Proceedings of the ASME 2013 Pressure Vessels and Piping Conference
PVP2013
July 14-18, 2013, Paris, France

PVP2013-97076

TECHNICAL JUSTIFICATION SUPPORTING OPERATION WITH A TUBE INSTALLED IN A MIS-DRILLED HOLE OF A STEAM GENERATOR TUBESHEET

Mr. Roberto Ruiz
ENSA Engineering Department
Avda Juan Carlos I, 8, 39600
Maliano, Cantabria, Spain
Tel: +34-942-200101
Email: ruiz.roberto@ensa.es

Dr. Enrique Gomez
ENSA Engineering Department
Avda Juan Carlos I, 8, 39600
Maliano, Cantabria, Spain
Tel: +34-942-200166
Email: gomez.enrique@ensa.es

Mr. Robert M. (Con) Wilson
Private Consultant
3609 Cherry Hill Drive, Orlando, Florida USA
Tel: 407-761-1337
Email: conwilson1@aol.com

ABSTRACT

An evaluation is described for a tube with manufacturing induced bending, resulting from installation in a tubesheet mis-drilled hole. Considerations include manufacturing processes such as tube installation and tube expansion plus evaluations of the resulting tube stresses using ASME B&PV Code Section III rules. Also considered are operating issues such as potential interaction with neighboring tubes, tube vibration and wear, and the potential for accelerated tube corrosion. This is a companion paper to “ASME Section III Stress Analysis of a Heat Exchanger Tubesheet with a Mis-drilled Hole and Irregular or Thin Ligaments”.

NOMENCLATURE

ASME	American Society of Mechanical Engineers
d	tube outer diameter and drilled hole inner diameter, 0.75-inch
ENSA	Equipos Nucleares S.A.
h	nominal ligament between tubesheet holes, 0.25-inch
h_a	minimum ligament at mis-drilled tubesheet hole, 0.10-inch
Primary Side:	The face of the tubesheet where the tubes are attached and the tube inside surface.
P	Tube pitch: tubesheet hole center-to-center distance, 1.0-inch
p	pressure, psi

P_m primary membrane stress, ksi
Q secondary stress, ksi
R Tube outside radius, 0.375-inch
Secondary side: The face of the tubesheet where the tube exits the tubesheet and the outer surface of the tube where steam is generated.
σ_x Axial bending stress, ksi
σ_r Radial stress due to pressure, ksi
σ_{TTS} Tube bending stress at the top-of-tubesheet, ksi ,
σ_{TSP} Tube bending stress at a tube support plate intersection, ksi
t Tube wall thickness, 0.040-inch
T Temperature, ^{o}F
TSP Tube Support Plate (TSP #1 is nearest to tubesheet)
TS Tubesheet
TTS Top of Tubesheet (secondary side or face)

INTRODUCTION

Tube plugging is a common method of removing steam generator tubes from service when their structural integrity has been compromised. The purpose of this paper is to demonstrate that a tube installed in a mis-drilled tubesheet hole does not have compromised structural integrity and that plugging such tubes is not necessary.

The drilling of nuclear steam generator tubesheets is a very precise process that almost always yields smooth parallel holes in their proper positions. However, there are situations when a hole is mis-drilled such that it is not parallel to its neighbors. A tube inserted into such a non-parallel hole differs from a nominal tube and requires special evaluation to determine its technical acceptability. This paper takes the mis-drilled hole described in PVP2013-97075 [Ref. 1] and evaluates the effects of such a change in geometry on the integrity of the tube passing through it.

GEOMETRY

The steam generator described in this paper has 7,220 U-tubes that are connected to the tubesheet. The tube material is ASME SB-163, Alloy 690. The tubesheet is 30 inches thick and has 14,440 0.76-inch diameter tube holes. The tubesheet hole diameter is 0.010-inch larger than the tube outer diameter to permit tube insertion; but for this analysis the hole inside diameter and tube outer diameter are conservatively assumed to be 0.75-inch. The tube is assumed to have a 0.040-inch wall thickness.

The tubesheet has a hot leg side where the hot reactor coolant enters the tube bundle. The hot leg side has 7,220 holes, each containing the hot leg end of the 7,220 U-tubes. The U-tubes transfer heat from the reactor coolant to the secondary side fluid to produce steam and the reactor coolant exits the bundle through the cold leg side of the tubesheet. The hot leg and cold leg sides of the tubesheet are separated by a non-drilled (solid) tubelane that extends across the full diameter of the tubesheet. The steam generator also has a solid divider plate that joins the tubesheet to the channel head and forces the hot reactor coolant to flow through the U-tubes.

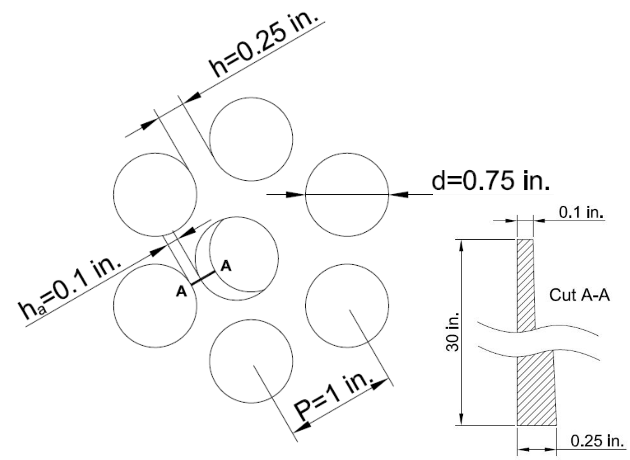

Figure 1. Mis-Drilled Hole Geometry

The mis-drilled hole is located 42.73-inches from the center of the tubesheet (on the primary face) where the nominal primary side ligament is 0.25-inch. The secondary side ligament due to the mis-drilled, non-parallel configuration is 0.10-inch. The mis-drilled hole geometry is shown in Figure 1.

For purposes of evaluating the influence of the mis-drilled tubesheet hole on the tube stress it is not necessary to model a full U-tube. Rather, it is sufficient to model a straight tube that extends upward from the tubesheet through a few tube support plates (TSPs). The analysis discussed in this paper includes four TSPs.

TUBE INSTALLATION IN A NOMINAL HOLE

After the steam generator tubesheet has been drilled and all of the tube support plates (TSPs) have been installed into the lower shell assembly, the tubes are installed. The tube installation process includes many steps. Each U-tube is inserted one at a time into the appropriate holes in the top TSP and then through the remaining TSPs and the tubesheet. The next step is to expand the tubes through the full thickness of the tubesheet, thus eliminating the gap. The final step is to weld the tube ends to the clad surface on the primary face of the tubesheet.

The tubes have no interaction stresses at the intersections with the TSPs and the tubesheet when they are installed in nominal holes. However, if one of the tube ends is inserted into a mis-drilled tubesheet hole, it will have additional fabrication-induced bending stresses.

TUBE INSERTION IN A MIS-DRILLED HOLE

In the case where a tube is installed in a nominal tubesheet hole, it is pushed through the hole. In the case where a tube is installed in a mis-drilled tubesheet hole it is pulled through the hole. The pulling of the tube end is accomplished through the use of a special guide piece that is attached to the tube end prior to installation and another tool is inserted through the tubesheet hole where it can capture the tube end and then be used to pull the tube into the mis-drilled hole.

For the mis-drilled hole in this evaluation, the entrance of the tubesheet hole is out of position by 0.15-inch. As the tube is pulled through the hole the maximum tube bending moment is at the secondary face of the tubesheet. There is also contact at the TSPs, particularly the 1st and 2nd TSPs, where tube bending is also present, but to a lesser degree.

The friction force that must be overcome to pull the tube into the mis-drilled tubesheet hole is the sum of the friction at the TSPs and the tubesheet hole entrance. Experience gained from insertion (and extraction) of sample tubes in similar configurations indicates that this magnitude of mis-alignment does not damage the tube. The absence of tube damage is due, in large part, to the smooth contact surfaces of the TSPs and tubesheet holes.

Mockup experiments with mis-drilled holes show that the tooling and processes used to expand tubes into nominal tubesheet holes are equally effective for mis-drilled holes. This is because the tooling-to-tube clearances are greater than the variations between nominal and mis-drilled holes.

Tube expansion experiments with a set of nominal holes surrounding a single mis-drilled hole (based on 0.76-inch diameter holes and a 1.0-inch triangular tube pitch) indicate that tube expansion in the mis-drilled hole does not produce interference in the neighboring holes that would affect tube insertion or the ability to expand the tubes in the neighboring holes.

TUBE STRESS EVALUATION – NOMINAL CASE

The ASME Code, Section III [Ref. 2] stress evaluation for a nominal steam generator tube at the tubesheet intersection is considered here. Stresses in other locations along the U-tube are outside the scope of this paper.

During operation, the tubesheet experiences small rotations and displacements that are caused by differential pressures and temperature. The tubesheet deflection and thermal growth cause the attached tubes to bend, with the maximum tube bending occurring at the intersection with the secondary face of the tubesheet.

ASME Section III [Ref. 2] NB-3213.9 classifies such bending stress as Secondary (Q) because the tube is connected to a gross structural discontinuity (the tubesheet) and that the tubesheet movement is displacement limited. This means that the tube bending at this location need not be evaluated against Primary Stress limits, but only against the Secondary Stress limits. These include the [Ref. 2] NB-3222.2 Primary Plus Secondary Stress Intensity Range requirement and the NB-3222.4 Fatigue requirement.

The tube bending stress at the intersections with the tube support plates (TSPs) that is induced by tubesheet rotation / displacement and TSP displacement is also classified as Secondary (Q) and is not required to meet the Primary Stress requirements.

Table 1 displays the ASME stress classifications as a function of loading that apply to the tube stress state at the secondary surface of the tubesheet or at the TSP intersections. Note that bending is always classified as Secondary (Q).

Table 1. ASME [Ref. 2] Stress Classifications for Tubes at Tubesheet and TSP Intersections

Loading	Type of Stress	ASME Code Classification	Service Level
Pressure	Membrane Bending	P_m Q	Design, A, B, Test
Thermal	Membrane Bending	Q	Design, A, B
Tubesheet / TSP Interaction	Bending	Q	Design, A, B, Test

TUBE STRESS EVALUATION – MIS-DRILLED HOLE

The tube stress classification is unchanged for the case where the tube is inserted into a mis-drilled tubesheet hole. However, after installation, the tube will have additional manufacturing-induced, residual bending stress. The ASME Code, Section III [Ref. 2] does not place analytical limits on manufacturing-induced stresses or residual stresses. Such stresses represent a non-zero, mean stress state that is generally present in all structures, including steam generator tubes installed in nominal tubesheet holes.

An example of a residual stress that is commonly present in tubes at the tubesheet secondary face, is the residual stress state produced by the tube expansion process. The magnitude of these stresses is significant [Ref. 3] but not included in the ASME Section III stress analysis.

The ASME Code accounts for the presence of residual stresses by basing the fatigue curves on the maximum mean stress [Ref. 4]. A high mean stress reduces the cyclic fatigue life of a structure.

The affect of the misalignment of the mis-drilled hole or misalignment of TSP holes is to produce a “mean” manufacturing-induced bending stress in the tube at each intersection. This manufacturing-induced bending stress does not affect the fatigue usage factor and does not affect the primary plus secondary stress intensity range because it is part of the constant mean stress, around which all cyclic loads fluctuate.

Therefore, the mis-drilled tubesheet hole and the associated manufacturing-induced stress state do not change the tube’s ASME structural integrity margin.

Having noted that the ASME rules for structural integrity do not apply to residual stresses, the following evaluation is made to further demonstrate their acceptability evaluating them against the ASME Section III [Ref. 2] stress limits.

Using an ANSYS one-dimensional finite element beam model [Ref. 5] a single straight length of tube is modeled using dimensions from Figures 1 and 2. The loading condition is based on the imposed displacement and rotation of the mis-drilled tubesheet hole, while maintaining the TSP nominal hole positions (referred to as the Base Case). A second analysis (shown in the following section) assumes that the TSP holes are offset conservatively so as to produce the maximum tube bending stress (referred to the TSP-offset Case).

For the Base Case (see Fig. 2), the tube off-set at the secondary side of the tubesheet is 0.15-inch off-center, while the tube is located at the nominal on-center position at the tubesheet primary side and all of the TSPs. The tubesheet thickness is 30-inches. The distance between the tubesheet secondary surface and the first TSP centerline is 25-inches, and the distance between TSP centerlines is 40-inches.

The free length of the modeled tube is therefore 145-inches above the tubesheet and there is a 30-inch straight length that is constrained to be straight along the mis-drilled hole path within the tubesheet. The tube lateral displacement at the TSP elevations is constrained to be zero.

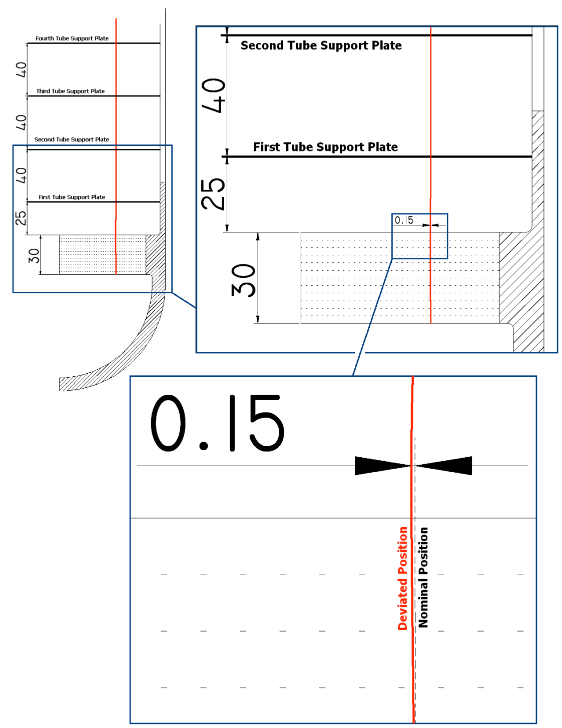

Figure 2. Tube Configuration with TSPs and Tubesheet

INFLUENCE OF TSP HOLE POSITION

The TSP-offset Case is based on the following assumptions: at the TSP #1 elevation, a 0.040-inch offset is conservatively oriented in the opposite direction of the mis-drilled tubesheet hole. At the remaining three TSPs their positions vary alternately by 0.040-inch in the opposite directions with the goal of establishing a conservative upper bound tube bending stress due to TSP fabrication offsets.

The comparison of the Base Case tube bending stresses to those of the TSP-offset Case is shown in Table 2. It conservatively demonstrates the influence of the TSP hole position on the tube bending stresses.

Table 2. Tube Bending Stress due to Mis-Drilled Hole
Base Case: + No TSP Hole offsets
TSP-offset Case: ±0.04” TSP Hole offsets

Tube Bending Stress	σ_{TTS} (ksi)	σ_{TSP-1} (ksi)	σ_{TSP-2} (ksi)	σ_{TSP-3} (ksi)	σ_{TSP-4} (ksi)
Tube elevation, inch	30	55	95	135	175
Base Case	-18	7	-2	0	0
TSP-offset Case	-22	11	-5	3	0

Note that the tube bending stresses associated with a 0.15” mis-drilled hole and 0.04” TSP offsets are all elastic and relatively small compared to the tube yield stress (> 40 ksi). The maximum tube bending for the TSP offset case is 22 ksi.

TUBE STRESS DUE TO TUBESHEET BENDING

Table 3 shows a number of steam generator operating events that cause differential tubesheet and TSP movements and subsequently produce operational tube stresses at the secondary face of the tubesheet. All these operating conditions correspond to the 10 Events described in companion report PVP2013-97075 [Ref. 1].

Table 3. Steam Generator Operating Conditions

Transient	$T_{Primary}$ (TS Temp)	$T_{Secondary}$ (TSP Temp)	$P_{Primary}$	$P_{Secondary}$
	ºF	ºF	psi	psi
1	70.0	70.0	0	0
2	608.3	517.5	2220	1050
3	610.0	517.7	2250	800
4	603.9	511.1	2200	750
5	389.9	557.0	1545	1100
6	328.1	445.1	1915	400
7	288.1	527.4	1600	860
8	611.9	518.8	2220	1050
9	70.0	70.0	3100	0
10	120.0	120.0	0	1500

Table 4 shows the tube stresses due to tubesheet rotation and TSP displacement for each operating event (assuming a tube in a nominal tubesheet hole at the mis-drilled hole location).

Table 4. Tube Stresses Due To Tubesheet Rotation
(Nominal TS hole at the mis-drilled hole location)

Tube Bending Stress	σ_{TTS} (ksi)	σ_{TSP-1} (ksi)	σ_{TSP-2} (ksi)	σ_{TSP-3} (ksi)	σ_{TSP-4} (ksi)
Elevation, inch	30	55	95	135	175
Transient-1	0	0	0	0	0
Transient -2	0	0	0	0	0
Transient -3	0	0	0	0	0
Transient -4	0	0	0	0	0
Transient -5	-6	3	-1	0	0
Transient -6	-7	3	-1	0	0
Transient -7	-8	4	-1	0	0
Transient -8	0	0	0	0	0
Transient -9	3	-1	0	0	0
Transient -10	-3	1	0	0	0

It can be seen from Tables 2 and 4 that the maximum tube bending occurs at the top-of-tubesheet elevation. The bending stress due to tubesheet rotation is 8 ksi (from Table 4, Transient 7) and the bending stress due to the maximum TSP-offset is 22 ksi (from Table 2). The sum of these two effects produces a maximum bending stress of 30 ksi (oriented in the axial direction along the tube at the top of tubesheet elevation). For a manufacturing-induced stress, this is a very small value.

Manufacturing-induced (residual) stresses are typically produced by straining the material beyond the yield point. The stresses produced by the mis-drilled hole combined with conservative TSP offsets are well within the elastic range of the tube material.

TOTAL TUBE STRESS EVALUATION

The nominal tube stress due to pressure is small at the top-of-tubesheet (TTS) elevation because the tube is expanded into the tubesheet and fully supported. However, for conservatism and simplicity the free-length pressure stresses will be calculated and combined with the manufacturing induced stress to see how the result compares to the ASME Section III [Ref. 2] stress limits.

Since the maximum stress due to the mis-drilled hole occurred at Transient 7, the tube pressure difference for that transient (i.e. 740 psi) will be used in this calculation. The free-length pressure stress in the axial direction is approximately 3.5 ksi (i.e. pR/t = 740 psi x 0.375" / (2 x 0.040")). The corresponding hoop stress is double the axial stress, or 7 ksi and the radial stress is -0.4 ksi (i.e. $-p/2$). Conservatively adding the 3.5 ksi free-length axial pressure stress to the 30 ksi manufacturing-induced bending stress produces a total axial stress of 33.5 ksi or a maximum stress intensity of 34 ksi {i.e. $| \sigma_x - \sigma_r |$ = 33.5 – (-0.4)}, which is small compared to the $3S_m$ (80 ksi) allowable limit that applies to secondary stresses at this location. This analysis indicates that the tube satisfies the ASME Section III [Ref. 2] stress limits with significant margin.

Since this calculation shows significant margin to the stress limits and recognizing that the manufacturing mis-alignment contributed most of the stress (rather than tubesheet rotation) it is evident that this result is independent of tubesheet hole location and applicable to all tubes.

INFLUENCE OF A MIS-DRILLED HOLE ON TUBE VIBRATION

Today's steam generators are fabricated so precisely that the alignment of the tube support plate (TSP) holes and the tubesheet holes is nearly perfect. This means that most of the tubes have negligible contact forces at the supports in the cold condition. When the steam generator is at operating conditions differential thermal expansion and pressure dilation generally increase these tube contact forces. However, tube wear is not entirely uncommon indicating that the tube-to-TSP contact forces are sometimes smaller than the fluid excitation forces.

In contrast, a tube passing through a mis-drilled tubesheet hole will have higher tube-to-TSP contact forces and will be better supported than tubes installed in nominal tubesheet holes.

INFLUENCE OF A MIS-DRILLED HOLE ON TUBE CORROSION

The small increase in tube wall stress associated with a mis-drilled tubesheet hole has a negligible influence on the tube's potential for corrosion. Alloy 690TT tube material is very resistant to all forms of corrosion that are common to steam generators and has demonstrated excellent corrosion resistance for nearly three decades in hundreds of operating steam generators. Extensive laboratory tests of this material under accelerated conditions of high stress, high temperature, and concentrated water chemistries indicate this material has great margin against corrosion under normal steam generator operating conditions.

All steam generator tubes have residual stresses that were produced by exceeding the yield stress, including those due to forming of the U-bends and from tube-to-tubesheet expansion during assembly [Ref. 3]. The tube strain from these processes exceeds the yield strain and is significantly larger than what is produced by a mis-drilled tubesheet hole where the fabrication-induced tube stresses are in the elastic range.

Tube corrosion is also a function of temperature. The NACE International Resource Center [Ref. 6] describes this relationship: "Most electrochemical reactions proceed at faster rates with increasing temperature, approximating to a doubling of rate for each 10^{o}C (18^{o}F) rise in temperature whether the corrosion process involves dissolution leading to general attack or to a more localized form such as cracking."

This indicates that the potential for corrosion of the steam generator cold leg tube ends is lower than for their hot leg counterparts where the temperature is typically ~70^{o}F hotter. Tubes passing through mis-drilled holes on the cold leg side of the tubesheet have greater corrosion margin than those on the hot side.

Tube corrosion also requires an aggressive chemical environment that is not available in today's modern steam generators that operate within the EPRI Water Chemistry Guidelines [Refs. 7 and 8] as proven by years of successful steam generator operating experience.

In summary, because the mis-drilled tubesheet hole introduces small, elastic tube stresses to tubes that already have much larger, plastic residual stresses, they have no influence on their long-term corrosion performance.

POTENTIAL FOR TUBE-TO-TUBE CONTACT WITH A MIS-DRILLED HOLE

Figure 3 shows the approximate geometry of a nominal tube and a tube installed in a mis-drilled tubesheet hole (the figure is exaggerated to help visualize this concern).

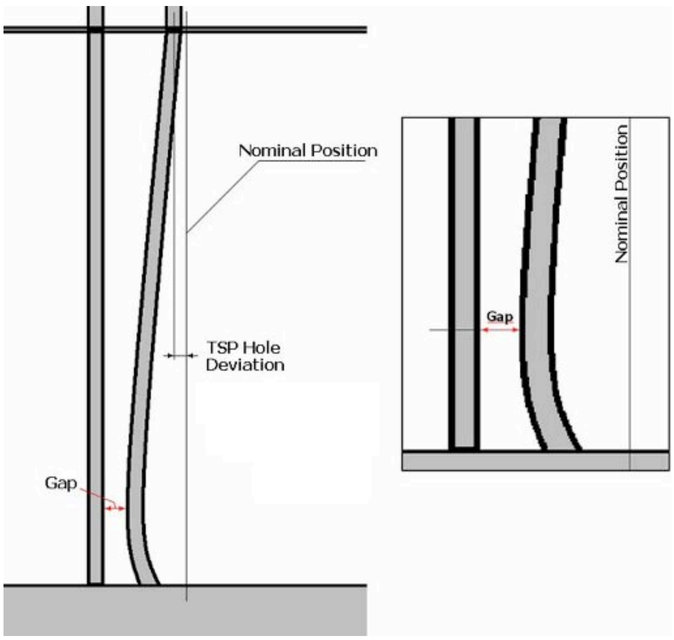

Figure 3. Tube-to-Tube Clearance

The finite element analysis used to calculate tube stresses (above) indicates that the elevation where neighboring tubes are closest is approximately 6-inches above the tubesheet. The distance between tubes at that elevation is 0.090-inch (assuming that the 0.150-inch deviation is aligned with the axis of the minimum tube-to-tube ligament) as compared to a 0.100-inch distance at the top of the tubesheet.

Since these tubes pass close to each other, it seems possible that they may touch during operating conditions. The only operating conditions that may push the tubes together are the flow forces during operation.

The tube rigidity is extremely high and prevents these tubes from touching. The force needed to produce tube-to-tube contact is greater than 400 pounds distributed along the entire tube span from tubesheet to the 1st TSP. To put this in perspective, the maximum fluid cross flow force is less than 1-lb/in and it only occurs on the tubes at the periphery of the tube bundle. Based on this assessment, the tube passing through the mis-drilled tubesheet hole will not contact the neighboring tubes.

CONCLUSION

A tube installed in a mis-drilled tubesheet hole satisfies the identical structural requirements as a tube installed in a nominal hole based on the ASME Section III [Ref. 2] rules for pressure boundary structural integrity. The relatively small changes in tube straightness and the presence of small elastic manufacturing-induced stresses are not detrimental to long-term operation. There is no technical basis to plug such tubes. This conclusion is independent of tubesheet hole location and applicable to all tubes.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contribution of Equipos Nucleares S.A. (ENSA) and Mr. Enrique Casado in the development of this report.

REFERENCES

1. E. Gomez, R. Ruiz, R. Wilson, “ASME Section III Stress Analysis of a Heat Exchanger Tubesheet with a Misdrilled Hole and Irregular or Thin Ligaments”, PVP2013-97075, July 2013, Proceedings of the ASME 2013 Pressure Vessels & Piping Division Conference
2. ASME Boiler & Pressure Vessel Code, Section III, “Rules for Construction of Nuclear Power Plant Components,” 2010 Edition, 2011 Addenda, Subsection NB, The American Society of Mechanical Engineers, New York, New York.
3. J. Hwang, D. Harrod, W. Middlebrooks, "Analytical Evaluation of the Hydraulic Expansion of Steam Generator Tubing into Tubesheets," International Conference of Expanded and Rolled Joint Technology, Paper C.10 (Toronto, Ontario: Canadian Nuclear Society, 1993)
4. “1969 Criteria of the ASME Boiler and Pressure Vessel Code for Design by Analysis in Sections III and VIII, Division 2”, American Society of Mechanical Engineers, United Engineering Center, 345 East Forty-Seventh Street, New York, NY 10017, copyright 1969 by the ASME
5. ANSYS Inc., “Release 10.0 Documentation for ANSYS,” 2005.
6. NACE International – The Corrosion Society, NACE Resource (online) Center > “Corrosion – Design” > “Temperature Influence on Corrosion”, web address:events.nace.org/library/corrosion/Design/Temperature-effects.asp
7. Pressurized Water Reactor Primary Water Chemistry Guidelines – Revision 6, December 2007, Electric Power Research Institute (EPRI)
8. Pressurized Water Reactor Secondary Water Chemistry Guidelines – Revision 7, December 2008, Electric Power Research Institute (EPRI)
9. ASME Boiler & Pressure Vessel Code, Section II, “Materials,” 2010 Edition, 2011 Addenda, Part D, The American Society of Mechanical Engineers, New York, New York.