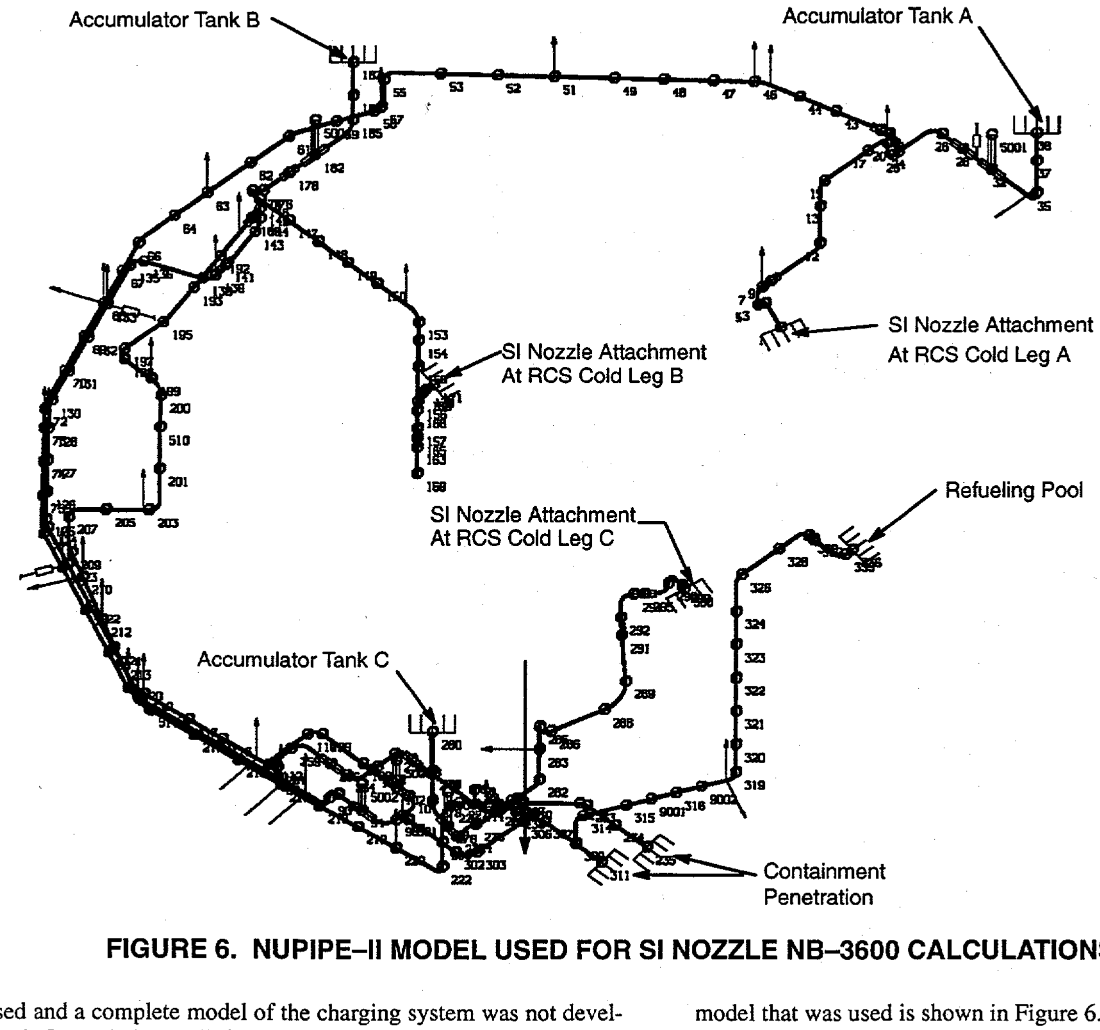

FIGURE 6. NUPIPE–II MODEL USED FOR SI NOZZLE NB–3600 CALCULATIONS.

used and a complete model of the charging system was not developed. Instead, the small, four element model shown in Figure 5 was used for the charging nozzle. The SI nozzles at this plant are attached to the residual heat removal (RHR) piping system. Since other analyses were performed on the RHR system as part of the NUREG/CR–6260 work, the piping system model developed for the other analyses was also used to perform the NB–3600 calculations for the SI nozzle. The RHR piping system finite element model that was used is shown in Figure 6. The locations of the SI nozzles are also indicated in Figure 6. Both models used different piping cross sections to represent the various piping components included in the nozzles and attached piping. Typically, this included accurately modeling the nozzle body sections, nozzle weld end sections, attached piping, etc., as would be appropriate in a typical piping analysis.

ANALYSIS METHODOLOGY

Since the charging and SI piping systems were designed to the rules of the B31.1 piping code, no fatigue analyses had been conducted. Consequently, we performed a fatigue analysis using representative transients based on the charging and SI nozzle analyses from the other PWR plants reviewed in the NUREG/CR–6260 study. The methods of both NB–3200 (design by analysis) and NB-3600 (piping) of the 1992 edition of the ASME Code were used. The previously described analytical models were used throughout for the analyses.

Transients And Cycles Assumed

Our review of transients used for similar plants involved in the NUREG/CR–6260 study showed that, for this type of plant, six transients were the major contributors to the charging nozzle cumulative usage factor (CUF). These transients and the assumed number of cycles are shown in Table 1.

Similarly, our NUREG/CR–6260 review of transients used for similar plants indicated that there were two main transients that were the major contributors to the SI nozzle CUF. These transients were emergency injection and residual heat removal (RHR) initiation during cooldown. It was observed that the specified number of design basis cycles ranged between 60 and 260 while the expected number of cycles ranged between 30 and 100 for this transient. We assumed 70 cycles for our calculations on the SI nozzle during emergency injection. A similar approach led us to assume 200 cycles for initiation of RHR during cooldowns. Other transients (e.g., plant heat up/cool down, plant trip, etc.) were included in the calculations for the SI nozzle but were found not to be significant CUF contributors and will not be tabulated for the sake of brevity.

Analysis Comparisons

Calculations for the nozzle CUFs were completed using the methods of NB-3600 of the ASME Code and the NUPIPE-II computer code. NUPIPE–II is the piping analysis computer code used by the INEL. It is a well known and commonly used nuclear industry piping analysis computer code and includes the capability to automatically calculate piping component CUF's when performing a Class I analysis. While there are several other piping analysis computer codes used throughout the industry, the NUPIPE results should be representative of the CUF results that would be obtained by using the NB–3600 approach.

Three areas of each nozzle were considered: the nozzle-to-pipe weld, the area at the thermal sleeve junction, and the nozzle body where the nozzle is connected to the main coolant piping, which was considered to be a branch connection. Moments applied to the nozzle by the connecting piping for the various transients were supplied by the licensee and these moments were used in the analysis. The piping models shown in Figures 5 and 6 were used for the charging nozzle and SI nozzle, respectively.

An NB-3200 finite element analysis was also performed for the charging and SI nozzles using the same pressures, thermal transients, moments, and numbers of cycles as were used in the NB-3600 analysis. A table of temperature-dependent moduli of elasticity were used in the finite element model instead of a single temperature, so the alternating stress intensity ranges were adjusted by multiplying by the ratio of the modulus of elasticity on the fatigue curve to the modulus of elasticity at the average temperature during the transients that made up the load pairs (300°F).

NB-3200 provides different classifications for the linear portions of the stresses due to radial thermal gradients in Tables NB-3217.1 and NB-3217.2. For vessels, Table NB-3217.1 classifies these stresses as secondary stresses whereas for piping, Table NB-3217.2 classifies them as peak stresses. The piping definition in Table NB-3217.2 was used in the calculations to compute the primary plus secondary stress intensity range. The text in NB–3213.9 (secondary stress definition) and NB–3213.13 (definition of thermal stress) makes no differentiation between vessels and piping, and the wording is consistent with Table NB–3217.1. It appears that Table NB–3217.2 is consistent with the deletion of the ΔT_1 term from Equation 10 of NB–3650 for piping components, and since we consider the charging nozzle to be a piping component, the stress caused by the radial thermal gradient was considered to be a peak stress. In the region of the nozzle–to–charging system piping junction, we could clearly differentiate between the stresses caused by radial and axial gradients, because the axial gradients were negligible. However, in the knuckle region, the stresses resulted from a combination of axial and radial gradients, so the linear portions were considered to be secondary stresses.

TABLE 1. MAJOR TRANSIENTS ASSUMED IN THE CHARGING SYSTEM ANALYSIS.

Set Number	Load Set	Cycles
1	Charging and letdown shutoff	1460
2	Delayed return to service after transient 1	100
3	Letdown shutoff with prompt restart	200
4	Letdown shutoff with delayed restart	20
5	Charging shutoff with prompt restart	20
6	Charging shutoff with delayed restart	20

COMPARISON OF RESULTS FOR NB–3200 AND NB–3600 CUF CALCULATIONS

Charging Nozzle

The NB–3600 calculations showed that the CUF was 0.460 for the branch connection to the RCS cold leg piping, but low (0.022) for the weld to the charging system piping and (0.008) at the thermal sleeve. The major contributor to the CUF was the letdown shutoff with delayed restart transient (Transient 4 in Table 1). The axial thermal gradient (the $\alpha_a T_a - \alpha_b T_b$ term) produced most of the stress intensity at the branch connection, whereas the ΔT_1 and ΔT_2 terms produced most of the stress intensity in the charging system piping region of the nozzle.

The NB–3200 calculations showed that the individual usages were negligible for most of the transients. This was consistent with the NB-3600 analysis results. The major contributing transients were various combinations of charging and letdown shutoff, and recovery from those transients. The maximum CUF was 0.030 in the region above the thermal sleeve, and 0.020 for the nozzle body region. The maximum stress intensity from initiation of cold charging water into the hot nozzle (such as from the letdown shutoff event) occurred part-way into the transient for the nozzle-to-charging system piping region where the radial thermal gradient caused most of the stresses. However, for the nozzle body region, the maximum stress intensity occurred after the steady-state condition had been reached when the charging system piping region was at the cold injection water temperature (assumed to be 32°F), the main coolant piping was hot (560°F), and an axial thermal gradient existed in the knuckle region. A comparison of the three highest S_{alt} values (which contributed nearly all of the CUF) and the fatigue usage for each load pair are shown in Table 2. The load pairs were all various combinations of the load sets listed in Table 1.

The difference in the NB-3200 results upstream of the thermal sleeve and at the piping weld is that stress indices were applied to the NB-3600 stresses to represent the field weld. If NB-3600 stress indices were applied to the NB-3200 stresses to represent the field weld, the CUF for the field weld would be higher for the NB-3200 results than for the NB-3600 results. Although the element meshing in the axisymmetric model (Figure 2) is comparable to the meshing used in many of the licensees' analyses that we reviewed for the NUREG/CR–6260 project, extrapolation of the stress gradient to the surface may require a finer mesh size.

While the NB-3200 and NB-3600 results were comparable for the S_{alt} computed for the nozzle-to-charging system junction region, the S_{alt} was reduced by more than a factor of four in the nozzle body (considered to be a branch connection in the NB-3600 analysis) region using the NB–3200 finite element analysis. Most of the NB–3600 CUF resulted from a single load pair. The reduction in CUF at this region can be attributed to the C_3K_3 stress indices of 1.8 X 1.7 = 3.06 applied to the $\alpha_a T_a - \alpha_b T_b$ term in the NB–3600 analysis, the resulting 3.333 K_e penalty factor, and smoothing of the axial temperature gradient in the NB–3200 analysis. While the NB–3200 and –3600 results for the S_{alt} values computed for the nozzle–to–charging system piping region are comparable, the highest S_{alt} was reduced significantly in the nozzle body region using the finite element model.

SI Nozzle

The NB–3600 calculations showed that the CUF was high (1.993) for the branch connection to the main coolant piping, but low (0.046) for the weld to the SI system piping and (0.010) at the thermal sleeve. The major contributor to the CUF was the emergency injection transient/plant trip load pair, with the former transient providing almost all of the stress range. The axial thermal gradient (the $\alpha_a T_a$ - $\alpha_b T_b$ term) produced most of the stress intensity at the branch connection, whereas the ΔT_1 and ΔT_2 terms produced most of the stress intensity at the weld to the SI system piping and the thermal sleeve region of the nozzle.

The NB–3200 calculations showed that the individual usages were negligible for most of the transients. This was consistent with the NB-3600 analysis results. The maximum stress intensity from initiation of cold emergency injection water into the hot nozzle occurred part-way into the transient for the nozzle-to-SI system piping junction region where the radial thermal gradient caused most of the stresses. However, for the nozzle body region, the maximum stress intensity occurred at the end of the transient. A comparison of the highest S_{alt} (which contributed nearly all of the CUF) and the CUFs (summed from the individual usages of all load pairs) are shown in Table 3.

TABLE 2. RESULTS FOR CHARGING NOZZLE USING BOTH NB-3200 AND NB-3600 METHODS.

Location	Load pair	NB-3600		NB-3200	
		S_{alt}	Usage	S_{alt}	Usage
Branch connection/ nozzle body	1	363.53	0.452	87.69	0.007
	2	46.00	0.004	80.94	0.020
	3	46.00	0.004	29.47	0.000
Nozzle-to-pipe weld	1	84.62	0.006	NA	NA
	2	70.04	0.012	NA	NA
	3	52.11	0.004	NA	NA
Nozzle region upstream of thermal sleeve	1	NA	NA	84.79	0.006
	2	NA	NA	82.86	0.022
	3	NA	NA	46.15	0.002

TABLE 3. RESULTS FOR SI NOZZLE USING BOTH NB-3200 AND NB-3600 METHODS.

Location	NB-3600		NB-3200	
	S_{alt}	CUF	S_{alt}	CUF
Branch connection/nozzle body	400.22	1.976	32.88	0.002
Upstream of thermal sleeve	NA	NA	92.48	0.031
Nozzle-to-pipe weld	102.57	0.046	125.14	0.095

The difference in the NB-3200 results upstream of the thermal sleeve and at the piping weld is that NB-3600 stress indices were applied to the NB-3200 stresses to represent the field weld. The S_{alt} was reduced by more than a factor of 10 in the nozzle body (considered to be a branch connection in the NB-3600 analysis) region using the NB-3200 finite element analysis. The reduction in CUF can be attributed to the C_3K_3 stress indices of $1.8 \times 1.7 = 3.06$ applied to the $\alpha_a T_a - \alpha_b T_b$ term in the NB-3600 analysis, the resulting 3.333 K_e penalty factor, and smoothing of the axial temperature gradient in the NB-3200 analysis. The NB-3200 S_{alt} and CUF at the nozzle-to-pipe weld (which incorporated NB-3600 stress indices) are higher than the NB-3600 results.

CONCLUSIONS

Not surprisingly, the results show that different CUFs will be determined when using the NB–3600 rules as opposed to application of the NB–3200 rules. When the alternating stress intensity results mainly from a through-wall (radial) thermal gradient, as in the case of the region of the nozzle-to-piping system junction (e.g., the top portion of the model in Figure 2), the alternating stress intensities computed using NB-3200 and NB-3600 methods were comparable. This is because NB-3600 uses the result of an equation developed from an exact analysis of a radial temperature gradient in a cylinder for the ΔT_1 and ΔT_2 terms. However, when the alternating stress intensity is mainly the result of an axial gradient in the nozzle, as is the case in the nozzle body region where the $\alpha_a T_a - \alpha_b T_b$ term is the major contributor, then using an NB-3200 finite element model can reduce the CUF considerably.

Although this paper reports on a very limited sample size, the results indicate that when the more recent ASME Code fatigue analysis rules were applied to older components, CUFs comparable to what might be expected for similar components of later vintage design were determined.

In a case such as this where no fatigue analyses had been performed and the plant was well into its design operating life, considerable time could be spent developing accurate plant specific transient data if a fatigue analysis were to be undertaken today. This would make the time spent developing models and performing calculations a smaller portion of the overall effort to determine the CUF. The results for the components studied indicate that utilization of either approach may provide acceptable results, that is, a CUF less than the limiting value of 1.0. In the past, the use of the NB–3200 approach usually included the use of more complicated computer models than those employed by a NB–3600 approach. However, it would seem that given the recent advances in solid modeling technology and computational efficiency that the lower CUFs (longer fatigue life) calculated by the NB–3200 approach would make this approach somewhat more desirable for use on a present day analysis task.

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NOTICE