# ENGINEERING RESEARCH IN NUCLEAR COMPONENTS PART II: STEAM GENERATOR THERMAL-HYDRAULICS, ANALYTICAL AND EXPERIMENTAL

W.W.R. Inch, D.A. Scott, M.B. Carver

## *INTRODUCTION*

As recirculating-type steam generators are key components of CANDU[1] power plants, they must be designed for high reliability. Further, steam generator thermal-hydraulics should be optimized to maximize heat transfer and hence plant performance. We are actively involved in analytical and experimental programs aimed at meeting these objectives.

The analytical work is centered around the development of THIRST[2], a three-dimensional, homogeneous, incompressible two-phase flow code. THIRST predicts the thermal-hydraulics of steam generators, in terms of local velocity, quality, temperature, heat flux, density and pressure. The code has been used to assess the performance of several steam generators.

An experimental program is also underway to verify some aspects of the code. As steam generators may have a two-phase primary inlet, detailed void fraction measurements have also been made of air-water mixtures flowing in elbows simulating the inlet feeders to the steam generator primary head. As a result of both these studies, more fundamental investigations are underway to study the mechanism of two-phase flow using both air-water and steam-water systems.

## *ANALYSIS OF STEAM GENERATOR THERMAL-HYDRAULICS*

### Steam Generator Design

The salient features of a natural recirculation steam generator with integral preheater are shown in Figure 1. Hot primary fluid flows inside the bundle, transferring heat to the secondary fluid en route. Subcooled feedwater from the condenser enters the secondary side of the steam generator through the integral preheater or economizer. In the preheater, baffles force the flow across the tubes in a zig-zag pattern to enhance heat transfer. At the preheater exit, this flow, now raised to saturation, mixes with flow returning from the hot side. The resulting mixture, undergoes partial evaporation as it rises through the remaining bundle section into the riser and up into the separator bank where the phases are separated. The steam continues up through the secondary separator bank, out of the steam generator, and to the turbines. The remaining saturated liquid flows through the downcomer annulus to the bottom of the steam generator where it re-enters the heat transfer zone through windows cut into the shroud around the circumference.

### The THIRST Code

The THIRST computer code has been developed to predict local flow and heat transfer in steam generators. THIRST provides the designer with a tool to analyse steam generator designs, pinpointing, for example, areas of flow stagnation in the secondary side, where corrosion would be enhanced and heat transfer inadequate. Appropriate design changes can then be made to correct the flow patterns. Designers can also examine local phenomena which determine overall efficiency, and then maximize the performance of the unit by altering design features.

Typically, THIRST models a region extending from the face of the tubesheet to the separator deck and radially out to and including the downcomer annulus. Only one-half of the steam generator is modelled, since the design is symmetrical about a line through the center of the hot side and cold side. The code predicts the flow, pressure and enthalpy distributions for both the shell and the tube side. It calculates the overall pressure loss,

1 CANDU - CANada Deuterium Uranium
2 THIRST - Thermal-Hydraulic Analysis In Recirculating STeam Generators

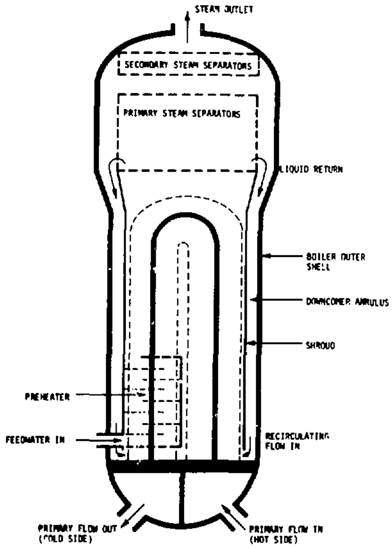



Figure 1 Steam Generator Features

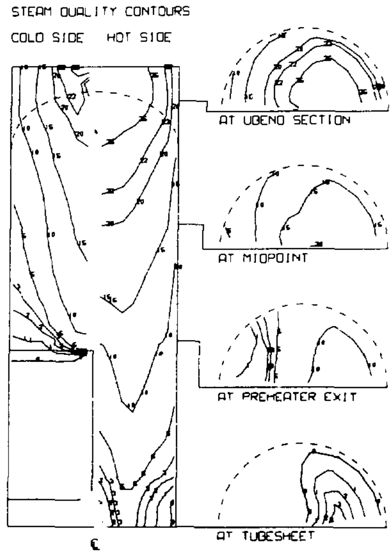



Figure 2 Computed Quality Contours

overall heat transfer and local heat flux, and can also calculate the circulation ratio for natural recirculation steam generator designs [1].

*THIRST* is a steady state, three-dimensional homogeneous model. Presently the code can handle roughly 5000 grid nodes with a core storage requirement of 300,000 octal words. Frictional and heat transfer resistances are calculated using empirical correlations. The conservation equations are expressed in finite difference form and solved by using a recursive technique [2]. Convergence is achieved after approximately 30 iteration steps, with each step taking approximately 6 CPU seconds on a CDC CYBER175 computer.

Input data required for the analysis of a steam generator involve the geometric layout; primary fluid inlet enthalpy, flow and pressure; secondary feedwater enthalpy and flow, outlet steam pressure, and normal operating water level. Eight different steam generator designs have been analysed. These have included a number of diverse features such as an integral preheater, square and round U-bends, and a range of feedwater entrance geometries.

## Typical THIRST Results

Velocity and quality distributions resulting from a typical THIRST analysis of the design discussed above are shown in Figures 2 and 3. Quality values are marked directly on the contours in Figure 2. The preheater section is below saturation, except for a small zone at the exit. The conical shape of the contours on the hot side illustrates the penetration of the downcomer flow into the center of the tube bundle. The lower horizontal cut shows the quality pattern on the tubesheet face. The second horizontal plane is located just above the preheater exit. Here the mixing of the higher quality fluid from the hot side with saturated liquid from the preheater results in steep gradients of quality on the cold side. As the mixture moves up through the remaining bundle the quality continues to rise. The hot side qualities are higher throughout.

The influence of the U-bend geometry can be seen by the shape of the quality patterns at the top of the vertical plane. This is more obvious from the velocity vectors in Figure 3. In the U-bend, the fluid tends to migrate out towards the shroud where the resistance to flow is lower. Just below the U-bend, the velocities are primarily axial and parallel to the tube bundle. At the preheater exit the higher flow on the hot side redistributes over the cold side. In the preheater the zig-zag pattern of the flow around the baffles is somewhat difficult to see because these velocities are relatively small. At the tubesheet face the downcomer flow is shown as coming in on the hot and cold side and converging at the center of the bundle corresponding to the point of highest quality.

## Applications of THIRST

Design Assessment. To demonstrate the use of THIRST as a design tool, the shroud window size was altered to determine its influence on performance. There is a significant effect, as all the downcomer flow must pass through these windows to enter the heat transfer zone. Figure 4 shows the influence of window size on the recirculation ratio, heat transfer and the maximum quality on the tubesheet. Smaller

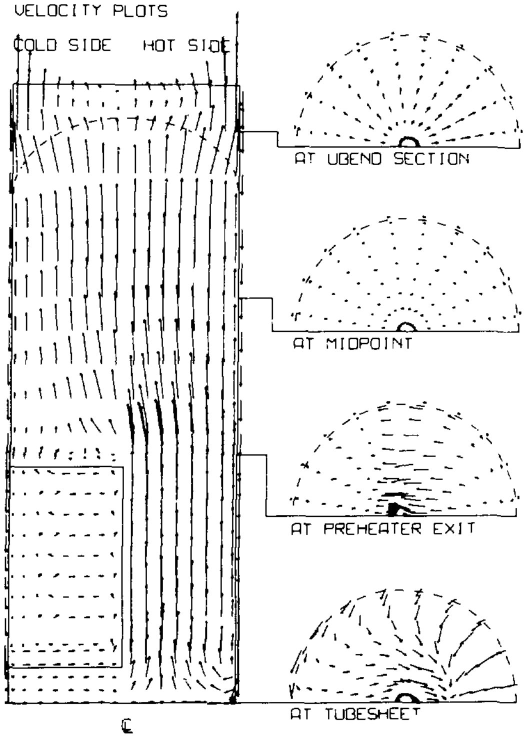



Figure 3 Computed Velocity Profiles

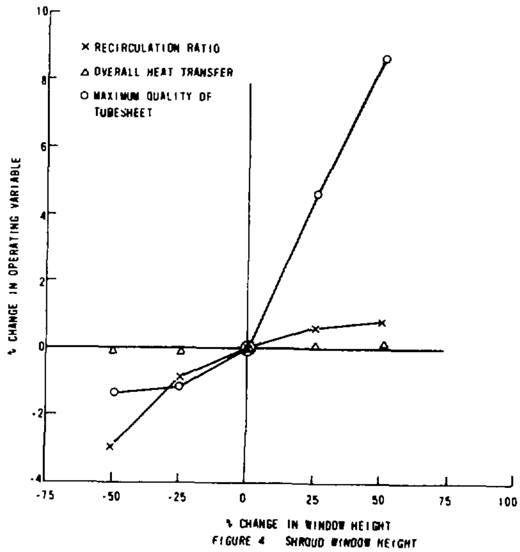



Figure 4 The Effect of Window Size

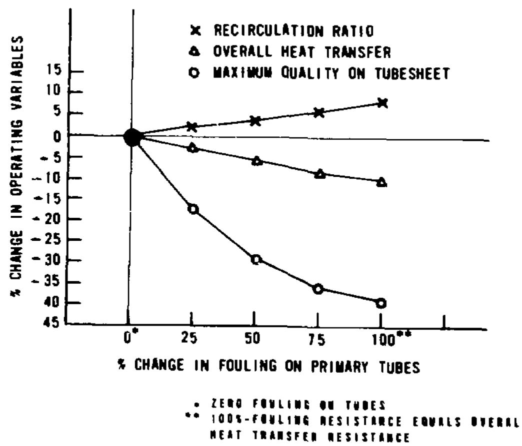



Figure 5 Fouling Effects

windows result in greater pressure loss and thus lower recirculation ratios. If the window height is reduced, the downcomer flow is concentrated closer to the tubesheet and although the total downcomer flow is less, the maximum quality on the tubesheet is reduced. As the main heat transfer mode is in boiling, the overall heat transfer varies only slightly with the reduction in secondary-side flows due to the lower recirculation ratios. There is a slight decrease (0.5%) in heat transfer when the window height is increased, as the downcomer flow is not forced to the bottom of the steam generator and thus the lower part of the bundle is partially by-passed. Decreasing the window height results in an escalating decrease in recirculation ratio with only small decrease in tubesheet quality. Increasing the window height rapidly increases the tubesheet quality, however, the recirculation ratio becomes fixed by the pressure loss in other regions of the steam generator.

Effect of Operating Conditions. THIRST can be used to assess the influence of adverse operating conditions such as a **buildup** of crud on the tube surface, known as fouling. Fouling margins are generally included in the sizing of shell and tube components. In *THIRST*, fouling is treated as an increase in resistance between the primary and secondary sides, and is assumed to act uniformly throughout the tube bundle. Figure 5 presents the influence of fouling levels on overall parameters. The first set of data was obtained for zero fouling on the tubes. This would be the situation when a component is first put into service. For the last set of data, the fouling conductance was equal to the average total conductance determined by the tube wall conductivity and the primary-and secondary-side convective coefficients, thus representing a resistance increase of 100% above zero fouling levels.

Fouling reduces the local heat flux for a given driving temperature and degrades the overall heat transfer. The resulting lower average secondary qualities generate lower pressure losses and higher recirculation ratios. The increase in recirculation ratio improves the penetration and coupled with reduced heat fluxes gives the pronounced reduction in maximum tubesheet quality. As primary fluid moves along the length of the tube, its temperature and thus the driving temperature is sustained, since less heat is transferred. At some point, the driving temperature compensates for the increased resistance and the local heat flux becomes higher than the zero fouling case. This shift in local heat flux values explains the large reduction in tubesheet quality and relatively small reduction in overall heat transfer.

Performance with Blocked Primary Tubes. Over the life of the steam generator, individual tubes may develop leaks. Standard repair procedure is to block these tubes at the tubesheet, effectively removing them from service.

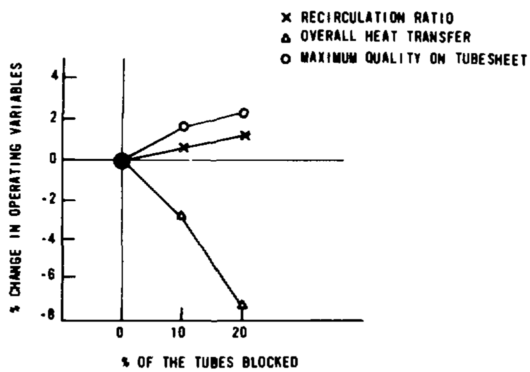



Figure 6 The Effect of Blockage

Blocking off primary tubes while maintaining the same overall primary flow requires the serviceable tubes to carry more flow. At the tubesheet the heat flux from the serviceable tubes changes little with the percentage of blocked tubes because the driving temperature is the same and the total heat transfer coefficient changes little with primary velocity. THIRST results, summarized in Figure 6, show that the maximum tubesheet quality varies only slightly with the percentage of tubes blocked. Individually, these serviceable tubes carry more energy and thus the primary temperature and hence the heat flux is sustained along their length. Secondary qualities around the serviceable tubes develop at a lower level in the steam generator. The effective reduction in heat transfer area results in an overall reduction in heat transfer. The lower average quality yields a reduction in pressure loss and the observed increase in recirculation ratio.

## Status of the THIRST Code

The development of the THIRST code has been completed, and a user-oriented version with a suitable manual will be ready for transfer to potential users in mid 1980. Further related development will include extending the application of the technique to heat exchangers. When this development is complete, a package of detailed analysis tools will be available to assist the designer in improving reliability and performance of shell and tube components.

## EXPERIMENTAL INVESTIGATIONS IN STEAM GENERATOR THERMAL-HYDRAULICS

In conjunction with the analytical work, experimental programs have been initiated at CRNL to investigate aspects of both primary and secondary flow. We concentrate here on two parts of this program, THIRST verification experiments, and those investigating the separation of two-phase flow in elbows.

### THIRST Verification Experiments

A first step towards experimentally verifying the numerical predictions in the THIRST code has been completed. The test section, though simple is designed to incorporate many of the flow features present in steam generators.

These include a gate to represent the windows through which feedwater and recirculated water enters the tube bundle, and also regions in the bundle where cross flow, axial flow or combinations of both exist.

Hot film anemometry was found to be the most effective technique for measuring local velocities, and most of our effort was spent on developing the X-type probe, particularly in reducing the frequency of probe breakage. Details of the measuring technique are given in reference 3; hence we merely illustrate results of a typical case.

The geometry of the test section, and velocities for a particular flow and gate opening are shown in Figure 7. These involved approximately 5000 velocity measurements. The results demonstrate that accurate velocity measurements in tube bundles can be made with hot film anemometry as the overall mass flow rate can be computed fairly closely from the velocity readings. For an inlet mass flow rate of 181.7 kg/s, flows calculated from measurements at eight different cross sections lay between 167 and 220 kg/s.

Measured velocities were compared with results calculated by a two-dimensional model in a simplified version of the THIRST code. The average error in velocity magnitude was approximately 13%, a figure comparable to the measured mass flow discrepancies. This is reasonably good agreement in view of the fact that no attempt was made to include three-dimensional effects in these calculations. Similar tests using air and water have now been initiated.

### Two-Phase Flow in Elbows

A further experimental program completed at CRNL studies two-phase flow on the primary side of steam generators. This program centered around a one-third scale model of the inlet head for 600 MW type reactors. Steam-water flows were simulated by air/water mixtures at equivalent void fractions. Possible phase separation in the inlet elbow and at the tubesheet was investigated.

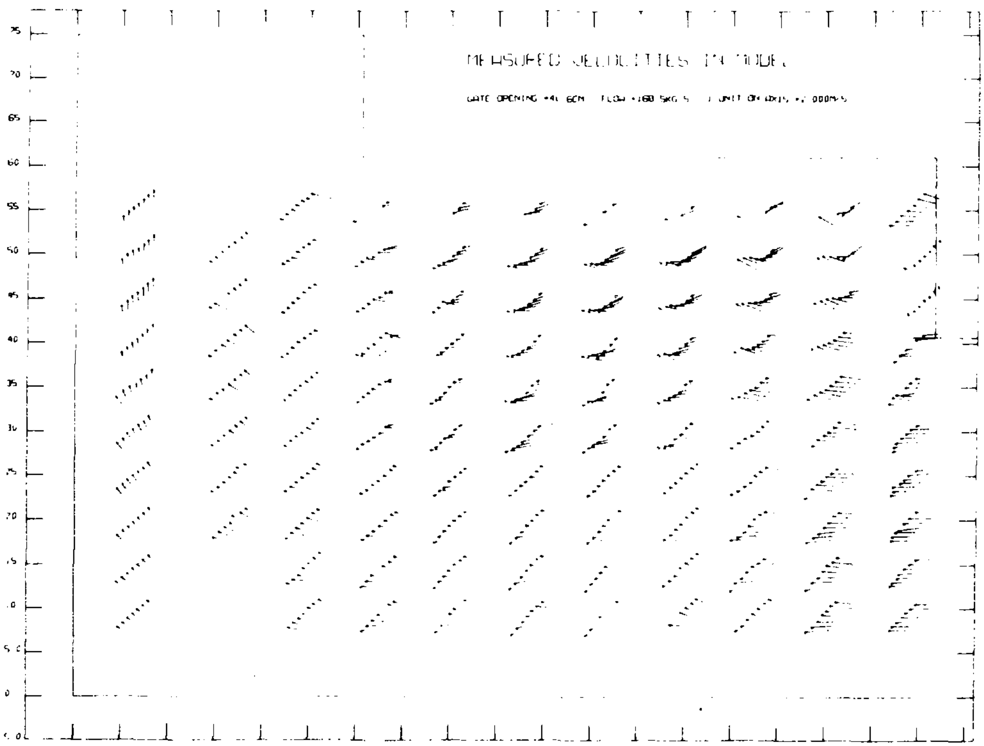
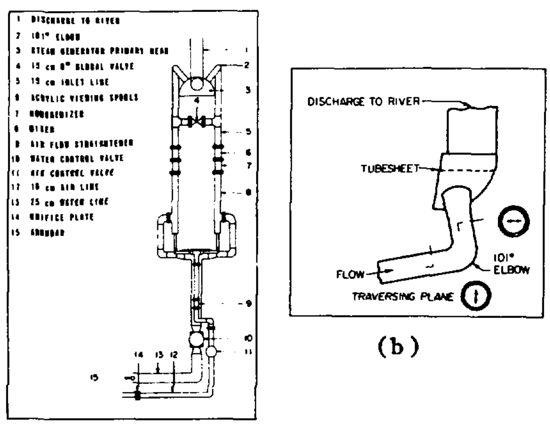


Figure 7 Test Section and Velocities

Steam generators for the 600 MW Gentilly II Nuclear Station are used as reference for our model, shown in Figures 8(a) and (b). In this model the two inlet lines are replicated by 150 mm diameter pipes fed by two homogenizer-mixers connected to the air and water supplies. The impedance of the tubes, through which the flow must go after entering the head is simulated by a perforated plate containing 200 holes installed at the location of the tubesheet. All measurement in the work used the isokinetic sampling technique, two-phase flow must be sampled in such a way that the phases and their relative velocities are not disturbed. Further details of the experimental technique are given in reference 4.

The prevailing conditions in steam generators for 600 MW reactors correspond to a flow of 89 kg/s with a void fraction of 0.36. We, therefore, studied the effect of void fractions from 0.27 to 0.57 at a constant water flow of 89 kg/s, water flows from 77 to 100 kg/s at an approximately constant void fraction of 0.36.

For each flow condition tested, velocity and void fraction readings were taken at seven locations across the diameter of the pipe, upstream and downstream of the elbow. The upstream readings were to confirm that the flow entering the elbow was homogeneous. Results of readings taken downstream are shown in Figures 9(a) and (b). Position 0 corresponds to the outer radius of the elbow. As expected, phase separation is more complete at high void fractions. Near the inside of the elbow the flow was 100% air for homogeneous entry void fractions greater than 0.45, and close to 100% for lower void fractions. On the outside of the elbow the local void fraction was correspondingly lower than the homogeneous void fraction. The local flow velocity was fairly uniform except for large void fractions, where the air velocity near the inside of the elbow was higher than the average velocity. Generally, the boundary of separation between air and water was clearly defined.




(a) (b)

Figure 8 Primary-Side Inlet Experimental Model

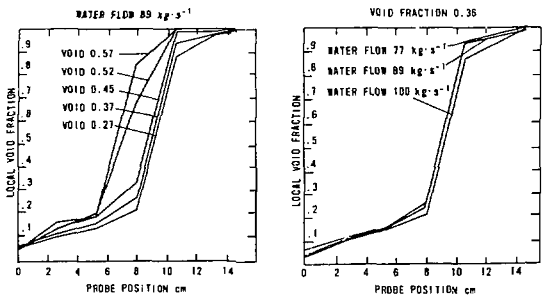



Figure 9 Void Fraction Profiles
a) Void Effects b) Flow Effects

Partly because the separation found in these tests was so extreme and partly because of the difficulty in relating these results to steam-water flows, further investigations are underway. These involve additional air-water tests, steam-water tests, and analytical modelling of the phenomenon.

*REFERENCES*


1. W.W.R. Inch and R.H. Shill, THERMAL-HYDRAULICS OF NUCLEAR STEAM GENERATORS: ANALYSIS AND PARAMETER STUDY. Paper submitted to ASME Nuclear Engineering Division Conference, San Francisco, August 1980.

2. S.V. Patankar and D.B. Spalding, A CALCULATION PROCEDURE FOR HEAT, MASS AND MOMENTUM TRANSFER IN THREE-DIMENSIONAL PARABOLIC FLOWS. Int. J. Heat Transfer 15, 1972, p. 1787.

3. D.A. Scott and J.D. Shaw, MEASUREMENT OF THE FLOW FIELD IN A TUBE BUNDLE BY HOT WIRE ANEMOMETRY. Proceedings of the 7th Annual Canadian Congress on Applied Mechanics, Sherbrooke, 1979, p. 725-6.

4. D.A. Scott, TWO-PHASE FLOW SEPARATION IN ELBOWS, Transactions Canadian Nuclear Association, Student Conference, Ottawa, 1979, p. 58-61.


ACKNOWLEDGEMENTS

This work was partially funded under the Ontario Hydro, Atomic Energy of Canada Common Development Program (CANDEV).