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Considerations for Structural Analysis and Evaluation of Nuclear Steam Generator Internals

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ABSTRACT

Steam generators in a nuclear power plant extract heat from the primary coolant and produce steam for power generation. While the pressure boundary components of a steam generator contain high temperature and high pressure fluid, the internal components (or simply referred to as internals) provide structural support to tube bundle and allow circulation of secondary side fluid (water) and separation of steam from steam water mixture. Proper design of the internals is important for safety of nuclear power plants since the steam generators also act as primary heat sink. Evaluation of the internals is also important for plant life management and plant life extension studies. There are set rules and standards for design and evaluation of pressure boundary components. However, there appear to be no such rules or such rules are not commonly available for structural design of the internals. This paper provides a methodology for structural analysis and evaluation of the internals. A brief description of the internals and various aspects of the analysis with reference to loading, stresses, seismic modeling and damping values to be considered for evaluation are included in this paper.

INTRODUCTION

Steam generators in nuclear power plants play a key role of producing steam for power generation. In general, these steam generators are of U tube types. For the purpose of design, the components of a steam generator are considered in two categories, i.e. the pressure boundary components and internal components (or simply referred to as internals). While most people are familiar with the pressure boundary configuration of steam generators, the intricacy of the design and evaluation of the internals are not so visible. The pressure boundary components contain the high pressure and high temperature fluids. The internals primary functions include distribution of the feedwater, separation of steam from the water steam mixture and supporting the tube bundle. The design of the pressure boundary components is critical for the safety of the nuclear power plants. A proper design and evaluation of the internals are equally important for safe operation of the steam generator and for it to act as a heat sink. In addition, internals design should be compatible with the specified life of the steam generators. There are set rules and standards (e.g. ASME Boiler and Pressure Vessel Code, Ref. 1) for design, analysis and evaluation of pressure boundary components. However, there appear to be no such rules or standard for the design of the internals or such information is not commonly available. This paper provides methodology and considerations for structural analysis and evaluation of the internals. It should be noted that the terminology used in this paper in referring to primary and secondary stresses and their stress limits correspond to Subsection NB of the ASME Code (Ref. 1).

BRIEF DESCRIPTION OF INTERNALS

Figure 1 illustrates a typical arrangement of a steam generator for CANDU (Canadian Deuterium Uranium) nuclear power plant. The arrangement of steam generator internals in a PWR (Pressurized Water Reactor) type power plants used in the United States is similar with some differences. The steam generator internals can be considered in three parts viz., lower shell internals, feedwater distribution system and steam Separation System located in the steam drum. A brief description of these components is given below.

Lower Shell Internals

These components include shroud and supports for straight and U bend regions of the tube bundle. In this region, the heat is transferred from the primary coolant flowing inside the tubes to the secondary side water at the outer surface of the tubes where boiling takes place and the steam water mixture rises up. The shroud is in cylindrical form which surrounds the tube bundle and provide a barrier between the recirculating water and the boiling zone. At the bottom end, the shroud is supported by lugs attached to the secondary shell or the secondary side of the tubesheet. In addition, radial support pins are provided at several elevations which restrain the shroud laterally with respect to the steam generator shell. The U bend support system consists of fan bars, arch bars and tie tubes as illustrated in Figure 2. The fan bars provide restraint for flow induced vibration. The fan bars together with arch bars and tie tubes form a flexible load sharing system between the tubes for loads acting in the out of plane direction of the tubes. The tube lateral supports are in the form of lattice grids located at several elevations in the shroud to restrain the straight region of the tube bundle. A lattice grid has cross bars enclosed in a ring. A portion of a lattice grid is shown in Figure 3.

Feedwater Distribution System

The primary function of the feedwater distribution system is to distribute the feedwater for uniform mixing and extracting heat. In a CANDU steam generator, this system is in the form of a box attached to the shroud near the bottom of the preheating zone. The feedwater flows through a thermal sleeve attached to the feedwater nozzle and the feedwater box. In a PWR steam generator, the feedwater distribution system is in the form of circular ring pipe located above the tube bundle in the annular space between the shroud and steam generator shell. This pipe is connected to the feedwater nozzle via a thermal sleeve and supported by the lugs attached to the top portion of the shroud. Several small tubes are attached to the ring pipe to distribute the water in the annulus for mixing with the downcomer fluid.

Steam Separation System

This system provides the equipment for separation of steam from the water steam mixture. This is accomplished in two stages which correspond to primary and secondary cyclone separators. There are 66 primary separators with equal number of secondary separators in a CANDU 6 steam generator. The primary separators are welded to the primary deck which is supported by radial lugs welded to the steam drum. The secondary separators are welded to the secondary deck which is hung by a thin seal skirt. The top end of the seal skirt is welded to the steam drum.

LOADING AND STRESSES

The internals are subject to a variety of loading which includes deadweight, flow induced loads, seismic loads, thermal effects and pipe rupture loads due to postulated breaks in primary coolant pipes, feedwater pipe and main steam line.

Consideration for Thermal Stresses

Thermal stresses occur due to restraint on thermal growth, use of dissimilar materials and presence of through thickness temperature gradients. For steam generator under thermal transient conditions, the tubes and the internals heat up faster than the thick pressure boundary of the secondary shell causing differential thermal expansion effects. The stresses arising due to this effect are minimized by some key features incorporated in the design of the internals. For example, clearances are provided between the tubes and the lattice grid cells of the lateral support grids to permit free thermal growth of the tubes. These clearances are limited so that antivibration properties of the supporting arrangement are not affected. The primary separator deck assembly is supported on sliding radial lugs which permit radial growth of the deck with respect to steam drum. The secondary separator assembly is supported via a thin cylindrical seal skirt attached to the steam drum at the top of the steam generator. Such built in flexibility features reduce the stresses due to differential growth of the components. The thermal stresses due to the use of dissimilar materials may need to be considered specifically for the welds joining such components. These stresses are function of temperature and differences in the Young's modulus and coefficient of thermal expansion of the materials. Normally these stresses are minimized by detail design. For consideration of the stresses due to through thickness temperature gradients, it is noted that the thickness of internal components is much smaller than the thickness of the pressure boundary components. Also the internals get heated up from all sides. This indicates that temperature gradients and thermal stresses for most of the internals should be small. To confirm this, a thermal analysis was carried out using conservative finite element models. The results of this analysis indicated that the through thickness temperature gradients are small for all internals except for the feedwater distribution system. The most critical area for the thermal stresses is the thermal sleeve in the feedwater distribution system. This area, because of its interaction with the feedwater nozzle, is generally analyzed as part of the pressure boundary component analysis.

Consideration of Cyclic Stresses and Fatigue

The cyclic stresses result due to thermal, seismic and flow induced effects. With the exception of the feedwater distribution system, the internals are not subject to significant stresses due to thermal transients. For seismic loads, the number of cycles is small. The flow induced loads having significant number of cycles occur under normal operation. However, the fluctuating load component of this loading is small. Therefore, it is considered that a fatigue analysis of the internals is not necessary. It is noted here that the thermal sleeve is analyzed as part of the pressure boundary components and it represents a bounding fatigue analysis for other components of the feedwater distribution system.

Load Combinations and Primary Stresses

Considering that the fatigue analysis is not necessary, the internals need to be analyzed for primary stresses. Similar to the pressure boundary components, the loading for the internals is considered under Level A, B, C and D service conditions. The load combinations for these service levels are usually specified as follows:

Service Condition	Load Combination
Level A	Deadweight (DW) + Normal Flow Induced Loads (FL)
Level B	DW + Operating Basis Earthquake (OBE*) + FL
Level C	DW + Design Basis Earthquake (DBE*) + FL
Level D	DW + SRSS**[Safe Shutdown Earthquake (SSE*) or DBE, PR***]

* The term DBE applies to CANDUs and OBE and SSE apply to PWRs.

** SRSS means the square root sum of the squares.

*** PR represents pipe rupture loads which correspond to loss of coolant accident (LOCA), main steam line break (MSLB) or feedwater line break (FWLB).

ALLOWABLE STRESSES FOR EVALUATION

The materials used in the construction of the internals are generally in accordance with Section II of the ASME Code or ASTM Code. During manufacturing and fabrication a strict quality control process is followed. Also the structural evaluation of the internals is based on detailed analysis. Therefore, the stress limits used for their evaluation could be similar to those applied to primary stresses for pressure boundary components as given in Reference 1. These allowable stress values are listed in Table 1. A number of structural welds for the internals are fillet welds. The stresses in these welds are generally more critical than in the components. Therefore, it is very important to check the adequacy of the welds. The allowable stresses used for evaluation of the welds are also given in Table 1.

Table I: Allowable Primary Stresses for Various Service Conditions

Type of Stress	Design, Level A and Level B	Level C	Level D
General Primary Membrane Stress (P_m)	S_m*	Greater of ($1.2S_m$, Sy)*	0.7Su*
Primary Membrane + Primary Bending Stress ($P_L + P_b$)	$1.5S_m$	Greater of ($1.2S_m$, Sy)	1.05Su
Shear Stress at Throat of Fillet Welds	0.3Su	0.45Su	0.6Su

* Sm, Sy and Su represent the design stress intensity, yield stress and ultimate tensile strength respectively.

Appropriate corrosion allowance should be applied on the thickness for calculating the stresses in the internal components and their welds. Depending upon the material, temperature and flow velocity, the flow accelerated corrosion (FAC) effects can be significant. These aspects are also important for assessment of the remaining life of the internals.

ANALYTICAL MODELING

The intricate design and complex arrangement of the internals make the structural analysis difficult and challenging. Finite element methods utilizing commercially available software are commonly used. The flow induced loads, MSLB and FWLB loads are given as the pressure difference at various elevations of the internals. The LOCA loads are specified as pressure drop along the tube axis. Consideration of these and the deadweight loading is relatively easier. The seismic loading is generally given as shell response spectra specified at internals support locations in the steam generator shell. If this response spectra is not available, a coupled analysis considering the steam generator, its supporting arrangement and the internals has to be carried out for determining the seismic loading for the internals from the response spectra given at the steam generator support locations. The seismic modeling of the internals (specifically the lower shell internals) is the most challenging aspect of the analysis. For illustrating the complexity involved in the analysis, some aspects of the seismic modeling of the lower shell internals are given below.

Seismic Model of Lower Shell Internals

The seismic input is resolved in three orthogonal directions (i.e. tube inplane, tube out of plane and vertical directions). The seismic loading corresponding to tube inplane and vertical directions is obtained by considering the tubes individually supported laterally at the lattice grid locations and fixed at the tubesheet location. The loading at the lattice grids and shroud is obtained by conservatively taking the absolute sum of all individual tubes. For out of plane seismic analysis, interaction of tubes occurs due to the load sharing system in the U bend region. This necessitates that all tubes and lower shell internals (shroud, shroud supports, lattice grids and U bend supports) should be modeled together in a single model. A simplified illustration of the model for out of plane seismic analysis is shown in Figure 4. The following is a brief description of this model:

Steam generator pressure boundary is considered fixed.

Shroud and shroud support lugs are represented by beam elements.

Shroud lateral support pins accounting for the local stiffness of the shroud are represented by truss/spring elements.

The lattice grids and baffle plates are represented by equivalent truss/spring elements.

In the straight portions of the tube bundle, the tubes are grouped together into conglomerate tubes and represented by beam elements with equivalent properties. The mass density includes the effect of water inside and outside the tubes.

U bend assembly is represented by three dimensional beam and truss elements. All tubes are first grouped in about 20 planes. Within each plane, the tubes are grouped again and each group is represented by an equivalent tube radius.

The fan bar and connector bar assemblies are modeled by beam elements with geometrical properties defined by the number of bars in each equivalent plane. The fan bars are connected to the equivalent tubes with truss elements at the points of their contact. One end of the fan bar is connected to the connector bar and the other end to the arch bar. The arch bars are modeled using beam elements. The circular tie tubes are connected to the arch bars.

The lumped U tubes are extended down to the top lattice grid and include one lattice span before they are merged with the lower straight conglomerate portion of the straight tubes.

Primary deck and primary separators are represented by equivalent beams to consider their interaction effect on the shroud.

This model is subject to the out of plane seismic excitation and the loading for various components is established. The calculated out of plane loading is combined with the other two directions on SRSS basis for establishing the resulting seismic loads.

Damping Value for Seismic Loading

The seismic input is given as FRS for different values of damping. Use of appropriate damping values is important. A conservatively low value of damping will result in high seismic loads and make it difficult to meet the stress limits. Literature survey, analysis and testing were carried out to establish the applicable damping values for various internal components. This study took into account the presence of material damping, frictional effects, nonlinearities and hydrodynamic effects. The testing was carried out on a full scale steam generator to derive damping for the lower shell internals including shroud, lattice grids and tube bundle. Based on these considerations the damping values listed in Table 2 are considered reasonable for seismic analysis of the internals.

Table 2: Damping Values for Steam Generator Internals

Component	Damping Value		
	OBE	DBE	SSE
Lower Shell Internals (Shroud, Lattice Grids, Tubes Combined)	5%	7%	7%
Primary Deck and Primary Separator Assembly	4%	7%	7%
Secondary Deck and Secondary Separator Assembly	2%	3%	4%

CONCLUSIONS

A brief description of steam generator internal components is presented. These components are subjected to a variety of loading. Significant loading includes deadweight, seismic, LOCA and pipe rupture effects. It is recognized that a proper design and analysis are important for safety of the plant. Considering the material testing, quality control during manufacturing and detailed analysis of the internals, it is reasonable to limit their primary stresses similar to Class I components. Consideration for cyclic stresses and fatigue is not necessary except for the feedwater distribution system. A set of damping values based on testing and analysis are provided for seismic analysis of the internals.

REFERENCES

1. ASME Boiler & Pressure Code, Section III, 1995 Edition.

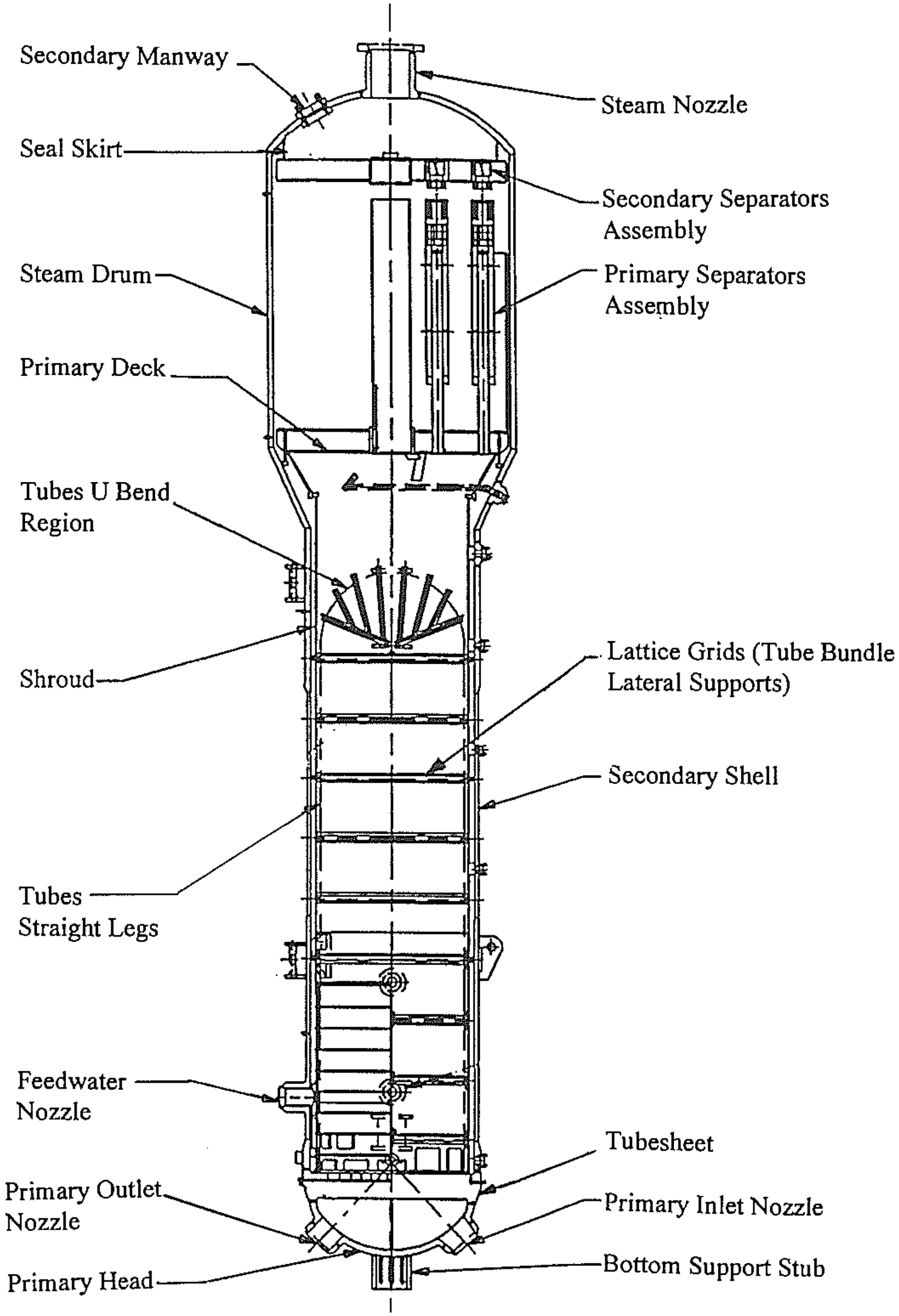

Figure 1: Typical Configuration of a CANDU Steam Generator

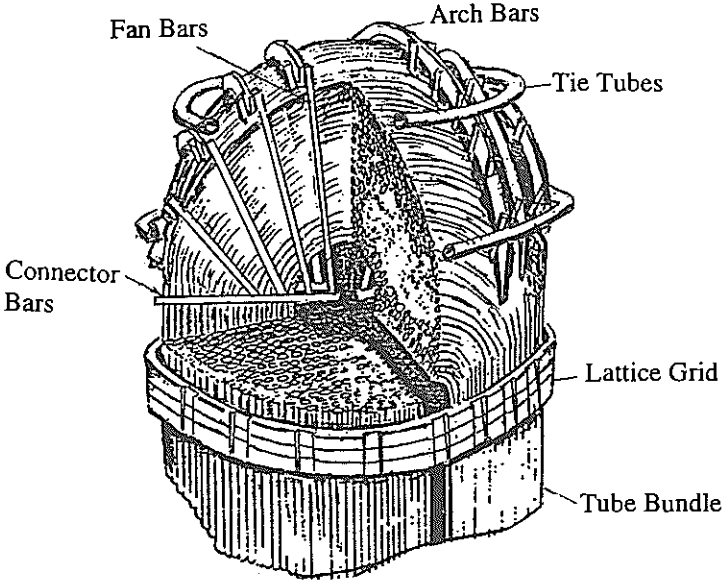

Figure 2: Illustration of U Bend Support Arrangement

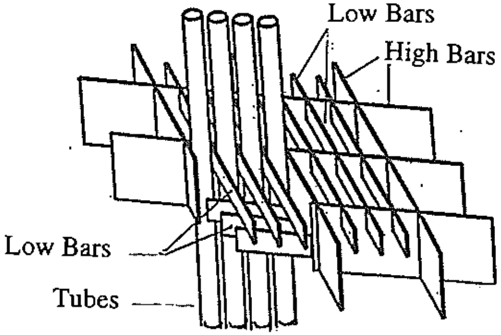

Figure 3: Lattice Grid Cell Pattern for Tubes Lateral Support in Straight Leg Region

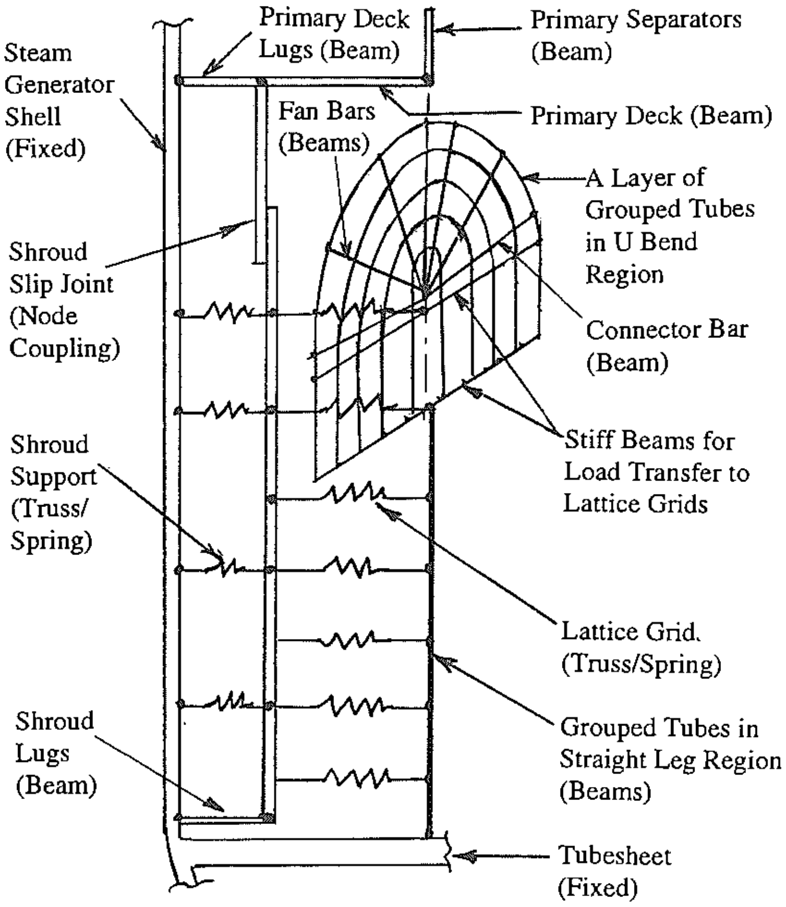

Figure 4: A Simplified Illustration of Lower Shell Internals Model (Note: Only one layer of grouped tubes is shown. Arch bars and tie tubes are not shown)