COMPARING DYNAMIC RESPONSES OF RECIRCULATING AND ONCE-THROUGH STEAM GENERATORS FOR NEXT-GENERATION LWRS

by

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ABSTRACT

Two types of steam generators are under consideration for next-generation (pressurized) light water reactors: a recirculating type and a once-through type. The steady-state and dynamic characteristics of these steam generators were compared to facilitate optimization of a particular reactor system design. To compare, the dynamic responses of the two types, as indicated by the feedwater flow, steam generator level, steam flow, steam pressure, steam enthalpy, primary-side pressure and cold-leg temperature, were assessed using Babcock & Wilcox's Modular Modeling System. The once-through steam generator showed a tremendous flexibility to produce superheated steam under diverse conditions (i.e., constant or variable steam throttle pressure and constant or variable average primary temperature) with excellent speed and accuracy in following the load demand. Since the primary and steam sides are closely coupled with the feedwater, the pressurizer should be sized liberally to lessen the sensitivity of the primary response to feedwater upsets and the reliability of the feedwater train should be enhanced. In contrast, the recirculating steam generator must be operated with variable steam throttle pressure and variable primary average temperature, and the speed and accuracy of following the load demand are not as good. While the recirculation provides an effective cushion for the primary and steam sides from feedwater upsets, it also amplifies the level response caused by upsets in steam pressure and feedwater temperature affecting the level controllability and moisture separation performance. The recirculating steam generator should be designed to incorporate features to improve level controllability by constant-inventory control strategy. Also to survive a reactor-coolant pump trip, the design with one reactor-coolant pump per loop should be considered.

I. INTRODUCTION

Steam generators (SGs)[*] are important heat transfer components in a nuclear reactor system and their operating characteristics significantly contribute to the safe operation of the system. Two types of SGs are under consideration for next-generation (pressurized) light water reactors (NGLWRs): a recirculating SG (RSG) and a once-through SG (OTSG).

In an RSG, the saturated water on the secondary side recirculates from the moisture separators to the bottom of the U-tube bundle through the downcomer. It then travels up through the riser on the outside of the U tubes while receiving heat from the primary-side water flowing inside the tubes. The steam from the two-phase steam-water mixture leaving the riser is separated by the moisture separators and goes to the steam outlet nozzle. Since the heat transfer surface is fixed, the variation in heat transfer with load has to be accomplished by a variation in the average temperature difference between the primary and secondary. The recirculation is sustained by the pressure head created by the difference between the downcomer and riser fluid densities. At low power this head becomes very small causing instability in recirculation.[1] While the recirculation attenuates the effect of feedwater (FW) upsets on the primary side, it amplifies the effect of steam pressure and FW temperature upsets on downcomer level, an important plant safety parameter, making it difficult to control the level to a constant setpoint. The amplification is due to the "shrink and swell" phenomenon marked by the release or collapse of steam voids caused by steam pressure and FW temperature upsets. An alternative to constant level control is constant inventory control in which the level setpoint is increased with load to offset the increase in riser void.[2,3] To realize improved level controllability by constant inventory control, superior moisture separators are necessary.

In contrast, an OTSG has no recirculation; the feedwater enters the downcomer, travels to the bottom of the straight tube bundle, and travels up on the outside of the tubes while receiving heat from the primary-side water flowing downward inside the tubes. By the time the feedwater reaches the top of the tube bundle, it becomes superheated steam and leaves through the steam outlet nozzles. Three main variable-length heat transfer regions exist along the tube bundle: nucleate boiling, film boiling, and superheat. The variable-length of the nucleate boiling zone, in which most of the heat transfer takes place, provides an additional degree of freedom for heat transfer (in addition to the primary-to-secondary temperature difference). This provides the operational flexibility to the OTSG. Also the superheat assures dry steam and improves cycle efficiency. However, the OTSG has a smaller inventory of water and the feedwater is closely coupled with the primary and steam sides.

Although both types of steam generators can be designed and built for the safety and operational requirements of NGLWRs, their steady-state and dynamic characteristics are quite different. With the NGLWRs still on the drawing board, it is timely to compare the steady-state and dynamic characteristics of the two SG types to facilitate optimization of a particular reactor system design.

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[*] A list of abbreviations is included at the end of the paper.

The characteristics of the two SG types were compared by building two dynamic simulation models using Babcock & Wilcox's Modular Modeling System (MMS),[4-7] an automated, user-friendly, and well-validated system widely used in the electric utility industry for developing dynamic models of power plants. The two models represented:

Model 1. Two-loop plant with OTSGs.
Model 2. Four-loop plant with RSGs.

A four-loop plant with RSGs was considered because of its potential for surviving reactor coolant (RC) pump trips; for example, if one RC pump tripped, the RSG in that loop can be isolated from the main steam header and the small amount of steam produced in that loop can be bypassed to the condenser. Because of the flexibility of the OTSG to operate with variable steam throttle pressure and variable primary-side average temperature (T_{avg}), the first model was run with two boundary conditions:

BC1 - constant steam throttle pressure and T_{avg}.
BC2 - the same variable steam throttle pressure and T_{avg} as used for the RSG.

Runs with BC2 facilitated in bringing out the differences between OTSG and RSG characteristics. Since design data for the NGLWR were not available, assumed boundary conditions for the primary inlet, feedwater inlet, and steam throttle pressure were used in both models. Figures 1 and 2 show the schematic of the two models developed for this study. Again, due to the unavailability of design data, the parameters of both models were derived by scaling presently operating OTSGs and RSGs to match the following NGLWR characteristics:[8]

Electric power rating:	600 Mwe
RC pump capacity:	3.249 m^3/s (51500 gpm)/pump (4 pumps)
RC pump motor rating:	2759.1 kw (3700 hp)
RC pump inertia:	210.7 kg-m^2 (5000 lbm-ft^2)
RC pressure:	155.7 kg/cm^2 (2215 psia)
Temperature of RC:	
entering SG:	312.2 C (594 F) at 100% power
leaving SG:	277 C (530.7 F) at 100% power
Steam flow:	3701 T/h (8.16×10^6 lbm/h) at 100% power for RSG plant 3528.7 T/h (7.78×10^6 lbm/h) at 100% power for OTSG plant
Steam pressure:	54.5 kg/cm^2(775 psia) at 100% power
Steam superheat:	24.7 C (44.5 F) for OTSG at 100% power
Turbine bypass capacity:	50% of 100% steam flow
Steam safety valve capacity:	100% flow at 54.5 kg/cm^2 (775 psia)
Steam safety setpoint:	70.31 kg/cm^2 (1000 psia)
FW temperature:	216.5 C (421.7 F) at 100% power
Main FW pump capacity:	75% of 100% FW flow/pump (2 pumps)

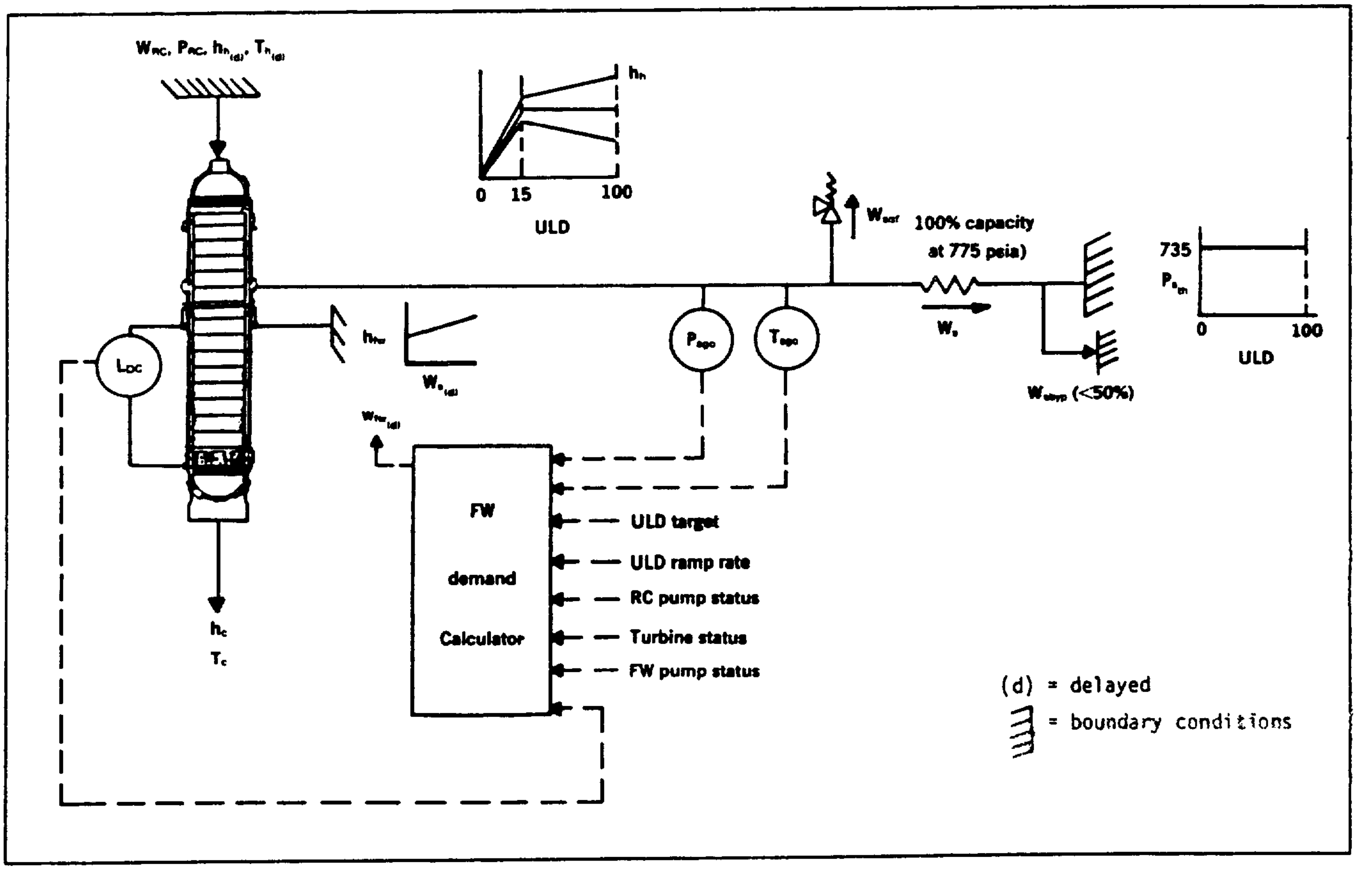

Figure 1. OTSG with boundary conditions.

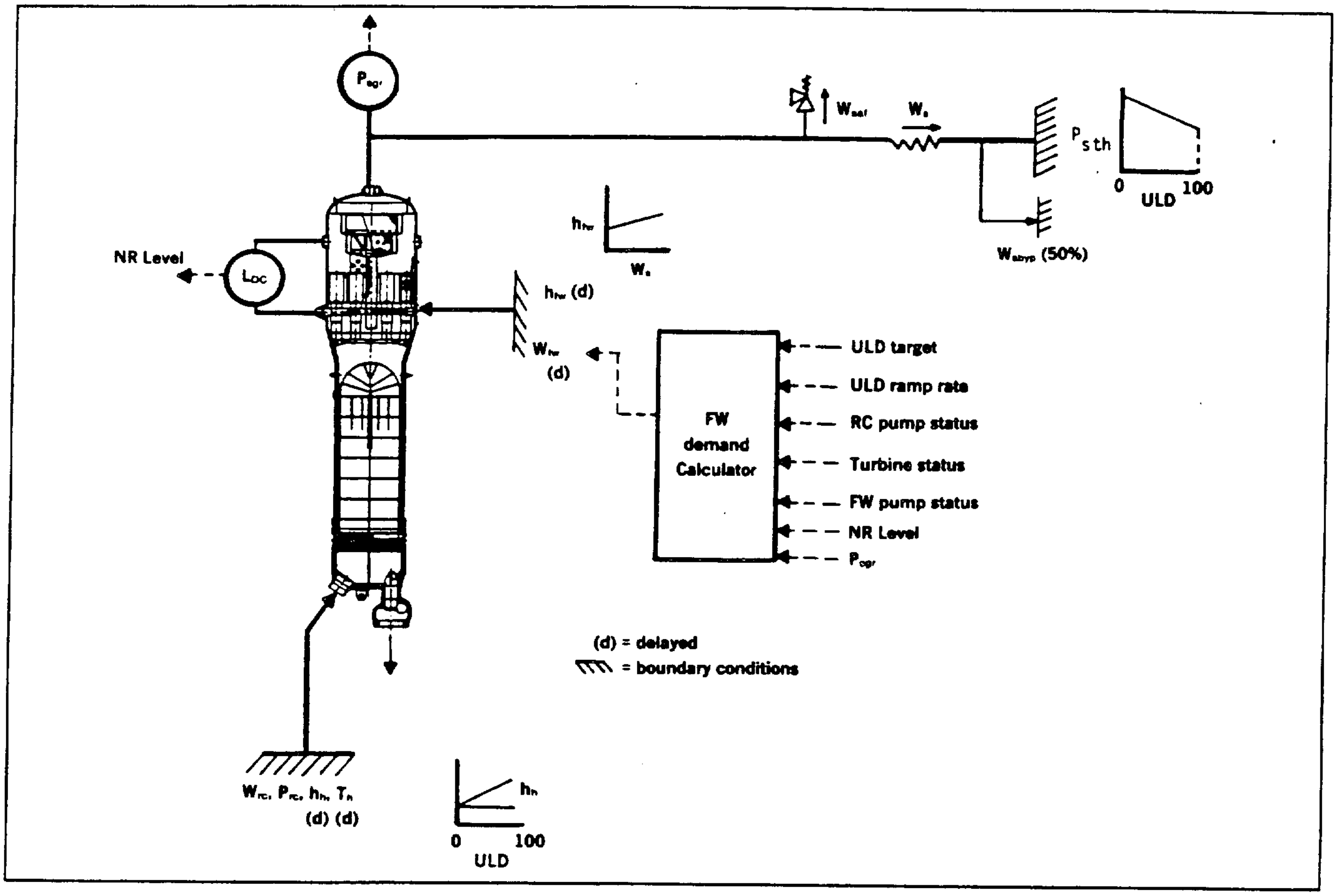

Figure 2. RSG with boundary conditions

The rated steam flow for the OTSG was based on the same heat transfer and FW temperature as the RSG, but with a superheat of 24.7 C (44.5 F); this is somewhat less than the superheat of about 31.7 C (57 F) in the presently operating OTSGs. The steady state characteristics of the OTSG and RSG are shown in Figs. 3 and 4, respectively.

Approximations to the following transients were run for each model using appropriate boundary conditions:

- Normal power changes.
- Trip of a FW pump.
- Reactor trip without turbine trip.
- Turbine trip with reactor runback.

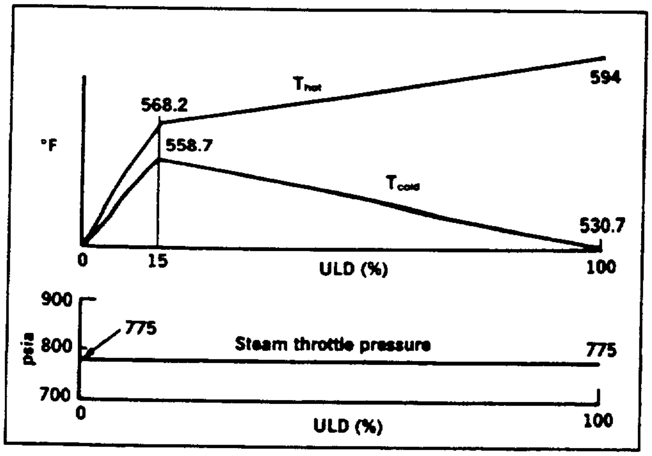

Figure 3. Steady-state characteristics of OTSG, Model 1, BC1.

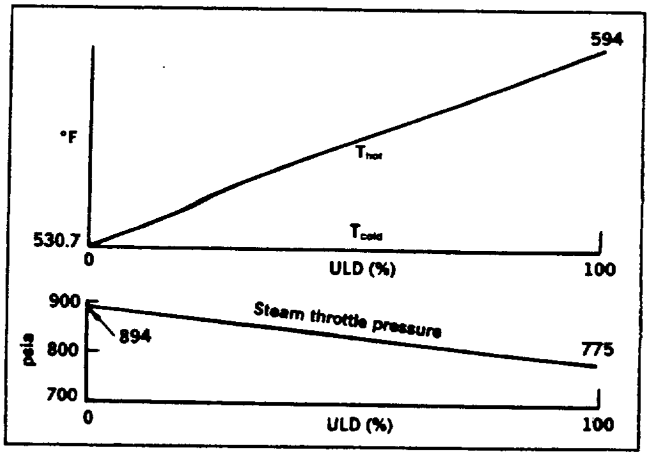

Figure 4. Steady-state characteristics of RSG (also of OTSG in Model 1, BC2).

The transient in which one RC pump is tripped is a standard OTSG transient for Model 1, BC1, a trivial transient for Model 2 (4-loop RSG plant) since the RSGs in the other three loops continue operating, and turns out to be the standard OTSG transient for Model 1, BC2. Therefore this transient is not included in this paper.

The rest of the paper is organized as follows:

II. Model development.
III. Model responses.
IV. Observations.
V. Conclusions.
VI. Abbreviations.
VII. References.

II. MODEL DEVELOPMENT

The models were developed using the commercially available MS. Pretested modules of OTSGs and RSGs available in the MMS were customized to the NGLWR parameters using the auto-parameterization available in MMS-EASE+. These modules were then combined with the dynamic boundary conditions representing changes in plant parameters with plant load and trip of plant components. The resulting models were automatically translated to fortran, compiled, and linked using the MMS workstation. The input for auto-parameterization was prepared by scaling existing OTSG and RSG data; the OTSG was parameterized for constant steam throttle pressure, constant T_{avg} operation. The resulting parameters were adjusted during initial model runs to match the heat transfer and flow rates of the NGLWR. The boundary conditions were fine-tuned to achieve reasonable transient behavior based on similar data on existing plants. The above procedure is typical of that used to develop models using MMS. The four transients included in this paper were then run for each model using predefined identical run-time commands and the results were plotted using the run-time plot commands.

III. MODEL RESPONSES

Although many response parameters were recorded for each model and each transient, plots of only the important ones are included in this paper:

1 Unit load demand (ULD) and actual Mwe produced by Model 1 and Model 2 (Mw_{eo} and Mw_{er}); $_o$ denotes OTSG and $_r$ denotes RSG.
2 Hot and cold leg temperatures and T_{avg} (T_{ho}, T_{co}, T_{avgo}, T_{hr}, T_{cr}, T_{avgr})
3 OTSG FW flow (W_{fwo}).
4 FW temperatures (T_{fwo} and T_{fwr}).
5 OTSG steam flow demand and actual flow (W_{sdo}, W_{so}).
6 OTSG and RSG pressures (P_{sgo}, P_{sgr}); OTSG downcomer level (L_{dco}), and steam superheat (T_{sh}).
7 RSG FW flow (W_{fwr}).
8 RSG steam flow demand and actual flow (W_{sdr}, W_{sr}).
9 Recirculation ratio (RR), and downcomer level of the RSG (L_{dcr}). The range of the RSG level plot is the same as the narrow-range level. Thus the 11% range represents the "Lo-Lo" level mark, the 25% range represents "Lo" level mark, and 75% range represents the "Hi" level mark.

Where possible, same scales are used on plots of same variables for various transients to facilitate comparison.

1. Power ramp from 100% to 75% at 5%/min

In this transient, the hot leg enthalpy and, for Model 1, BC2 and Model 2, also the steam throttle pressure, were ramped starting at 10 sec from their steady-state values at 100% power to those at 75% power at 5%/min and then were held at 75% up to 400 sec. The hot leg enthalpy was lagged to represent the transport lag from the reactor outlet to SG inlet. Feedwater enthalpy was also reduced as a function of lagged steam flow. Feedwater flow demand was calculated to meet the steam demand for the OTSG and to maintain the downcomer level for the RSG. The actual FW flow was delayed by a first-order lag. The resulting responses for Model 1, BC1 are shown in Fig. 5, while those for Model 1, BC2 and Model 2 are shown in Fig. 6. The plots are arranged in the same sequence as the variables listed above.

Discussion:

Model 1, BC1: All responses are smooth as expected. Mw_e follows the ULD, T_{avg} is maintained, and T_{sh} increases. As the steam flow ramps down, the pressure drop in the steam line decreases, causing a drop in SG pressure while the steam throttle pressure is held constant. This is true for all the Model 1, BC1 transients discussed in this paper.

Model 1, BC2: All responses are smooth. The OTSG operates very well in the variable steam throttle pressure, variable T_{avg} mode. Note the almost-perfect tracking of the ULD. The downcomer OTSG level does not drop as far as in Model 1, BC1. The superheat drops slightly in stead of increasing as in Model 1, BC1.

Model 2: The responses are smooth as expected. The level is maintained quite well and the recirculation ratio increases.

2. Trip of a FW pump

This transient is started at 10 sec from 100% steady state. The FW pump trip effect is approximated by momentarily dropping the total FW capacity to 50% before recovering to 75%, the capacity of the remaining pump; the recovery is usually fast enough to cause a drop typically only to 65% capacity. The plant power is run back to 70% at 20%/min and then held at 70% up to 200 sec. The responses for Model 1, BC1 are shown in Fig. 7, while those for Model 1, BC2 and Model 2 are shown in Fig. 8.

Discussion:

Model 1, BC1: The FW flow momentarily dips to 57% before recovering to 75%. The FW flow capacity relative to its demand is limited until 78 sec affecting the FW flow, steam flow, Mw_e, steam pressure, and T_{avg}, while the steam throttle pressure setpoint is held constant.

Model 1, BC2: The close coupling of the feedwater with the primary and steam sides is obvious from the primary temperature response (T_{avgo}, T_{co}) and steam-side responses (W_{so}, P_{sgo}). A highly reliable FW train will minimize such transients.

Model 2: The effect of FW pump trip on the primary and steam sides is negligible. Although the accuracy of Mw_e response is not so good, it is better than in Model 1. However, note the dip in the RSG level below the "Lo" level. Presumably the RSG level control can be improved with advanced methods to improve the level response.

3. Reactor trip without a turbine trip

The reactor trip is approximated by ramping power from steady state at 100% to 4% in 6 sec and then running at 4% up to