Evaluation Of Weld Indications Detected In Inservice Inspections For Class 1 Ferritic Steel Components

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Abstract

For different class 1 ferritic steel components, acceptance standards for flaws detected in inservice inspections are stipulated in the ASME Code, Section XI, Subsection IWB. For flaws exceeding ASME Code acceptance standards, analytical evaluation can be used to justify if the flaws are acceptable. The end-of-service size of a flaw is used to determine if the flaw is acceptable for service without repair. Growth of the flaw can be calculated based on the stress conditions at the flaw location and environment. A case of a heater nozzle/head weld of a pressurizer with indications is evaluated to demonstrate the analysis procedure.

1. Introduction

The requirements for inservice inspection of Class 1 components are stipulated in Subsection IWB of ASME Code Section XI [2]. All detected flaws shall be characterized by the rules of IWA-3300 [2] to establish the dimensions of the flaws and evaluated based on the acceptance standards in IWB-3000 [2]. Acceptance standards for different flaws in different types of welds and components are specified in Table IWB-3410-1 [2] and details of these acceptance standards are provided in IWB-3500 [2]. For flaws that exceed the acceptance standards of Table IWB-3410-1 [2], analytical evaluation procedure described in IWB-3600 [2] can be used to justify if the flaws are acceptable.

As specified in CSA-N285.4-94 [3], acceptance criteria in Subsection IWB-3000 of ASME Code Section XI [2] are applied to periodic inspections for CANDU plant components. In addition, these criteria are also applicable for evaluation of indications detected during inaugural inspections, as illustrated in Figure 3 of CSA-N285.4-94 [3].

Analytical procedure for ferritic steel components with 4″ and greater thickness is provided in IWB-3610 [2]. For ferritic steel components with less than 4″ thickness, no analytical procedure is available now and the analytical procedure in IWB-3610 can also be used. In IWB-3610, growth of a flaw can be calculated by using the procedure described in Appendix A of Section XI [2] to get the final flaw size a_f.

In order to perform flaw growth calculation and justify end-of-service flaws, stress data for different service conditions are required. If stress data used for fatigue analysis at the flaw locations are available, the data can be used for growth calculations of the flaws. If no stress data are available, full transient stress analysis has to be carried out. In such an analysis, only stress data around the flaw locations are needed.

For end-of-service flaws, the criteria of IWB-3611 or IWB-3612 [2] should be satisfied. In addition, primary stress limits of NB-3000 [1] should be also met, assuming a local area reduction (IWB-3610(d)(2)). Components accepted for continued service based on analytical evaluation shall be subsequently reexamined in accordance with IWB-2420(b) and (c) [2]. In this paper, the entire analysis procedure is applied to a heater nozzle/head weld of a pressurizer with indications.

2. Assessment of Indications Detected

During an inspection of a pressurizer, ultrasonic inspection method was used. Indications detected around a heater nozzle weld are illustrated in Figure 1. Amplitudes and locations of these indications are provided in the UT report of the inspection. Vertical extents are provided only for indications with amplitudes greater than –6 dB (50%). From the UT report, two of the 17 indications have amplitude results greater than –6 dB and only one indication has an amplitude greater than 0 dB (100%). The two indications can be classified as subsurface planar flaws based on the UT report and the rules in IWA-3300 [2]. Dimensions of the flaws are summarised in Table 1.

Acceptance standards for different flaws in different types of welds and components are specified in Table IWB-3410-1 [2]. For this case, limits in Table IWB-3512-1 [2] for subsurface flaws should be applied. From Table 1, it can be seen that the two flaws are acceptable.

However, as shown in Figure 1, several flaws are close to the two flaws assessed. These flaws are clustered into two larger flaws as shown in Table 1. The dimensions of each clustered flaw (***l*** and ***a***) are defined by the size of the bounding square or rectangle that contains all the individual flaws. The dimensions and assessment of the two clustered flaws are also presented in Table 1. Since the second clustered flaw exceeds its limit, further evaluation using IWB-3610 [2] is required.

3. Stress Analysis

In IWB-3610 [2], growth of a flaw may be calculated using the procedure in Appendix A of Section XI [2]. In this procedure, stress data for different service conditions are required. Since no stress data for fatigue analysis at the header nozzle weld location of the pressurizer were available, full transient stress analysis was carried out. The model shown in Figure 2 was generated for the analysis using general Finite Element (FE) analysis code ANSYS [4].

There are five heater nozzles around the lower head. Four heater nozzles are located 60° apart and one heater nozzle is located with larger spaces with its neighbouring two heater nozzles. The heater nozzle with 60° apart from its neighbouring two heater nozzles was considered more critical. Therefore, one half of the heater nozzle and a 30° angle of the lower head, inlet diffuser nozzle and shell were modelled. All details around the weld were considered and simplifications were made to the heater nozzle flange and the inlet diffuser nozzle.

Symmetric boundary conditions were applied to two sides of the model and the end of the inlet diffuser nozzle was restrained along vessel axis. For thermal analysis, temperature and heat transfer coefficient were applied to all inside surfaces of the model and all outside surfaces of the model were insulated. For stress analysis, pressure was applied to all inside surfaces of the model and blow-off pressure was applied to the top end of the shell.

Fifteen transients are specified for the vessel for Levels A, B, C and D conditions. These transients were lumped as six transients as summarised in Table 2. Based on the conditions of the transients, thermal transient analyses were performed to obtain temperature distributions of the model for all the transients. Maximum temperature differences between different locations were used to determine times for structural analyses. Structural analyses were then carried out with pressures and temperature distributions applied.

Stress class lines were defined across different locations of the weld and linearised stress data were output for fatigue analysis of these locations. Fatigue usage factors for these locations were calculated using a B&W Canada in-house fatigue analysis program. Linearised stress data for the location with the highest fatigue usage factor are summarised in Table 3 and used for further flaw growth calculation.

4. Flaw Growth Calculation

Calculation of flaw growth can be performed using the method stipulated in Appendix A of ASME Code Section XI [2]. Stress intensity factor for a flaw can be calculated using Eqn. (1) and parameters in Eqn. (1) can be obtained from Article A-3000 [2].

$$\boldsymbol{K_I} = \left[\left(\boldsymbol{\sigma_m} + \boldsymbol{A_p}\right)\boldsymbol{M_m} + \boldsymbol{\sigma_b M_b}\right]\sqrt{\pi/\boldsymbol{Q}}\sqrt{\boldsymbol{a}} \qquad (1)$$

where:

$\boldsymbol{\sigma_m}$ and $\boldsymbol{\sigma_b}$ are membrane and bending stresses at the flaw section.
$\boldsymbol{a}$ is one half flaw depth for a subsurface flaw or flaw depth for a surface flaw.
$\boldsymbol{M_m}$ and $\boldsymbol{M_b}$ are correction factors for membrane and bending stresses.
$\boldsymbol{Q}$ is flaw shape parameter.
$\boldsymbol{A_p}$ is the internal vessel pressure for internal surface flaw or zero for other flaws.

Parameters $\boldsymbol{M_m}$ and $\boldsymbol{M_b}$ for subsurface and surface flaws are determined differently in Article A-3000 [2]. For one flaw, $\boldsymbol{M_m}$ and $\boldsymbol{M_b}$ for two points can be determined based on flaw geometry data. Higher values of $\boldsymbol{M_m}$ and $\boldsymbol{M_b}$ for the two points of a flaw can be used for the flaw to bound the two points.

Flaw growth rate is characterised in terms of the range of applied stress intensity factor $\boldsymbol{K_I}$ in Article A-4000 [2] as:

$$\boldsymbol{da/dN} = \boldsymbol{C}_0(\Delta \boldsymbol{K_I})^{\boldsymbol{n}} \qquad (2)$$

where:

$\boldsymbol{C_0}$ and $\boldsymbol{n}$ are determined based on $\boldsymbol{\Delta K_I}$, $\boldsymbol{R}$ ratio ($\boldsymbol{K_{min}/K_{max}}$) and environment. Using the data for each pass in Table 3, $\boldsymbol{\Delta K_I}$ and $\boldsymbol{R}$ can be calculated based on Eqn. (1) for a given flaw size of $\boldsymbol{a}$. Thus, $\boldsymbol{C_0}$, and $\boldsymbol{n}$ can be determined. Let

$$\boldsymbol{F} = \frac{\Delta \boldsymbol{K_I}}{\sqrt{\boldsymbol{a}}} \tag{3}$$

If flaw size change for each pass is ignored, integrating Eqn. (2) for Pass No $\boldsymbol{i}$ gives:

$$\boldsymbol{a}_{i+1} = \left(\boldsymbol{a}_i^{1-\frac{\boldsymbol{n}}{2}} + \left(1 - \frac{\boldsymbol{n}}{2}\right) \cdot \boldsymbol{C}_0 \cdot \boldsymbol{N}_i \cdot \boldsymbol{F}_i^{\boldsymbol{n}} \right)^{\frac{1}{1-\frac{\boldsymbol{n}}{2}}} \tag{4}$$

Table 4 is a spreadsheet for calculating flaw growth for a subsurface flaw using Eqn. (4). The size $\boldsymbol{a}$ of the initial flaw is the flaw size of the second clustered flaw in Table 1 and the stress data are taken from Table 3. For each pass, flaw growth should be small. If flaw growth for one pass is large, this pass can be split into several passes. The flaw size after the last pass is the size of the end-of-service flaw under the specified transient conditions.

5. Evaluation of End-of-Service Flaws

The acceptance criteria stipulated in IWB-3611 and IWB-3612 [2] are based on flaw sizes and applied stress intensity factors, respectively. The principles for the criteria in the two subsections are the same. In the analysis in this paper, the acceptance criteria in IWB-3612 are used. These criteria can be summarised as:

<u>For normal conditions:</u>

$$\boldsymbol{K_I} < \boldsymbol{K_{Ia}} / \sqrt{10} \tag{5}$$

<u>For emergency and faulted conditions:</u>

$$\boldsymbol{K_I} < \boldsymbol{K_{Ic}} / \sqrt{2} \tag{6}$$

$\boldsymbol{K_{Ia}}$ and $\boldsymbol{K_{Ic}}$ represent the fracture toughness of the material and are critical values of the calculated stress intensity factor $\boldsymbol{K_I}$. Lower bound $\boldsymbol{K_{Ia}}$ and $\boldsymbol{K_{Ic}}$ versus temperature curves given in Article A-4200 [2] can be used for class 1 ferritic steel components, if data from the actual product form are not available.

In Table 3, data sets with high tensile stresses and lower temperatures are highlighted for evaluation of the end-of-service flaw. It can be seen that these data sets represent Level A/B, Test and Level C/D conditions, respectively. Stress intensity factors $\boldsymbol{K_I}$ for the three conditions can be calculated using the spreadsheet in Table 4 with the final flaw size. Since these stress intensity factors are below their limits, the flaw is acceptable for service without repair.

Area reduction due to the existence of the flaws is considered negligible, so that there is no need to check primary stresses. Enhanced periodic inspections to the area shown in Figure 1 are recommended.

6. Conclusions

For flaws exceeding ASME Code acceptance standards, analytical evaluation can be used to justify if the flaws are acceptable. Such an analytical evaluation may include stress analysis for the flaw location, flaw growth analysis and evaluation of the end-of-service flaw. Enhanced inservice inspections to the components accepted for continued service based on analytical evaluation are required.

7. References

[1] ASME, Boiler and Pressure Vessel Code, Section III, Division 1 – Subsection NB, "Class 1 Components", 2004 Edition.

[2] ASME, Boiler and Pressure Vessel Code, Section XI, "Rules for Inservice Inspection of Nuclear Power Plant Components", 2004 Edition.

[3] CAN/CSA-N285.4-94, Periodic Inspection of CANDU Nuclear Power Plant Components.

[4] SAS IP, Inc., "Release 10.0 Documentation for ANSYS" (Online Manual), 2005.

Table 1 Assessment of Flaws Detected Around a Heater Nozzle Weld

Indication Number	Amplitude	t (mm)	a (mm)	l (mm)	a/l	a/t %	Limit of a/t %
6	-2 dB	74.0	0.8	6.0	0.125	1.014	2.7
14	1 dB	75.1	0.5	8.0	0.063	0.666	2.3
4,7,12,14	/	75.1	1.25	47.0	0.027	1.664	2.1
3,5,6,13,15	/	74.0	2.125	28.0	0.076	**2.872**	***2.3***

All indications are classified as subsurface flaws.
50% signal is –6 dB and 100% signal is 0 dB.
Limits of ***a/t*** are based on Table IWB-3512-1 [2].

Table 2 Summary of Transients for Analysis

Tran. No.	Transient Name	No. Of Cycles	Deck File
1	Warmup/Cooldown	250	T01.f1 to .f17
2	Lumped A (Level A)	11000	T02.f1 to .f13
3	Lumped B (Level B)	1510	T04.f1 to .f9
4	System Hydrotest	20	T08.f1 to .f2
5	Crash Cooldown (Level C)	15	T05.f1 to .f7
6	Emergency Overpressurization (Level C)	1	T06.f1 to .f3

Table 3 Summary of Transients for Analysis

Pass	Cycle	Maximum					Minimum			
	N	Tran. No.	Deck File	σ_m (ksi)	σ_b (ksi)	Temp. °F	Tran. No.	Deck File	σ_m (ksi)	σ_b (ksi)
1	250	2	T02.f4	**14.2**	**11.7**	**511**	1	T01.f3	3.4	-5.9
2	1510	2	T02.f4	14.2	11.7	511	3	T04.f5	15.4	-4.1
3	20	2	T02.f4	14.2	11.7	511	4	T08.f1	0.0	0.0
4	9220	2	T02.f4	14.2	11.7	511	2	T02.f7	14.4	-4.0
5	1510	3	T04.f6	14.4	-4.0	526	2	T02.f7	6.8	7.9
6	250	1	T01.f7	12.1	3.8	511	2	T02.f7	14.4	-4.0
7	20	4	T08.f2	**20.2**	**0.3**	**100**	2	T02.f7	14.4	-4.0
CD	16	2	T06.f3	**20.2**	**2.4**	**635**	1	T05.f7	0.0	0.0

Table 4 Flaw Growth Calculation for a Subsurface Flaw

Pass	Cycle	Max. Stress (ksi)		Min. Stress (ksi)		K_I $(\text{ksi}\sqrt{\text{in}})$			Ratio	Air Environment n = 3.07		Flaw Size (in)
	N	σ_m	σ_b	σ_m	σ_b	K_{Imax}	K_{Imin}	ΔK_I	R	C_0	da/dN	a
										Initial Flaw 2.125 mm		0.0837
1	250	14.2	11.7	3.4	-5.9	11.27	0.01	11.3	0.00	1.99E-10	3.36E-07	0.0837
2	1510	14.2	11.7	15.4	-4.1	11.27	6.83	4.4	0.61	4.11E-10	4.01E-08	0.0838
3	20	14.2	11.7	0.0	0.0	11.28	0.00	11.3	0.00	1.99E-10	3.38E-07	0.0838
4	9220	14.2	11.7	14.4	-4.0	11.28	6.32	5.0	0.56	3.87E-10	5.27E-08	0.0843
5	1510	14.4	-4.0	6.8	7.9	6.34	5.91	0.4	0.93	6.61E-10	5.00E-11	0.0843
6	250	12.1	3.8	14.4	-4.0	7.52	6.34	1.2	0.84	5.76E-10	9.53E-10	0.0843

7	20	20.2	0.3	14.4	-4.0	11.00	6.34	4.7	0.58	3.95E-10	4.46E-08	0.0843

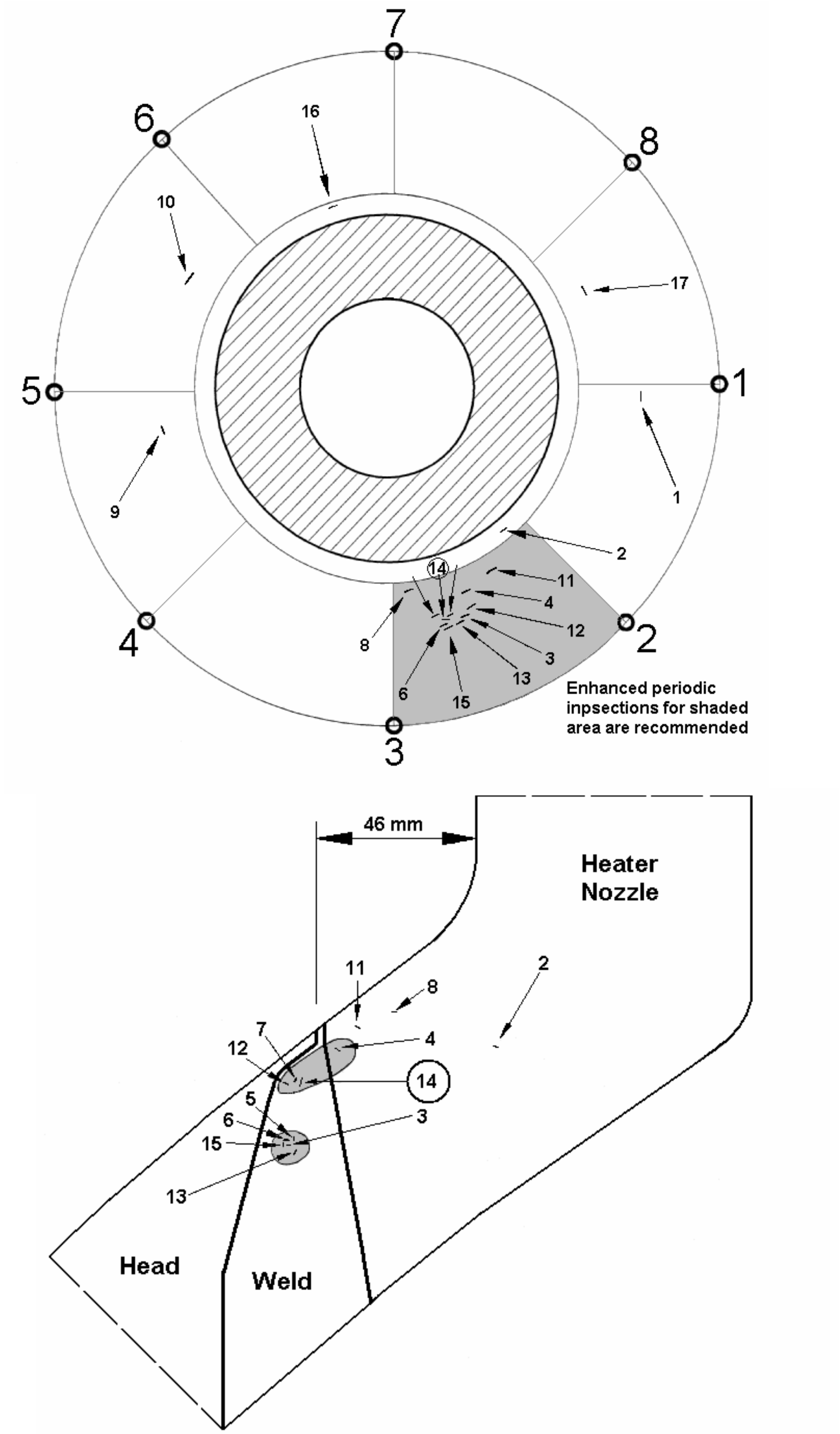

Figure 1 Indications Detected around Pressurizer Heater Nozzle/Head Weld

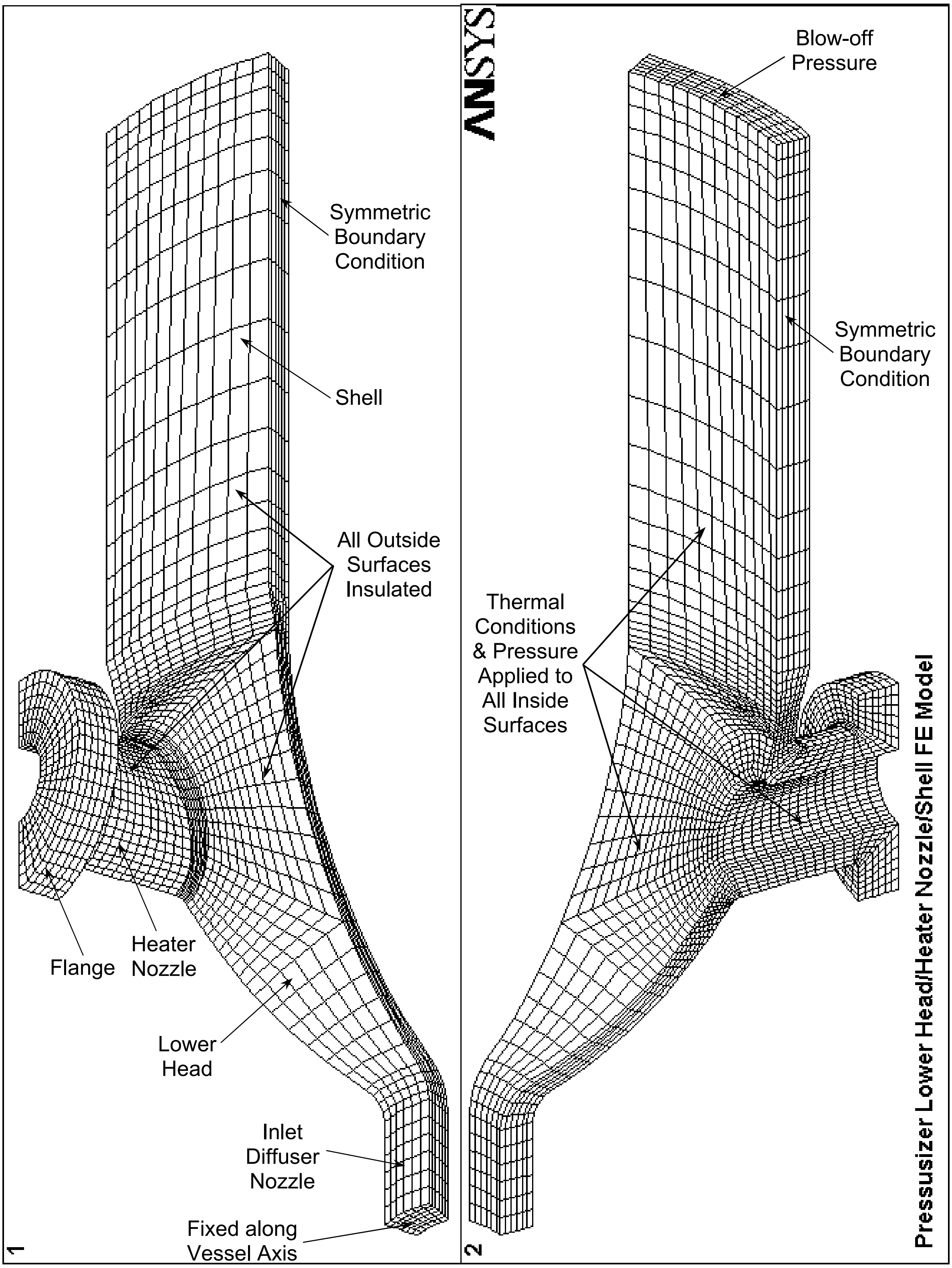

Figure 2 FE Model for Heater Nozzle/Head Weld Stress Analysis