THREE-DIMENSIONAL STUDIES OF THE 700 MWE STEAM GENERATOR DESIGN

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ABSTRACT

The next stage in the Indian nuclear power programme envisions building 700 MWe Indian Pressurized Heavy Water Reactor (IPHWR) units. This involves up-rating of all the plant equipment including the reactor, steam generators (SGs), turbo-generator, major pumps, etc. The SG used in the current generation of 540 MWe IPHWRs, is a mushroom type, inverted U-tube, natural-circulation SG. The 700 MWe SG is of the same type and has the same tube bundle design and the same heat transfer area. The tube diameter, tube pitch, and outer diameter of the SG sections are the same as for the 540 MWe SG. The geometry of the feedwater header, the flow restrictor in the downcomer and the flow distribution plate are different in the two designs. The changes were required due to a 26% increase in steam flow rate while maintaining the same circulation ratio. This paper describes the design of the 700 MWe SG and a thermalhydraulic analysis using a one-dimensional, in-house code and a three-dimensional code called THIRST developed by AECL. The codes were validated against the 540 MWe SG data. The analysis was made for the 700 MWe SG for two versions: with and without integral preheater. The results of the THIRST runs were used for a flow-induced vibration analysis. The results of the flow-induced vibration analysis show that the vibrations are not excessive.

1. INTRODUCTION

The Indian nuclear power programme primarily relies on Pressurized Heavy Water Reactor (PHWR) units. The previous generation consisted of both 220 MWe and 540 MWe units. The next stage in the programme envisions building 700 MWe units. This involves up-rating of all plant equipment including the reactor, steam generators (SGs), turbo-generator, major pumps, etc. The SG used in the current generation of 540 MWe PHWRs, is a mushroom type, inverted U-tube, natural-circulation SG. The 700 MWe SG was designed after exploring various alternatives to increase the capacity without major changes in SG geometry and primary temperature difference across the SG. This paper gives a brief description of the SG and the details of both the thermalhydraulic one-dimensional and three-dimensional analyses. Also, the results of a vibration analysis for the 700 MWe SG are discussed.

2. STEAM GENERATOR DESCRIPTION

A schematic view of the SG under consideration is given in Figure 1. The SG consists of several thousand inverted U-tubes fixed at a tubesheet at the bottom of the steam generator. The primary fluid inlet and outlet nozzles are connected to the hemispherical bottom, which is welded to the bottom side of the tubesheet, while the shell is welded to the other side of the tubesheet. The primary inlet and outlet plena are separated by a welded divider plate. The shell is expanded in the upper section to accommodate steam separators and to provide space for water inventory. Since the tubes are long and velocities are high, supports are provided at various elevations to provide lateral rigidity and prevent the tubes from excessive vibrations. A cylindrical shroud covers the U-tubes and provides a boundary between the riser and the down comer.

The primary-side fluid, heavy water, enters the inlet plenum of the SG through nozzles, flows inside the U-tubes and transfers the heat to the light water on the shell, secondary side. For the case without integral preheater, the feedwater is provided at the upper section, where it mixes with the water separated from the steam–water mixture by the steam separator and flows down through the annular space between the shell and the shroud called the downcomer. At the bottom of the downcomer, this water enters the shroud through the windows and flows upwards in the riser. The tube bundle in the riser allows the heat to be transferred from the primary fluid to the secondary fluid. As a result of the heat transfer process, the water is converted into steam and this two-phase mixture flows into the steam separators. The steam separators separate the steam from the steam-mixture and the separated water mixes with the feedwater. The steam exiting from the separator goes through the driers to further decrease the moisture content to less than 0.25 %. The SG has a continuous blowdown with a rate of 0.5% of feedwater flow rate.

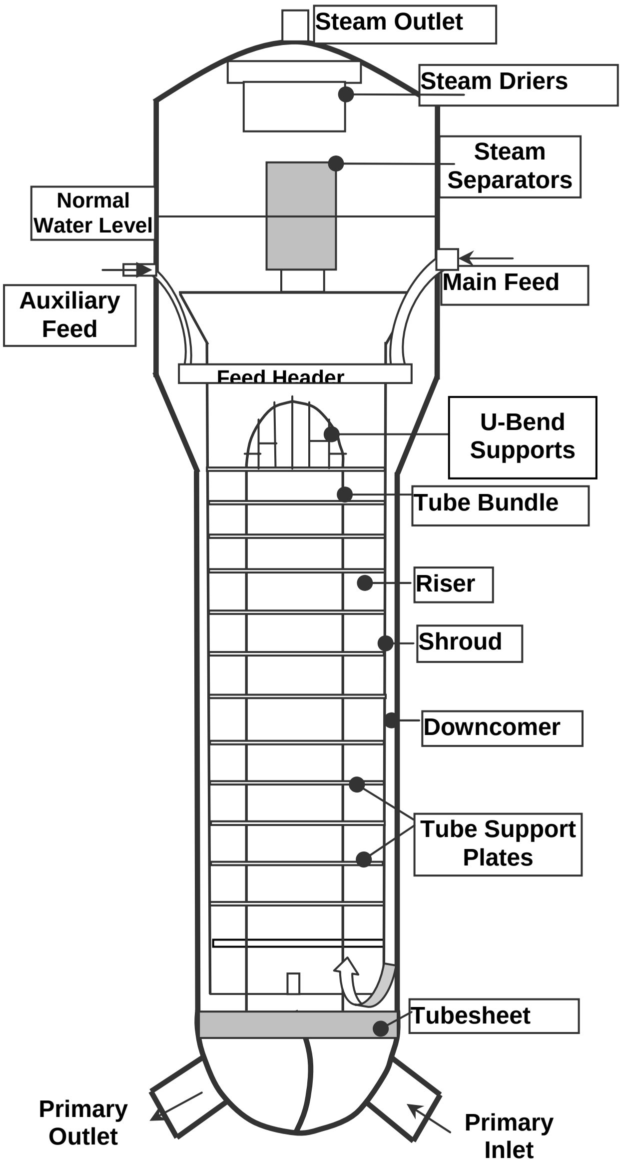


Fig.1. Schematic View of a PHWR SG without Integral Preheater

3. **700 MWE STEAM GENERATOR DESIGN**

The design features of the 540 MWe SG were maintained the same in the 700 MWe SG design to the maximum possible extent. The number of tubes, tube diameter, tube layout, pitch, the diameter of the shroud and shells have been kept identical to that of the 540 MWe SG. This is to ensure that design changes are kept to minimum to take the advantages of proven mechanical and process design aspects and established fabrication techniques, and to utilize the already procured major items such as shell and tubesheet forgings.

Table 1 gives a comparison of the geometrical and process data for both 540 MWe SG and 700 MWe SG. The major dimensions of the 540 MWe SG and the proposed SG for 700 MWe units are given in Fig. 2 and Fig. 3 respectively.

TABLE 1 Steam Generator Details

No.	Description	540 MWe SG	700 MWe SG
Geometry			
1	Number of tubes	2489	2489
2	Tube material	Incolloy 800	Incolloy 800
3	Tube outer diameter, mm	19	19
4	Tube thickness, mm	1.1	1.1
5	Tube pitch (rotated triangular), mm	26	26
6	Overall height, mm	20 240	23 240
7	Height of tubesheet top from SG bottom, mm	1885.8	1885.8
8	Inner diameter of bottom/ straight shell, mm	2458	2458
9	Inner diameter of top shell/steam drum, mm	3350	3350
10	Inner diameter of shroud bottom, mm	2197	2197
11	Tubesheet top elevation, mm	119 268	119 268
12	Center lane width, mm	182	182
13	Number of steam separators	23	29
14	Height of flow distribution plate from tubesheet, mm	225	275
15	Height of deck plate from tubesheet, mm	12670	15670
16	Heat transfer area, m^2	3321	3321
Nozzles and Pipes			
17	Feedwater velocity in the nozzle, m/s	3.5	3.5
18	Feedwater nozzle inner diameter, mm	295 (single)	235 (double)
19	Steam velocity inside the nozzle, m/s	93.6	168
20	Steam nozzle inner diameter, mm	375 (single)	Flow Restrictor
21	Auxiliary feed nozzle diameter, mm	90	NA
22	Condensate feed nozzle, mm	NA	90
Process Parameters			
23	Steam mass flow rate, kg/s	213	269
24	Feedwater inlet temperature, ^oC	180	180
25	Steam temperature, ^oC	252	256
26	Steam pressure, (g) bar	41.5	44
27	Steam density, kg/m^3	20.6	22.1
28	Circulation ratio	4.3	4.3
29	Water level above the tubesheet, m	13.4	16.4
30	Primary mass flow rate, kg/s	1953	2115
31	Primary inlet temperature, ^oC	304	310 (3% quality)
32	Primary outlet temperature, ^oC	260	266
33	Thermal output, MW	434	540

To increase the thermal output of the SG, necessary design changes in process parameters, geometry and internals of the SG have been carried out. The details of such changes, along with the design philosophy, are given below:

a) The feed flow rate was increased from 213 kg/s to 269 kg/s to provide a higher steam flow rate for the SG thermal power increase from 434 MW to 540MW.

b) To transfer the adequate amount of heat required for the production of the steam at the rate of 269 kg/s (at 100% operating conditions), maintaining the temperature difference between the primary inlet and outlet temperatures as 44 ^{O}C (equal to that of the 540 MWe SG), a three-fold approach was adopted, viz.

   i) boiling of the primary fluid up to 3% of quality at the reactor outlet,

   ii) a rise in the primary inlet temperature from 304^{o}C to 310^{o}C, and

   iii) an increase in the primary flow rate by 8%.

c) As part of the measures employed to attain the desired circulation ratio of 4.3, the level in the steam generator has been raised to 16.4 m. This has correspondingly raised the height of the shroud and upper shell by 3 meters. The other measures employed were the change in the height of the flow distribution plate from tubesheet from the present value of 225 mm to 275 mm, an increase of the low-resistance area in the flow distribution plate, an increase in the height of the shroud windows, and a reduction of the downcomer orifice resistance by increasing the orifice hole diameter.

d) In order to minimize the release of energy into reactor building during a main steam line break scenario, a steam nozzle has been provided with integral flow limiter. The design objectives of the integral flow limiter for 700 MWe SG are to achieve a required minimum flow area within the steam outlet nozzle to limit choked flow under accident conditions while minimizing normal operation pressure drop. These objectives are met by using seven venturi openings in the steam outlet nozzles.

e) The number of steam separators has been increased from 23 to 29, in proportion to the increase in the steam flow rate to 269 kg/s. To accommodate these separators certain modifications in the layout of inlet nozzles as well as the separator deck plate have been incorporated.

f) The number of main feedwater nozzles has been increased from 1 to 2 to provide for the increased feedwater flow rate as well as to accommodate the feedwater entry nozzle below the separator deck. The nozzles have been sized to maintain the same feed velocity.

g) To meet the station blackout scenario, the steam generator secondary side inventory was increased proportionately with the increase in power. Raising the height of the shell by 3 m, as stated above, provides an extra secondary side inventory of 10 tons of water during normal operation. In addition to this increased inventory, provision has been made for an emergency condenser. This condenser condenses the steam generated in the SG in the event of station blackout with no feedwater being pumped in and returns the condensate to the SG through a nozzle just above the tubesheet. This establishes a two-phase thermo-siphon cooling on the secondary side of the SG, with the ultimate heat sink being the 200 tons of water in the shell side of the emergency condenser which will boil off during an accident.

h) With these process parameters, the secondary side pressure increased from 41.5 bars (g) for the 540 MWe SG to 44 bars (g) for the 700 MWe SG.

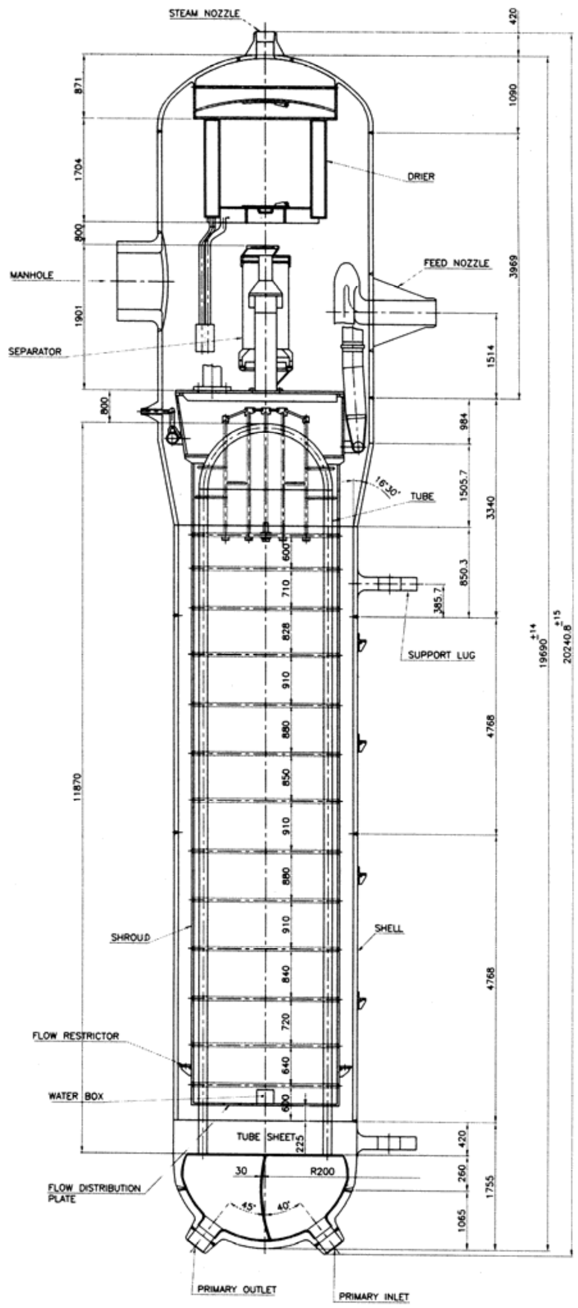


Figure 2 The 540 MWe SG Design

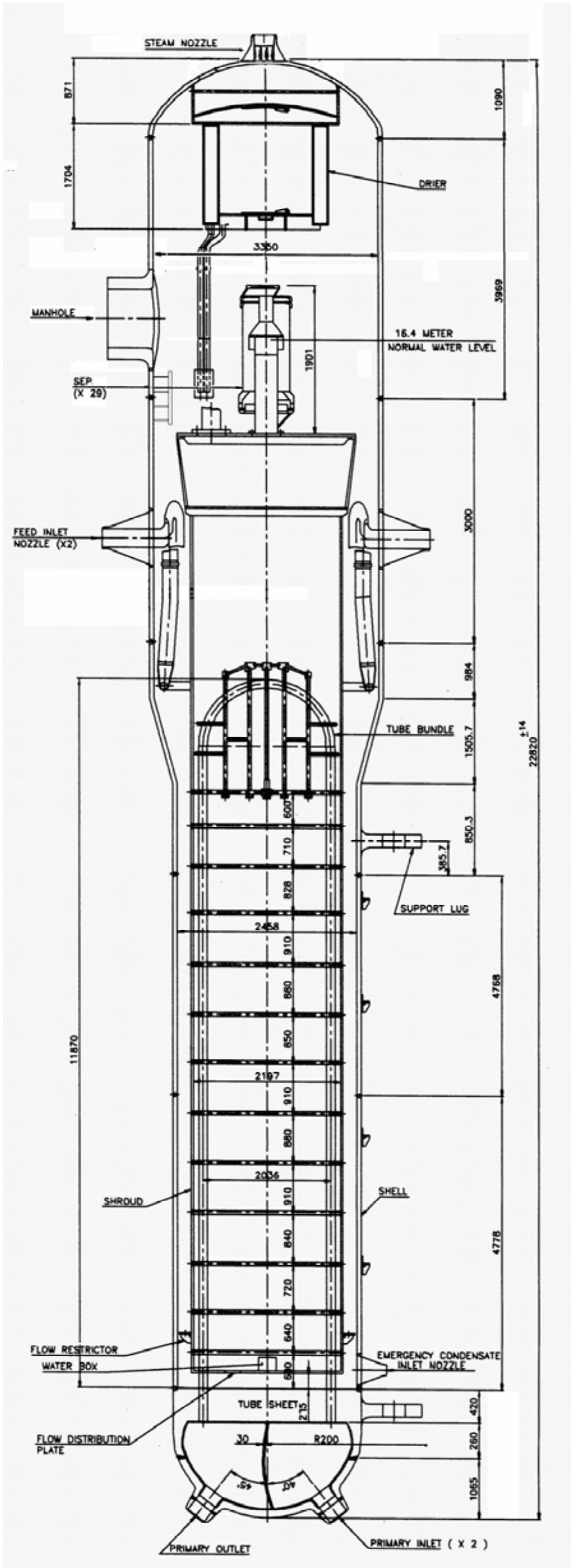


Figure 3 The 700 MWe SG Design

4. THERMALHYDRAULIC ANALYSIS

The thermalhydraulic analysis has been carried out for the 700 MWe steam generator to prove the adequacy of the process design using both a 1-dimensional code developed in-house and a 3-dimensional code developed by AECL. This section describes the codes and the analyses.

4.1 Analysis Using 1-Dimensional Code

A steady state, 1-dimensional, in-house code was developed for the thermalhydraulic performance evaluation of 220 MWe SGs. The code was validated against NPCIL plant data, TRICASTIN plant data and ATHOS code predictions for the TRICASTIN SG plant data. It takes primary inlet temperature, primary flow and secondary pressure as inputs and outputs primary and secondary side temperature profiles, the secondary side recirculation ratio, the steam flow rate and the secondary side void fraction and steam quality variations.

The code was modified to incorporate the 540 MWe SG geometry. To make the code suitable for 700 MWe SG studies, condensation of the primary fluid inside the tubes was incorporated.

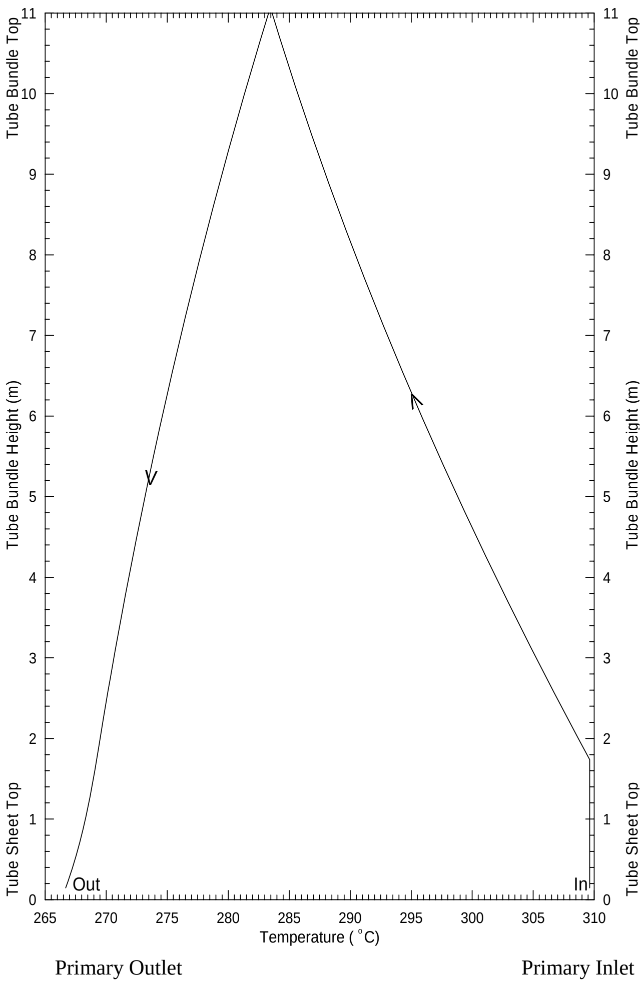


Figure 5 Primary temperature profile along tubes

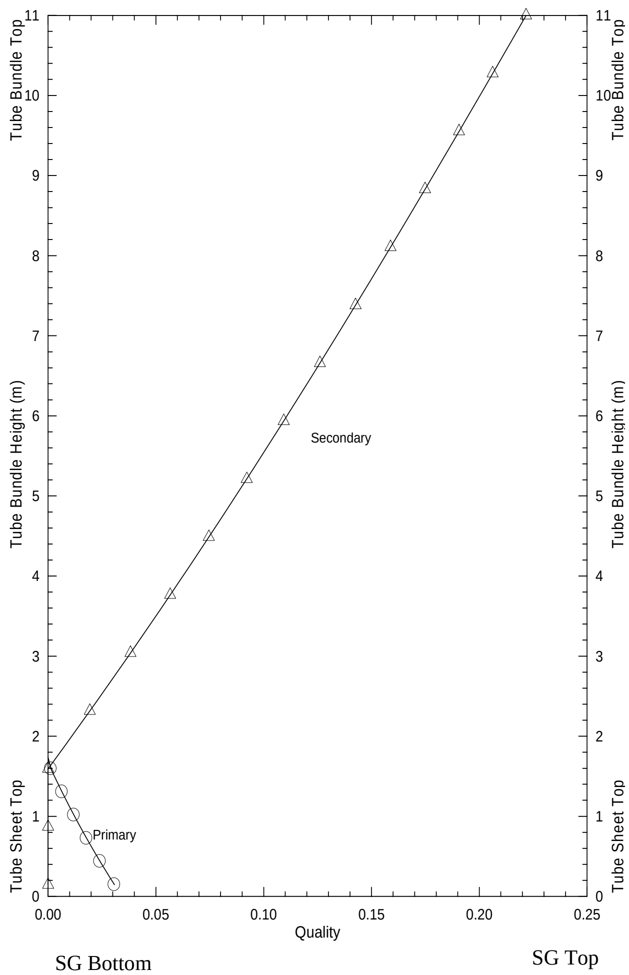


Figure 6 Primary and secondary steam quality distribution vs. elevation above the tubesheet

The temperature profile of the primary fluid is shown in Figure 5 on the horizontal axis. The vertical axis shows the elevation above the secondary side of the tubesheet and ends at the top of the tube bundle. With the same co-ordinates, Figure 6 shows the steam quality variation on the secondary side as well as on the primary side; from the latter variation, it is seen that the length of steam condensation on the primary side is 1.7 m. The primary fluid outlet temperature is 266.5°C and the average steam quality at the top of the tube bundle exceeds 22%.

4.2 Analysis Using 3-Dimensional Code THIRST

THIRST is a three-dimensional code that computes two-phase flow and heat transfer in vertical, recirculating steam generators. THIRST solves five balance differential equations for the secondary side of the steam generator, for the following quantities:

- mixture mass,
- energy,
- axial momentum,
- radial momentum, and
- angular momentum.

The heat balance equation for the secondary side is solved simultaneously with the heat balance for the primary fluid and together with other balance equations.

THIRST uses a control volume, integral approach to derive the finite difference approximations of the partial differential equations. A cylindrical coordinate system is used to divide the SG into a large number of control volumes. Each of the major thermalhydraulic parameters is calculated in each of the control volumes.

THIRST assumes that the flow is steady and incompressible, the shell and shroud walls are adiabatic, the downcomer flow is 2-dimensional (i.e., the calculated flow velocity, density, etc., are constant in the radial direction), laminar and turbulent shear stress forces are replaced by hydraulic resistances of internal structures, and heat conduction is negligible in comparison with heat convection. The tube supports and preheater baffles are treated as a resistance in the axial direction only, and there is no carry-over (i.e., water droplets in the outlet steam). Carry-under (i.e., steam bubbles in the downcomer flow) can be modeled by inputting the value of the primary separator efficiency, which is typically below 0.25%.

The region under consideration is enclosed by an adiabatic and impermeable shell (except for the feedwater inlet), an impermeable tubesheet (except for blowdown), and an adiabatic imaginary outlet plane that is located near the separator deck. The modeled region is treated as a continuum. This means that the tube bundle can be modeled using the porous-media concept. With this concept, the tube bundle, as well as other structural elements such as tube supports, are idealized as a continuum with an equivalent fluid flow area and fluid volume, and distributed hydraulic resistances. The local fluid flow area and fluid volume are based on the corresponding geometric values, but are decreased by a local isotropic porosity factor, which is defined as the ratio of flow volume to geometric volume. Hydraulic resistances of the structural elements are expressed by pressure loss coefficients for tube support plates, the tube bundle and other internal structures.

In these analyses, it is typically assumed that the flow is homogenous and the tube bundle resistance is anisotropic. Homogeneous flow is commonly used in vibration analyses, although slip velocity models give a more realistic approximation of the void fraction-steam quality relationship. Anisotropic tube bundle resistance is used, because the hydraulic resistance in the direction perpendicular to the tube is about 20-50 times larger than that in the direction parallel to the tube. This phenomenon is especially important in the U-bend region, where tubes constantly change direction, thus affecting the hydraulic resistance.

The required boundary conditions are the primary inlet enthalpy and mass-flow rate, feedwater enthalpy, an initial estimate of the feedwater mass-flow rate, reheater drains enthalpy and flow rate, primary inlet and secondary side pressures, the blowdown mass-flow rate, and the downcomer water level.

The closure relations include formulations for the volume porosity for each control volume in the region under consideration, solid-fluid pressure loss coefficients, primary-to-secondary heat transfer, and fluid properties.

For two-phase flow, the runs reported below used an algebraic slip model based on the Chisholm correlation. A typical run on a 2 GHz PC, using 50 000 control volumes, takes a few minutes of computer time and requires about 8 MB of RAM memory. A converged solution is usually achieved in 60-250 iterations.

4.1.1 Results of 3-Dimensional Analysis for SG without Integral Preheater

The THIRST code was first used to simulate the SG without integral preheater. The SG has 14 tube support plates, including the flow distribution plate located closest to the tubesheet and a set of horizontal and vertical U-bend supports. The tubes in the U-bend region have a variable tube pitch, which reduces the velocity in this region. This is especially important for gap velocities, which typically reach highest values in this region. In modeling, the U-bend region was simplified to an equivalent region with a uniform tube pitch, the same as for the straight tube section. This assumption slightly overestimates pressure drop in the U-bend region, and, therefore, underestimates the flow in the riser and the circulation ratio.

The THIRST model used 32 500 control volumes with a finer grid near the tubesheet and in the U-bend region. This grid resolution is fine enough so that the results have a negligible error due to discretization, for both global results and velocity distributions. The major global results are listed in Table 4-1.

Table 4-1 THIRST Global Results for the 700 MWe Steam Generator

Parameter	Unit	SG without Preheater	SG with Preheater
Circulation Ratio	-	4.5	3.9
Secondary Pressure	MPa (abs)	4.5	4.95
Average Outlet Steam Quality	%	23.2	25.8
Primary Outlet Temperature	°C	266.5	266.8

4.2.2 Results of 3-Dimensional Analysis s for SG with Integral Preheater

This design version includes an integral preheater and was also analyzed using the THIRST code. The integral preheater used in this analysis has 8 segmental baffles and a thermal plate separating the preheater from the riser on the bottom side. It also has a divider plate separating the preheater from the riser. The space under the preheater increases the riser flow, and therefore, the circulation ratio. It is assumed that all feedwater flow goes through the preheater, if leakage through the thermal plate is neglected. The rest of the SG design remains the same as that for the SG without integral preheater. The operating parameters are the same as for the no-preheater design except for the secondary pressure, which is increased now to 4.95 MPa (abs). The presence of the preheater, however, reduces the recirculation ratio because of the increased flow resistance in the lower section of the SG and increases steam quality in the U-bend region. This design change will improve the overall efficiency of the plant and it is estimated that the electrical rating will increase by 20 MWe. The grid was finer in this case because of additional axial grid points in the preheater area and the total number of control volumes was 44 200. Other global results are similar to the no-preheater design and listed in Table 4-1.

5. FLOW-INDUCED VIBRATION ANALYSIS

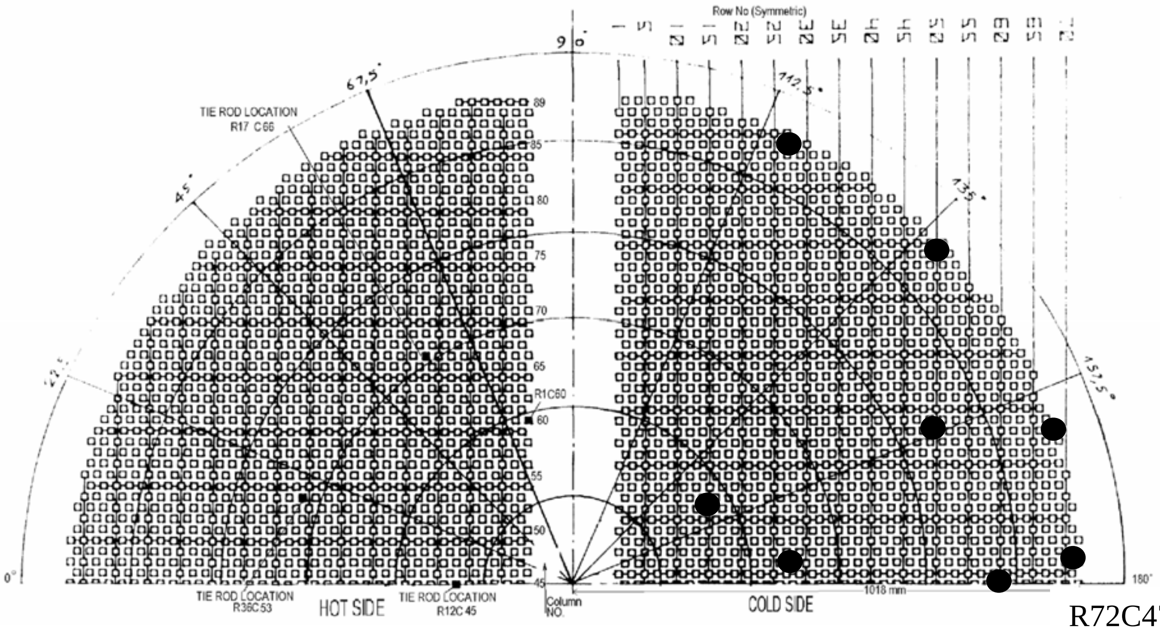
Flow-induced Vibration (FIV) analysis was done for the U-bend region. In the U-bend region, a possibility of fluid-elastic excitation was checked. Turbulence excitation is not considered in this paper because it is mostly used in a fretting-wear analysis.

The objective of the check was to determine whether the U-bend region is free from possible fluid-elastic excitation. Vortex shedding excitation was not considered, as it is very unlikely that this excitation can occur in this region due to the following reasons:

i) The longitudinal tube pitch is continuously increasing from short-radius tubes to long-radius tubes of the tube bundle.

ii) There is no evidence that vortex shedding excitation can occur in two-phase flows.

The map of all tubes and the tubes selected (black dots) for the FIV analysis for one half of the SG is shown in Figure 7. A tube is designated using both the row and the column number. The U-tube support details are given in Figure 8. Based on the cross-flow velocity and density profiles obtained from the THIRST analysis provided for the tube R72C47, and on the span length, the span shown in Figure 8 was selected. The selection was based on the most unfavorable, most conservative, combination of density, gap cross-flow velocity and span length based on the experience and results obtained for the 540 MWe SG. Other selected tubes were also analyzed, see Figure 7, and found to be less susceptible to FIV.



R72C47

Figure 7 Tubesheet Tube Layout with Selected Tubes for FIV Analysis (Black Dots).

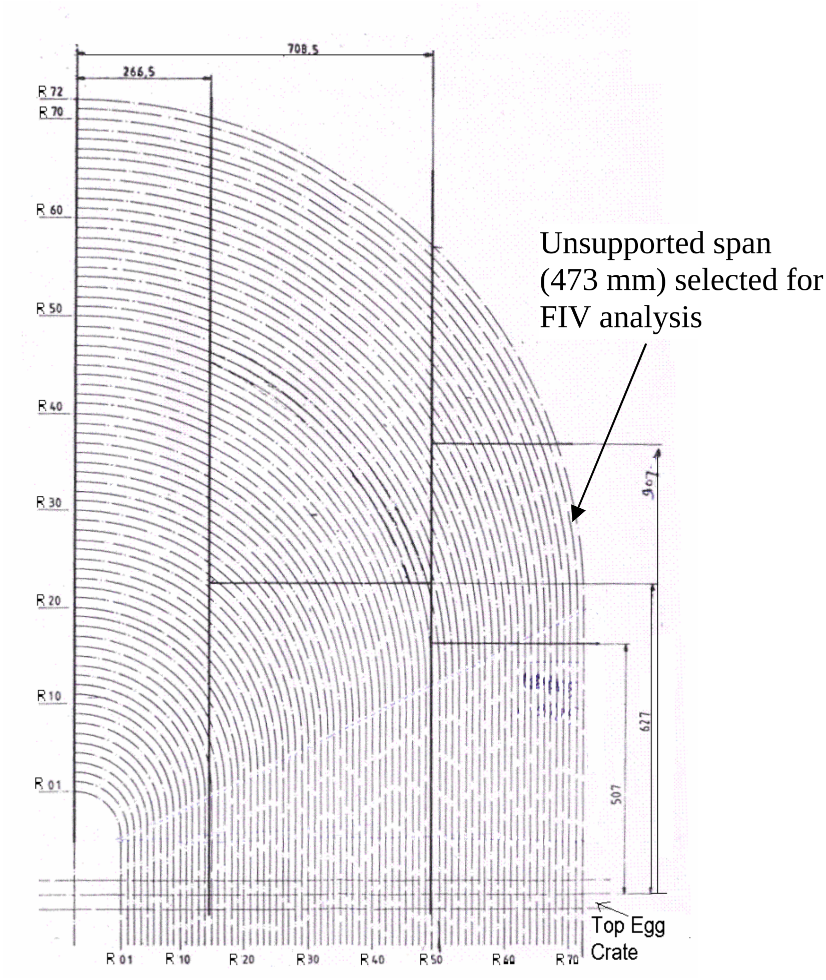


Figure 8 SG Tube Supports at the U-Bend Region

The FIV analysis followed the methodology given elsewhere. The most important input data used in the evaluation and results are summarized in Table 2.

Table 2 Results of FIV Analysis

NPP	Tube No.	ρ_{pf}	ρ_{sf}	W_e	V_{av}	V_{pk}	f_n	V_c
		kg/m^3	kg/m^3	kg/m	m/s	m/s	Hz	m/s
540 MWe	R72C47	830.7	137.8	0.736	7.347	9.33	176.2	15.06
700 MWe	R72C47	817.4	123.6	0.727	8.327	11.09	177.3	15.90

The symbols in the table are as follows:

ρ_{pf}	Density of primary fluid,
ρ_{sf}	Density of secondary fluid,
W_e	Equivalent mass,
V_{av}	Average velocity over the span considered,
V_{pk}	Maximum velocity in the span considered,
F_n	Natural frequency, and
V_c	Critical velocity.

It can be seen from the table that the average and maximum velocities are well below the critical velocities and, therefore, the tubes are far from the threshold for fluid-elastic instability. As expected, the margin is a little smaller for the 700 MWe design.

6. SUMMARY

The next phase of the Indian nuclear power programme envisions building Indian Pressurized Heavy Water Reactor units of 700 MWe power. The units need steam generators of increased thermal output of 540 MW. The SGs for the new units are similar in design to the SGs designed for the smaller reactors of 540 MWe power. The SGs for the larger units were designed using an in-house thermalhydraulic one-dimensional code and THIRST, a 3-dimensional thermalhydraulic code for recirculating steam generators. The codes were validated first for the smaller SGs and then used to model the 700 MWe SG design.

It was found that an increased thermal output by 26% and a corresponding increase in feedwater and steam flow rate are feasible using the same tube bundle. One of the design options for the 700 MWe SG is an integral preheater. The results of the simulations indicate that an integral preheater allows for an increase in steam pressure from 45 bars to 49.5 bars (abs). This change will improve the overall efficiency of the plant and the electrical rating will increase by 20 MWe. A flow-induced vibration analysis shows that the tubes have sufficient margin for the fluid-elastic instability.