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ASME Code Stress Evaluation of Manway Nozzle for PWR Steam Generator

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Abstract:

This paper presents a structural analysis of primary side manway nozzle for the PWR steam generator. The analysis was based on ASME section III, subsection NB-3200; 2017 edition for stress analysis in the shell, and on ASME BPVC.III.A-2017, Article XIII-4000 for stress limits in the bolts. In this analysis ASME code 2017 edition was used, although PWR steam generator design was based on ASME Sec. III NB-2007 with 2008 addenda and ASME Section III, NC-2007 with 2008 addenda were used. The analysis was carried for design, and level A conditions. ANSYS 18.1 was used as the tool of analysis. The analysis showed that the design of APR1400 manways satisfies the criterion in ASME code. The maximum stresses intensities were less than 1.5S_m for design condition and 3Sm for the level A condition. The actual bolt cross sectional area was determined to be more than the minimum required bolt cross sectional area.

Keywords - Bolt Analysis, Manway Nozzle, Steam Generator, ASME BNPV Code Sect. III

I. INTRODUCTION

Fig1 shows a typical man-way nozzle in a PWR steam generator. In this paper, 21-inch diameter manway openings on PWR Steam Generator (SG) that are located on the primary head, one on the inlet side and the other on the outlet side are investigated. These being large bore openings, this paper seeks to analyze their structural effects on the integrity of primary head. The stresses induced in the bolts used to secure manway cover are also investigated. The main objective of the study is to verify the design of the PWR steam generator inspection manway nozzle, manway blind flange, and the securing bolts to confirm that they satisfy the technical requirements on structural integrity to maintain the reactor coolant pressure boundary.

The analysis is carried out based on the criteria set in the ASME (American Society of Mechanical Engineers) BPVC section III, subsection NB (design by analysis) 3200[2]. The bolts design limits are investigated according to ASME BPVC Section III, Appendix XIII-4000, Stress limits for bolts [3]. The modeling and analysis are carried out in ANSYS version 18.1 and the scope is limited to Design and normal operating condition. The Manway under investigation is shown in Fig 1.

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Fig 1 Manway nozzle un-der investigation shown on the model in the center.

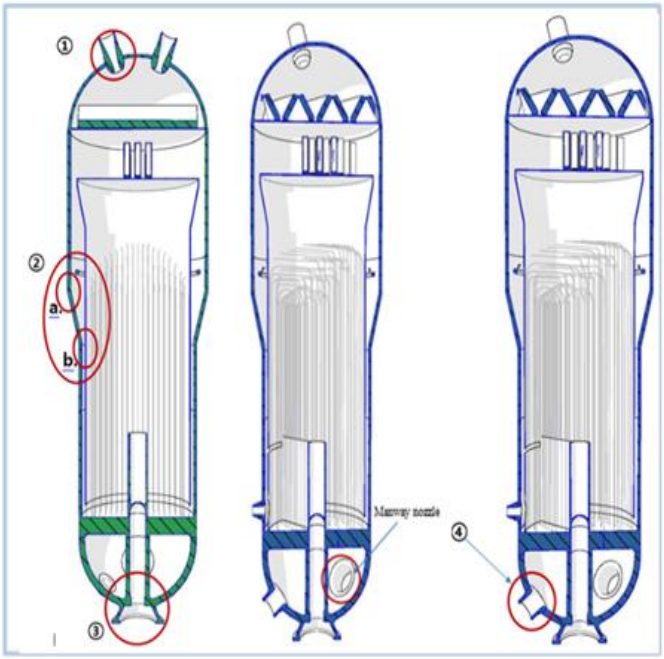

Figure 1. Manway nozzle under investigation shown on the model in the center

II. LOADS AND STRESS EVALUATION CRITERIA

II.I. Stress Limits in Shell and Nozzle Blind Cover

The headings and subheadings, starting with "**I. Introduction**", appear in upper and lower case letters and should be set in bold and aligned flush left. All headings from the Introduction to Acknowledgements are numbered sequentially using roman numerals, etc. Subheadings are numbered I.I, I.II, etc.

The stress limits for a class I components are given in ASME BPVC section III, subsection NB-3000. In both design and level A conditions, the calculated stress values are to be compared to the S_m values. The S_m value for the shell and cover material is as shown in Table 1.

Table 1. Design stress intensity values for shell and cover material

Shell and cover material SA-508 Gr.3 Cl.1				
Tensile strength	Yield strength	Stress Intensity S_m		
		300°C	325°C	350°C
550MPa	345MPa	184MPa	184MPa	184MPa

Design Loadings conditions are defined in ASME III, NB-3221. The stress intensity limits that must be satisfied for the Design: General Primary Membrane Stress Intensity, Local Membrane Stress Intensity, Primary Membrane (General or Local) Plus Primary Bending Stress Intensity, and External Pressure [4].

Table 2. Limits of stress intensities for design condition

	Limits of stress intensities for design condition
1	General Membrane Stress, $P_m < S_m$
2	(General Membrane Stress , P_m + Local Membrane Stress, P_L) <1.5S_m
3	(Bending Stress, P_b + Local Membrane Stress, P_L) <1.5S_m

Level A Service Limits conditions are defined in ASME III, NB-3222. Level A Service Limits must be satisfied for the Service Conditions for which these limits are designated in the Design Specifications and the four limits: Primary Membrane and Bending Stress Intensities, Primary Plus Secondary Stress Intensity Range, Expansion Stress Intensity, and Analysis for Cyclic Operation.

Table 3. Limits of stress intensities for level A and B conditions

	Limits of stress intensities for level A and B conditions
1	Secondary Stress, $expansion$, $P_e < 3S_m$
2	(Bending Stress, P_b + Local Membrane Stress, $P_L + P_e + Q$) <3S_m
3	(Bending Stress, P_b + Local Membrane Stress, $P_L + P_e + Q + F$) < S_a

II.II Bolt Design Stress Limits According to ASME code

The process to determine the bolts load is very critical in bolt analysis. In the design of flange bolts, the bolts design pressure W shall be sufficient to resist the hydrostatic end force H [5]. This is the force exerted by the design pressure on the area bounded by the diameter of gasket reaction. The design bolt load is determined by the equations provided in ASME, Section III.A-2017, Article XIII-4000 of the ASME code [5].

$$W=H + Hp = 0.785G2\ P+ [2b \times 3.14Gm\ P] \tag{1}$$

Where; W= is the design bolt load,

Hp = joint contact compression load,

H = Total hydrostatic end force which is equal to 0.785G2P,

G = Diameter at the location of gasket load reaction. It is the mean diameter of the gasket contact face,

b = Effective gasket or joint contact surface seating width,

P= Design pressure, m = is the gasket factor obtained from ASME code, table XI-3221.1-1 for this application m= 0, [4].

II.III Required Bolt Cross-section Area

ASME, Section III.A-2017, Article XIII-4000 Stress Limits for Bolts requires to evaluate bolt load and the corresponding Minimum required and Actual Bolt Areas that shall be greater than Minimum Required Bolt Area. ASME, Section III.A-2017, Article E-1000 and Article XIII-4000 gives the guideline for determining the minimum bolt cross-sectional area. The minimum area A_{m1} should be less than the actual bolt cross sectional area A_{actual}

$$A_{m1} < A_{actual} \tag{2}$$

And

$$A_{m1} = (\text{Bolt load, } W) / (\text{Allowable stress, } S_b) \tag{3}$$

Where S_b is the allowable bolt stress at the design temperature. From Table 4, the allowable bolt stress at 350oC is 238MPa.

II.IV Level A and B Stress Limits in Bolt

ASME BPVC section III.A-2017, Article XIII-4000 “stress limits for bolts”, gives the guidelines on how to determine the required number of bolts and its cross-section area for the bolts needed to resist stresses due to the design pressure [3]. For class 1 components, the allowable bolt design stresses shall be the value given in ASME BPVC Section II, part D, subpart 1, Table 4 for bolting material. The ASME code provides guidelines to determine the safe loading conditions in bolts. The stresses produced by loads in bolts are to be evaluated as for averaged and maximum stresses.

Average stress: The maximum value of the service stress averaged across the bolt cross-section shall not exceed 2/3 Sy values, neglecting stress concentrations.

Maximum stress: the maximum service stress values resulting from direct tension plus bending shall not exceed the yield strength values. In this application, the bolt material is SA-540 Gr. B24 Cl. 3 whose properties are shown in Table 4.

Table 4 Design stress intensity values for bolting material

Bolt material SA-540 Gr. B24 Cl. 3				
Tensile strength	Yield strength	Stress intensity S_m		
		300°C	325°C	350°C
1000MPa	895MPa	251MPa	245MPa	238MPa

In the analysis, the bolt preload will be calculated from equation (3). This is tension load created in a fastener when it is tightened [6]. The tensile force induced in the bolt creates a compressive force in the bolted joint. This compressive force created in the bolted components [6]. For reusable connections:

$$F_i = 0.75A_t * S_p \qquad (4)$$

Where A_t is the tensile area of the bolt and S_p is the proof strength of the bolt

III. ANALYSIS MODELING AND BOUNDARY CONDITION

This section discusses the steps followed to perform the APR1400 Manway nozzle structural integrity analysis based on ASME BPVC. Critical dimensions for the model are as shown in Table 5.

Table 5 Critical model dimensions [8]

	Critical model dimensions	mm
1	Internal radius of the shell	2330
2	Thickness of the shell	265
3	Manway opening reinforcement thickness	120
4	Thickness of cover	150
5	Bolt dimensions	M56
6	Manway Opening diameter	535

A 3-D model was created in ANSYS18.1 mechanical workbench analysis software. The model was composed of three bodies; the hemispherical shell, the manway cover, and the securing bolt. The manway nozzle is shown on SG model in Fig 2. To simplify the complexity of the model, a 15° section was used in the analysis [7].

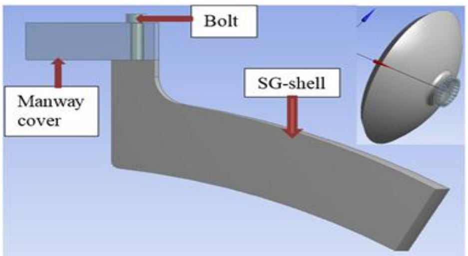

Figure 2. A 3-D model for the manway nozzle

Setting up the right mesh is critical in all FEM analysis [9]. We began by setting up default coarse mesh. Various mesh refining techniques such as body sizing, inflation, MultiZone, Face meshing, Contact sizing, and Hex dominant methods were tried. Fig 3 shows the meshing techniques used and the final meshed model.

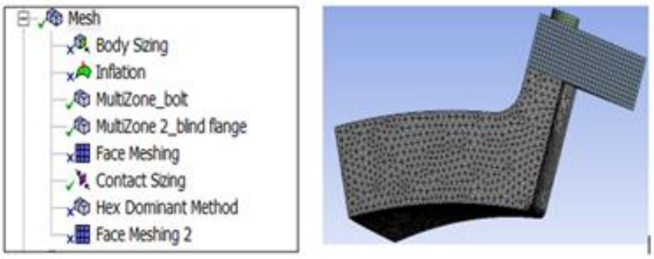

Figure 3. Meshing techniques used and meshed model

Contact Boundary Condition between the model bodies, shell, nozzle blind cover and bolt surfaces, was setup as shown in Table 5. The contact definitions are shown in Fig 4.

Table 5. Contacts definitions

	Bodies	Contact setup
1	Bolt stem and shell	bonded
2	Blind cover and Bold head	frictional
3	Blind cover and Shell	frictional

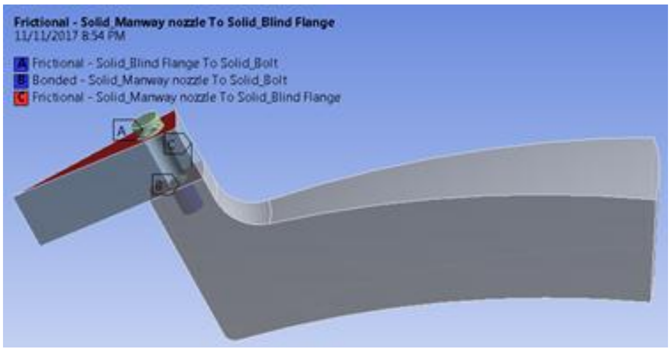

Figure 4. Contacts definition

The load setup in for design condition, and level A analysis is summarized in Table 6.

Table 6 Summary of design level boundary condition

	Property	Level A	Design Conditions
1.	Design Pressure	15.12 MPa	17.23MPa
2.	Design Temperature	323.9 °C	343.2 °C
3.	Bolt preload	6.0E+5 N	6.0E+5 N
4.	Outer Surface	Perfect insulation	Perfect insulation
5.	Support	Frictionless support	Frictionless support

Steady state thermal results were applied only under Level A analysis. This involved applying operating temperature of 323.9°C [8] to the inner surfaces of the model. The outer surfaces were taken to be perfectly insulated.

IV. RESULTS AND DISCUSSIONS

The results and discussion are presented in this chapter. The results presented are for Design condition and Level A conditions.

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IV-I. Design Condition Results for Shell and Nozzle Blind Cover

A total of four stress paths were created on the SG shell body in order to assess the maximum bending, and maximum membrane stresses. According to ASME section III (2017), the maximum sum of bending stress and membrane stress should not exceed $1.5S_{m.}$ APR1400 steam generator shell is made from SA-508, Gr.3 Cl. 1, which has S_m=182MPa for the design temperature of 343.2ºC. The stress paths locations and stress results along path C is shown in Fig 5. The analysis result is summarized in Table 7. The highest stresses are along stress path C which is located at nozzle-shell intersection. The highest stress in this region is 188.22MPa which is less than $1.5S_m$ = 276 MPa.

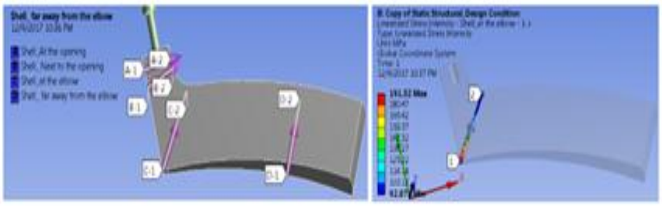

Figure 5 Stress path location on SG shell and stress result along path C

Table 7 Stress Path result for shell under design loading

Shell design condition stress paths analysis				$1.5S_m$
	P_m	P_b	$P_b + P_m$	276
Stress path A	65.58	31.07	84.93	276
Stress path B	85.72	38.06	112.56	276
Stress path C	127.57	83.71	188.22	276
Stress path D	92.64	13.08	105.66	276

Design condition stress analysis in blind cover

Just like for the SG shell, the manway blind cover is also made from SA-508, Gr.3 Cl. 1, which has S_m=182MPa for the design temperature. The stress paths locations and stress results along path D is shown in Fig 6.

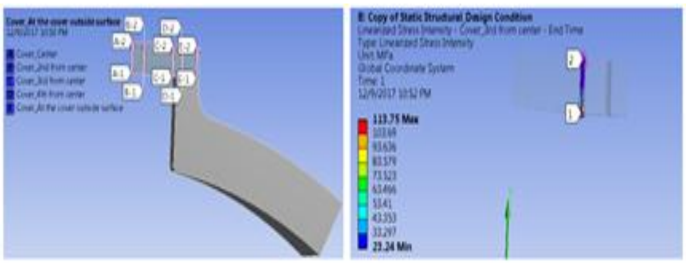

Figure 6 Location of stress paths and results for stresses along path D on blind cover

The highest tress of 82.17 MPa occur along stress path D. This stress path is located close to the bolt region. The summary results for stress along the stress paths A-E are shown in Table 8.

Table 8 Summarized linearized results for blind cover DC

Blind cover design condition stress paths analysis				$1.5S_m$
	P_m	P_b	$P_b + P_m$	276
Stress path A	23.04	23.63	46.65	276
Stress path B	25.29	19.47	43.32	276
Stress path C	35.14	48.99	79.36	276
Stress path D	35.36	50.51	82.17	276
Stress path E	29.50	35.52	64.90	276

IV.II Level A Condition Results for Shell and Nozzle Blind Cover

Level A analysis is based on normal operating condition. In this analysis, the operating conditions are the internal pressure of 15.23 MPa and operating temperature of 323.9ºC. During operation, the manway is usually tightly closed. Level A condition analysis was carried out in two stages: steady state thermal and static structural.

Steady State Thermal Analysis Results

The internal surface temperature was set at 323.9ºC. The outer surface was assumed to be perfect insulation, therefore no loss of heat to the surrounding. This setup is shown in Fig 7.

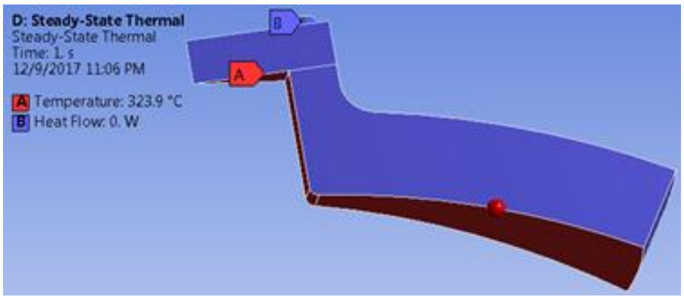

Figure 7 Steady-state model setup

Level A analysis of the shell

Generally, the stress in the SG shell and the blind cover are low compared to the design criteria of ASME code section III, subsection NB. The maximum stresses shall be less than 3S_mfor level A condition. The SA-808 Gr.3, Cl. 1 material has S_m value of 184 MPa, therefore the set limit for level A case is 556MPa. Figure 8 shows stress path D result for level A conditions.

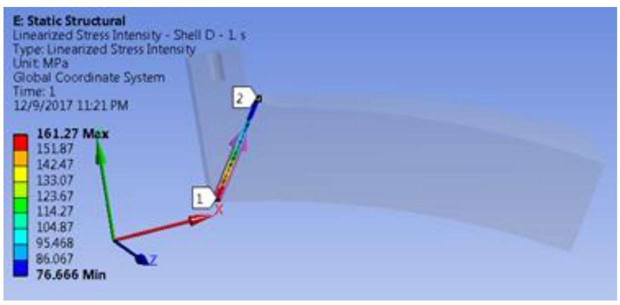

Figure 8 Sample stress path result for Shell under level A analysis

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The summarized result for linearized stresses in the shell is presented in Table 9. The maximum linearized stress of 171.01MPa in the shell occurs on path D. This is the path through the nozzle and shell intersection.

Table 9 Linearized stress result for shell under level A condition

Shell design condition stress paths analysis				$3.0S_m$
	P_m	P_b	$P_b + P_m + Q$	552
Stress path A	55.23	20.58	68.21	552
Stress path B	75.61	33.65	95.76	552
Stress path C	105.1	73.69	159.85	552
Stress path D	111.30	75.06	171.01	552
Stress path E	85.17	10.60	95.67	552

Level A analysis for the blind cover

Generally, the stress in the SG shell and the blind cover are low compared to the design criteria of ASME code section III, subsection NB. The maximum stresses shall be less than 3S_mfor level A condition. The SA-808 Gr.3, Cl. 1 material has Sm value of 184 MPa, therefore the set limit for level A case is 556MPa. A Sample stress path D result is shown in Fig 9.

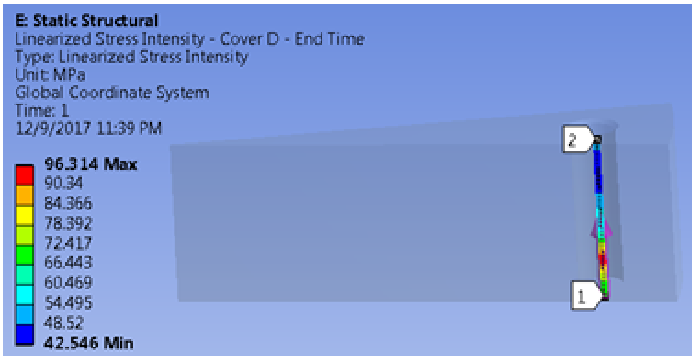

Figure 9 Sample stress path result for blind under level A analysis

The summarized result for linearized stresses the blind cover is presented in Table 10. In the blind cover, the maximum linearized stress of 90.10MPa occurs along path D. Path D of the blind cover is located on the outer surface of the cover. The minimum stresses 41.08MPa in the cover occur at the center of the cover.

Table 10 Linearized stress result for blind cover under level A condition

Blind cover design condition stress paths analysis				$3.0S_m$
	P_m	P_b	$P_b + P_m + Q$	552
Stress path A	20.33	20.76	41.08	552
Stress path B	27.26	10.45	31.39	552
Stress path C	26.44	45.19	70.20	552
Stress path D	48.94	60.08	90.10	552
Stress path E	27.31	31.34	58.48	552

IV.III Analysis Results of Level A and Level B Service Limit for Bolt

Actual stresses in bolts, such as those produced by the combination of preload, pressure, and differential thermal expansion, may be higher than the values given in the ASME tables. ASME, III. Article XIII-4000 provides guidelines on how to calculate the average stress and maximum stress. The article recommends that stresses due to stress concentrations should be ignored.

Average stress in bolt

The average stresses are the principal maximum stress experienced by the bolt. To avoid stress concentrations, the value of principal stress is obtained at the middle of the bolt cross-section. In in column 2 as membrane stresses Pm. The average stress is obtained from stress path D

$$\sigma_{avearge} = 301.59\text{MPa} < 2/3\text{, but } S_y = 596\text{MPa} \quad (5)$$

ASME BPVC III.A-2017, Article XIII-4000, requires that the average stress should be less than 2/3 Sy. For this application, 2/3 Sy=596 MPa. It can be concluded that the average stress is less than the set criteria, hence the bolt design meets the design requirements.

Maximum Stress in Bolt

To analyze the bolt, stress paths were set up as shown in Figure 10. The stress results along path A-D is summarized in Table 11

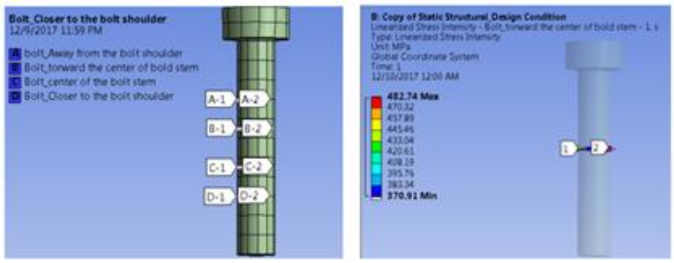

Figure 10 Location of stress paths and path C stress path result

Table 11 Level A stress path analysis results for bolt

Max. stresses in Bolt according to ASME Sec. III. App. XIII-4000 (ed. 2017)			Maximum (S_m)
	P_m	Maximum stress (MPa)	
Stress path A	254.83	262.13	895
Stress path B	301.59	482.74	895
Stress path C	307.30	321.27	895
Stress path D	166.85	181.00	895

Summarized results from the stress paths are presented in Table 12. The result taken as the maximum stress for this analysis is the one in stress path B. This is chosen because it is away from the effect of stress concentrations. On path B, the maximum stress is 482.74 MPa which meets the set criteria of Sy=895 MPa.

Table 12 Summary of the results

	Body	Loading condition	Criteria	Calculated value (MPa)	Allowable value (MPa)
1	Shell	Design condition	$P_b + P_m < 1.5\mathrm{S_m}$	188.22	276
2	Shell	Level A condition	$P_b + P_m + \mathrm{Q} < 3.0\mathrm{S_m}$	171.01	552
3	Blind Cover	Design condition	$P_b + P_m < 1.5\mathrm{S_m}$	82.17	276
4	Blind Cover	Level A condition	$P_b + P_m + \mathrm{Q} < 3.0\mathrm{S_m}$	90.10	552
5	Bolt	Level A (Max. str.)	$\sigma_{max} < \sigma_y$	482.74	895
6	Bolt	Level A (Ave. str.)	$\sigma_{average} < \frac{2}{3}\sigma_y$	301.59	596
Required minimum bolt cross section area M2					
1	Bolt	Design condition (cross-section area)	$A_{M_1} < \mathrm{A_{actual}}$	1.0608E-3 ($\mathrm{A_{actual}}$)	1.0154E-3 ($\mathrm{A_{M1}}$)

V. CONCLUSION

Structural integrity assessment was performed on APR1400 steam generator Manway nozzle. The main objective was to assess whether the structure of the shell and blind flange around the nozzle meets the ASME III subsection NB stress limits under design and level A loading conditions. The second objective was to assess whether the cross-sectional area of the bolts used to fasten the blind flange meets the minimum cross-sectional area requirement as per ASME BPVC III.A-Article XIII-4000.

In conclusion, the study on assessment of structural integrity of APR1400 manway nozzles has confirmed that the stresses induced in the nozzle components meet the stress limit recommended in ASME BPVC section III, subsection NB and related Appendixes. In the study, it was observed that the weakest link in the manway nozzle region is the bolt as it bears much of the loads. Therefore, care should be taken in the selection of the bolt material and manufacturing process for it to meet the design require-ments. For further study, I recommend a researcher to ex-tend this study to include other loading conditions such as for emergency conditions and fatigue analysis.

Acknowledgements

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