An Energy Balance Model for Watts Bar Nuclear Plant

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by

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Abstract

The Tennessee Valley Authority (TVA) has long been committed to plant performance issues and has implemented plant thermal performance monitoring and improvement programs at its nuclear and fossil-fired power plants for many years. As part of this program, TVA has extensively used energy balance programs to design, analyze, and evaluate its plants.

In early 1997, TVA in conjunction with Performance Engineering, Inc. (PEI), a Dallas-based consulting company, developed an energy balance computer model of the Watts Bar Nuclear Plant using the PEPSE (Performance Evaluation of Power Systems Efficiencies) computer program(1). This model is one of the largest heat balance computer models ever constructed using PEPSE. TVA is using this model for many purposes, including daily operations evaluations, plant design modification evaluations, power uprate studies, and future performance predictions.

This paper will discuss the development of this extensive PEPSE model, and provide current applications of the model at TVA.

Unit Description

The Watts Bar Nuclear Plant employs a four-loop Pressurized Water Reactor Nuclear Steam Supply System (NSSS) furnished by Westinghouse Electric Corporation. The NSSS will operate at 3,425 MWt including all contributions of heat to the Primary Coolant System from nonreactor sources, primarily reactor coolant pump heat. The turbine-generator set is also a Westinghouse design. The turbine is a horizontal, tandem compound unit with one double-flow high pressure (HP) turbine and three double-flow low pressure (LP) turbines. The gross electrical output is 1,218 MWe for the rated core power. The plant is located approximately 50 miles northeast of Chattanooga at the Watts Bar site in Rhea County, Tennessee along the banks of the Tennessee River.

Watts Bar's balance of plant possesses twenty-one feedwater heaters (FWHs) arranged in three strings of seven heaters each. All are closed heaters, and fifteen have internal drain coolers. There are two main feed pump turbine (MFPT) condensers which contribute in the cycle's regenerative heating of the condensate-feedwater. In addition, waste heat from the steam generator blowdown system is also recovered by the condensate system via water-to-water heat exchangers.

The main condenser has three zones, each operating at a different backpressure. The circulating water, supplied by a closed loop cooling tower circuit, is passed through each zone in series, causing an increasing circulation water inlet temperature to the subsequent zone.

Energy Balance Model Development

A rigorous heat balance computer model is an important element of an effective thermal performance program. It provides highly accurate baseline target values and corrections for seasonal variations in main condenser backpressure and for unit load. Heat balance computer models can also provide trending information and can be invaluable in identifying the performance impact of proposed plant modifications. Since the publication of the General Electric (GE) procedures(2,3) it has been possible to model the performance of steam turbines in the as-constructed plant configuration. This is important because of the limitations of the heat balances provided by the turbine-generator vendor. The vendor-supplied heat balances generally utilize fixed main condenser backpressures, FWH terminal temperature differences (TTDs), and drain cooler approaches (DCAs). In addition, over the years various modifications have occurred at most plants resulting in different cycle configurations, equipment, and system operating parameters than those analyzed by the turbine-generator vendor. With the capabilities of today's computer modeling programs, the plant thermal cycle can be simulated to better reflect off-design loads and as-constructed configurations.

A detailed PEPSE model of the Watts Bar balance of plant turbine cycle was developed based on the original Westinghouse heat balance diagrams and associated thermal hydraulic data and curves. This model was then modified to reflect the as-built configuration using actual plant drawings and equipment design data. The as-built PEPSE model schematic is shown in Figure 1 (on six separate pages because of its size).

Input data for the model was collected from several sources. Primarily, data from the vendor heat balances was used to characterize the performance of the HP and LP turbines. Since each manufacturer has a unique method of predicting turbine performance, models of non-GE units usually require modifications to the normal turbine expansion line calculations built into PEPSE, as was the case with Watts Bar. The PEPSE expansion line was both shifted and reshaped so that it would match the design characteristics of the Westinghouse turbines. Heat balances were then performed with the model in an attempt to match the vendor heat balances at valves wide open (VWO), 100, 75, 50, and 25 percent load. The PEPSE model produced agreement with the vendor balances within the range of 0.007% (MWe @ VWO) to 0.379% (Heat Rate @ 25%). These heat balances were performed utilizing design values of main condenser backpressure, FWH TTDs, and DCAs.

In order for the model to reflect the as-built performance of the cycle, the previously fixed performance parameters (main condenser backpressure, FWH TTDs, and DCAs) must be permitted to float (i.e., the computer code will be allowed to calculate these values using standard heat transfer equations in conjunction with component specific design data. All of the original FWHs at Watts Bar have been either replaced or retubed to eliminate the copper alloy tubes which have been known to contribute to steam generator tube degradation. Since all of the design TTDs and DCAs have changed, the FWHs were modeled in detail using the heater manufacturer's specifications. Thus, expected TTDs and DCAs can be determined for various unit load conditions. The main condensers and main feed pump turbine condensers were modeled utilizing the Heat Exchanger Institute (HEI) method for steam surface condensers based on the number of tubes, the tube material and their dimensions. The HEI method requires less inputs than the detailed modeling used for the FWHs.

The main feed pumps and their associated drive turbines were defined using the pump and turbine manufacturer's specifications. This enables the model to predict the steam flow requirements for various combinations of unit load and MFPT condenser backpressure.

Where necessary in the model, data tables, equations, and controls were used to achieve a specific performance input and/or output for a given component (FWH, heat exchanger, turbine, etc.).

Model Applications

Following the completion of the as-built heat balance model, it was immediately employed in varied applications which required a thermal cycle analysis. These applications are discussed in the following subsections.

Moisture Separator Reheater Tube Bundle Replacement

Watts Bar's moisture separator reheater tube bundles are to be replaced during the Fall 1997 outage. Improved performance from the steam reheaters is expected (i.e., the TTDs will be decreased along with fine tuning of the reheater vent flows). To complete the modification package, it was necessary to update the unit's heat balance drawings to reflect this change to the thermal cycle. PEPSE has a unique feature that allows the user to generate an actual heat balance drawing similar to those produced by the vendor on which the results of the model can be displayed. Thus, the design data for the new tube bundles was easily input to the model and new heat balance drawings were created for unit loads of 104.5, 100, 75, 50, and 25 percent. Note that a simplistic model of the MSRs was used which only required inputs of TTD, tube and shell pressure drops, and percent vent flow. The heat balance results projected that an increase of approximately 2 MWe would be realized at 100% load following the MSR modifications.

Main Condenser and MFPT Condenser Backpressure Impacts

During the summer months, the hotwell temperature of the main condenser approaches 140°F. This hot condensate is passed through the tube side of the MFPT condensers , which condense the MFPT exhaust steam (see Figure 1). The hot inlet temperatures produce high backpressures in the MFPT condensers, thereby the steam demand through the MFPTs is increased to match pumping power requirements. The MFPT backpressure limit has been approached and the increased flows have proven to be more than the current MFPT condenser drain system can handle. Several options were explored, using the PEPSE model, to determine the most cost effective solution to the problem. The proposed options include:

1. Duct the MFPT exhaust directly to the main condenser, thereby allowing a lower exhaust pressure and the elimination of the need for the MFPT condensers and associated drain system.
2. Remove the MFPT condensers from the condensate system and supply raw water, which would be cooler than the condensate, for cooling. This arrangement will lower the MFPT condenser backpressures and correspondingly decrease the steam demand and drain flow.
3. Supplement the closed loop cooling tower circuit with cold water to reduce the overall main condenser cooling water inlet temperature by roughly 3°F. This would be accomplished by running a large pipe from the nearby decommissioned Watts Bar Fossil Plant which previously received its condenser cooling water from the bottom of the lake reservoir directly upstream of Watts Bar Dam. This option would lower the condensate temperature to the MFPT condensers and increase the plant MWe output in response to the reduced main condenser backpressures.
4. Increase the circulating water flow to the main condenser using a spare circulating water pump from the deferred Watts Bar Unit 2, thus lowering the main condenser backpressure and correspondingly lowering the condensate temperature used to cool the main feed pump turbine condensers. An increase in MWe must be realized above the power requirements of the additional pump to make this option viable.
5. Utilize HP steam to supply the MFPTs during the hot weather to reduce the steam load on the MFPT condenser.

PEPSE case studies were performed on all options listed above. Based on the results of these studies, the following conclusions were reached:

- The impact on plant output for options which removed the MFPT condensers entirely from the condensate system (see options 1 and 2) was too great to pursue further. Both options 1 and 2 would have resulted in a loss of approximately 3 MWe. Upon further investigation, the routing of the necessary piping to implement either of these options was viewed unfeasible.

- It was projected that an additional 7-8 MWe would be realized during the summer months with the cold supplemental condenser cooling water (see option 3). This option would in turn lower the MFPT condenser backpressure by approximately 1" HgA. The MFPT steam supply would still be more than the drain system could handle.
- The additional pumping capacity of the main condenser cooling loop was shown to contribute an additional 4 MWe which was greater than the pump's 2 MWe power requirement. The resulting lower main condenser backpressures and hotwell temperature provided some backpressure relief to the MFPT condensers. The MFPT steam supply would still be more than the drain system could handle.
- The backpressure of and drain flows from the MFPT condenser were not reduced significantly by the utilization of HP steam. This fact combined with a loss of plant output showed this option to be unmerited.

Based upon these conclusions, the decision was made to proceed with further evaluation of both options 3 and 4 to provide backpressure relief on the main and MFPT condensers. An alternate drain path for the MFPT condensers is needed to handle the higher than design drain flows that would still exist.

Future Work

TVA in conjunction with Westinghouse is currently studying a T_{hot} reduction and possibly a corresponding power uprate at Watts Bar. A T_{hot} reduction program would aid in extending the life of the steam generator tubing. The PEPSE heat balance model has been utilized, thus far, to validate Westinghouse's MWe projections for various NSSS parameters. A final direction for this project has not been reached at this time, but it is evident that the PEPSE model will be utilized numerous times prior to its completion.

Conclusions

Heat balance computer programs, such as PEPSE, are powerful tools that allow plant engineers to analyze present and future plant performance. They offer a low-cost way of predicting the outcome of plant changes and operating changes on plant performance.

References

1. PEPSE Computer Code, Version 61, Scientech, Inc. (formerly Halliburton NUS Corporation), Idaho Falls. PEPSE is registered trademark of Scientech, Inc.
2. General Electric Company Publication GET-6020, "Predicting the Performance of 1800 RPM Large Steam Turbine-Generators Operating with Light Water-Cooled Reactors", by F. G. Bailey, J. A. Booth, K. C. Cotton, and E. H. Miller.
3. General Electric Company Publication GER-2454A, "Predicting the Performance of Large Steam Turbine-Generators Operating with Saturated and low Superheat Steam Conditions", by F. G. Bailey, K. C. Cotton, and R. C. Spencer.

WATTS BAR NUCLEAR UNIT 1
PEPSE TURBINE CYCLE MODEL

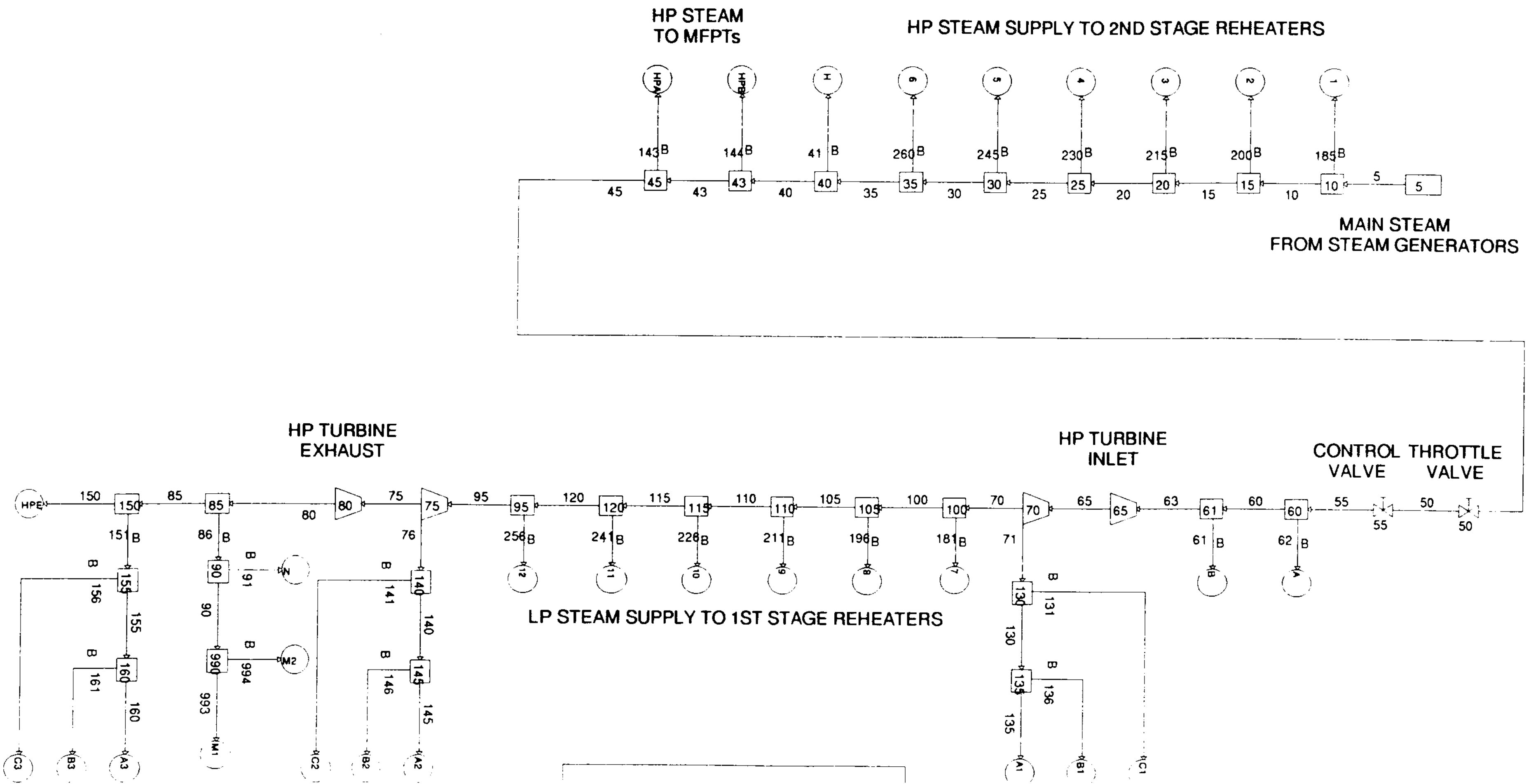

FIGURE 1 (Sheet 1)
Watts Bar Nuclear Plant
PEPSE Model Schematic

MOISTURE SEPARATOR REHEATERS

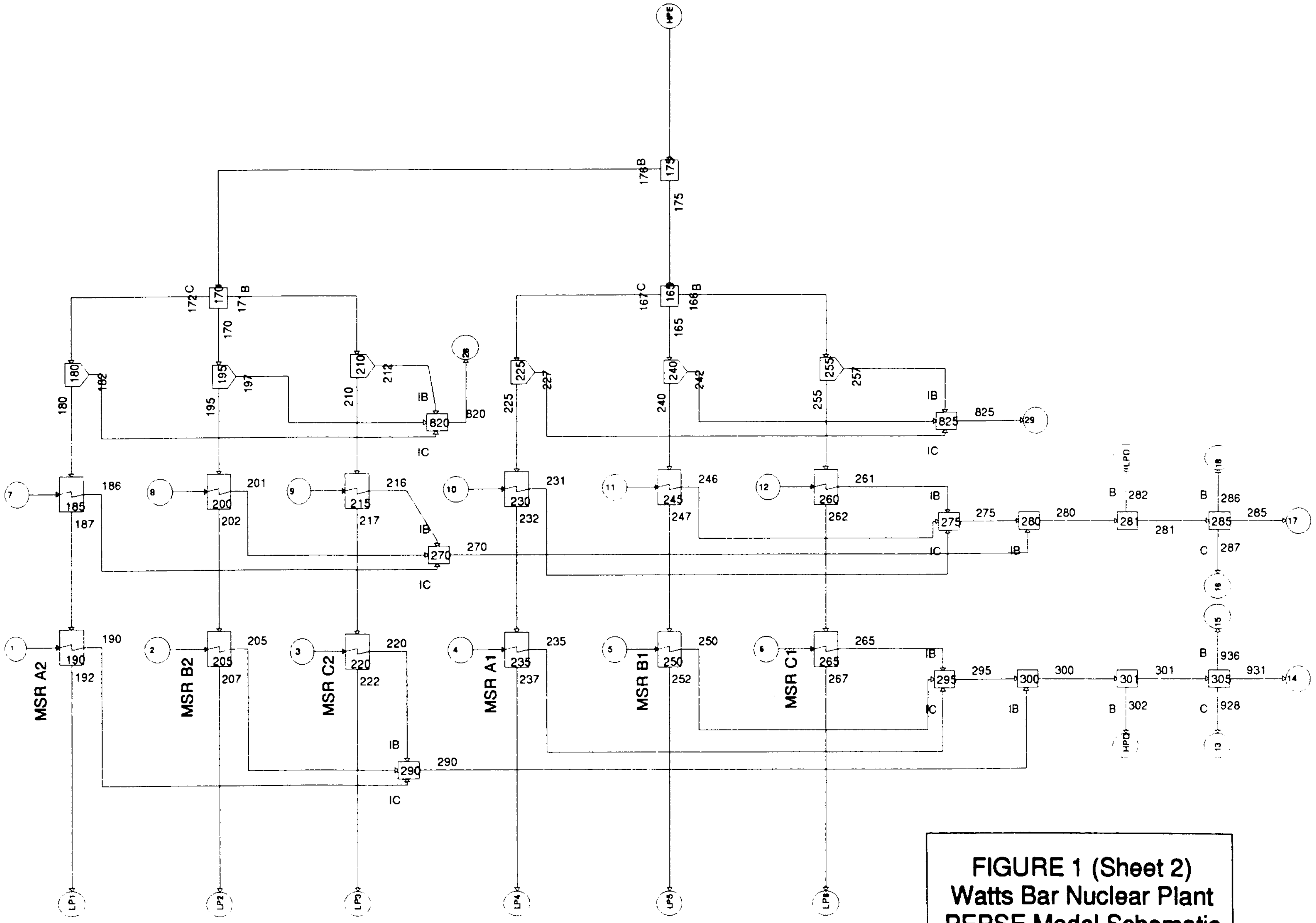

FIGURE 1 (Sheet 2)
Watts Bar Nuclear Plant
PEPSE Model Schematic

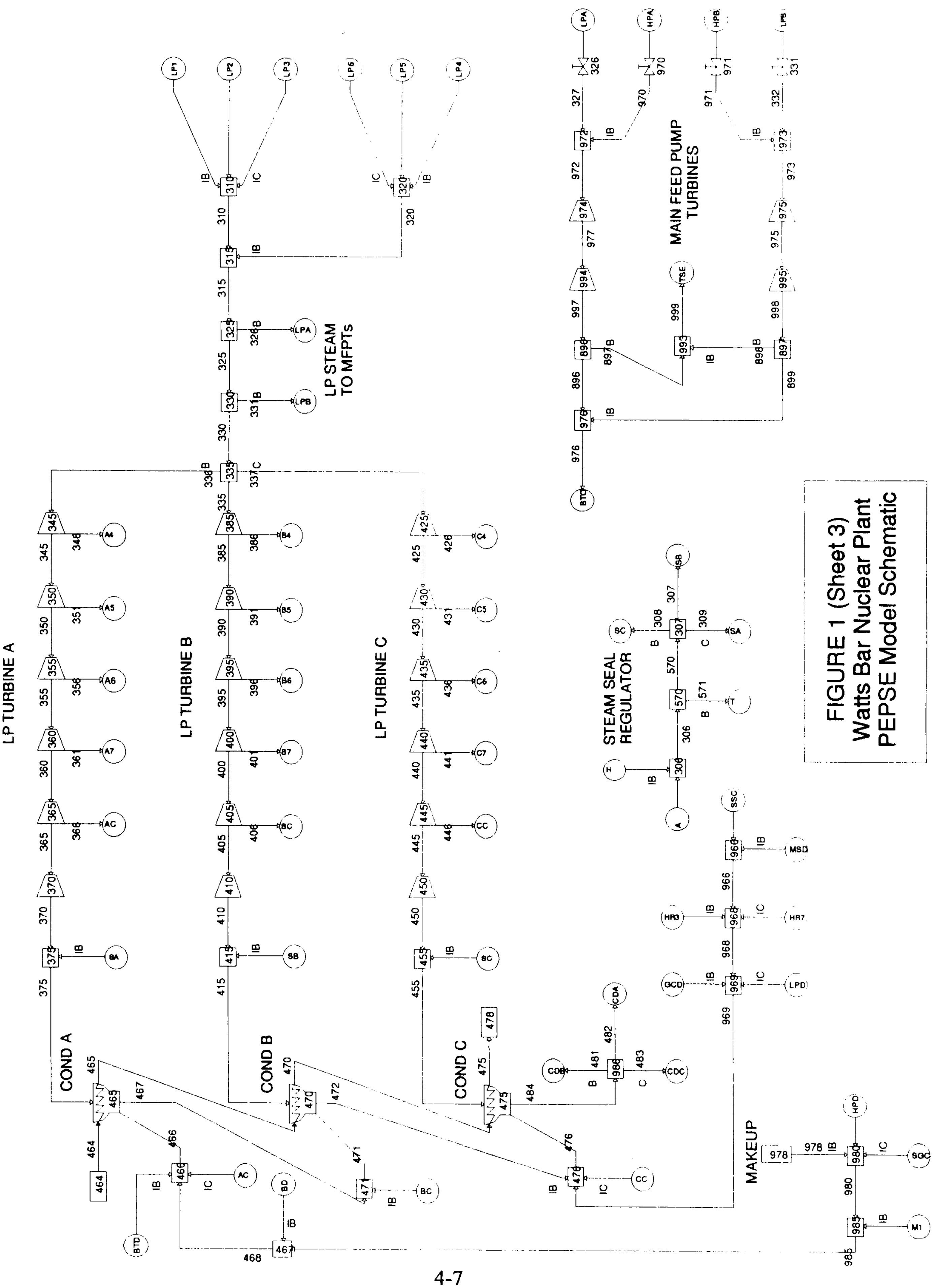

FIGURE 1 (Sheet 3)
Watts Bar Nuclear Plant
PEPSE Model Schematic

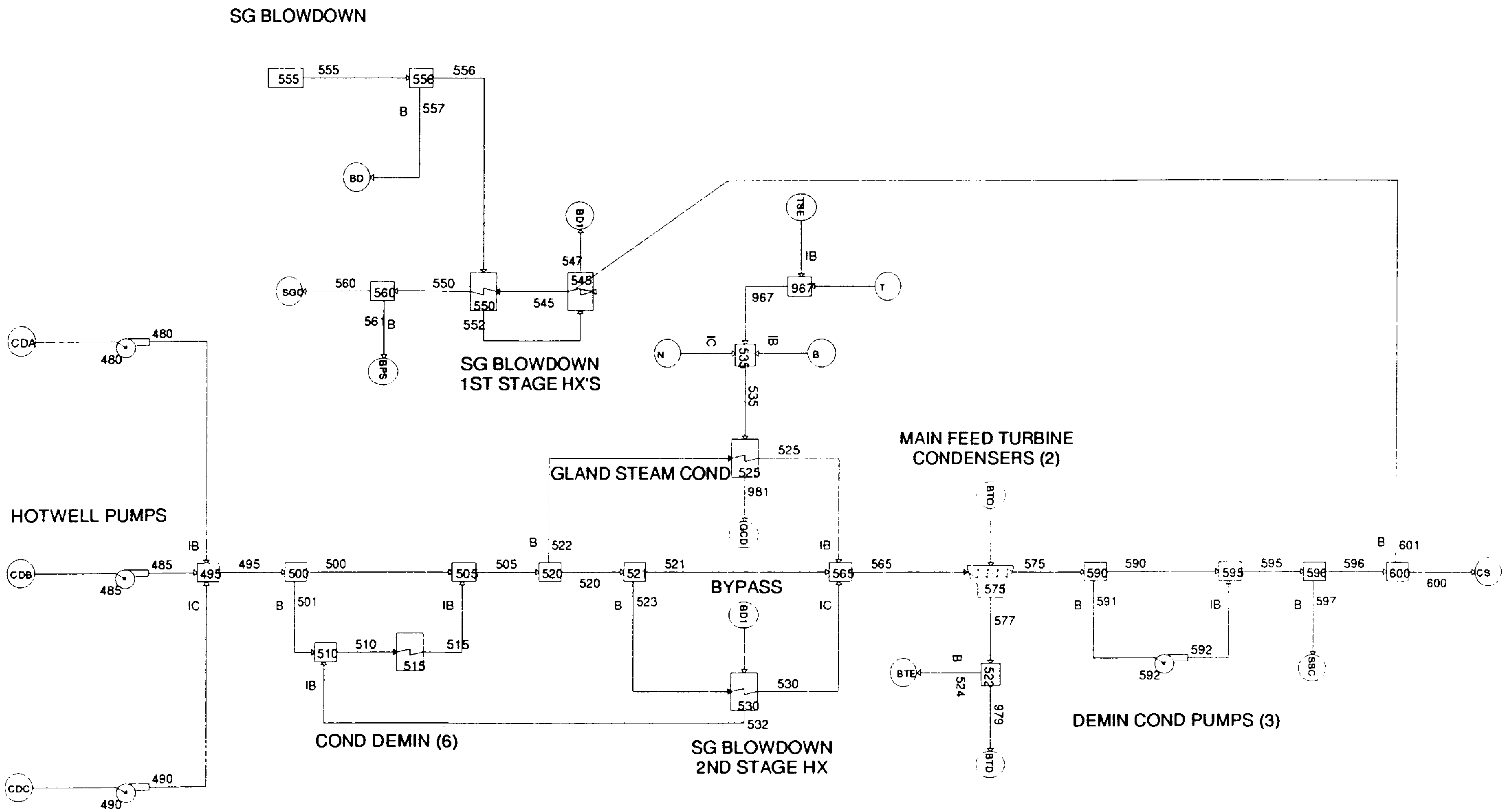

FIGURE 1 (Sheet 4)
Watts Bar Nuclear Plant
PEPSE Model Schematic

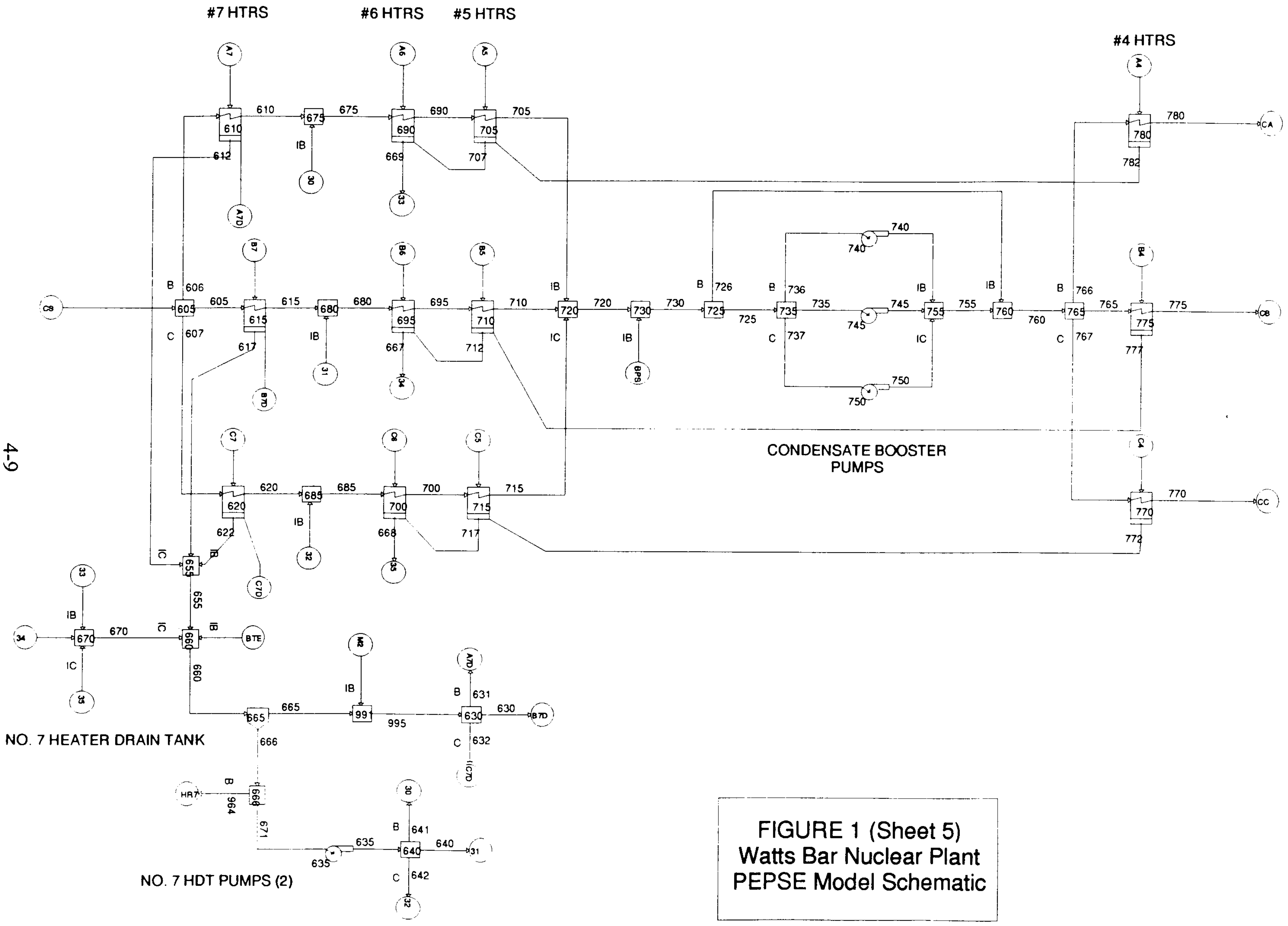

FIGURE 1 (Sheet 5)
Watts Bar Nuclear Plant
PEPSE Model Schematic

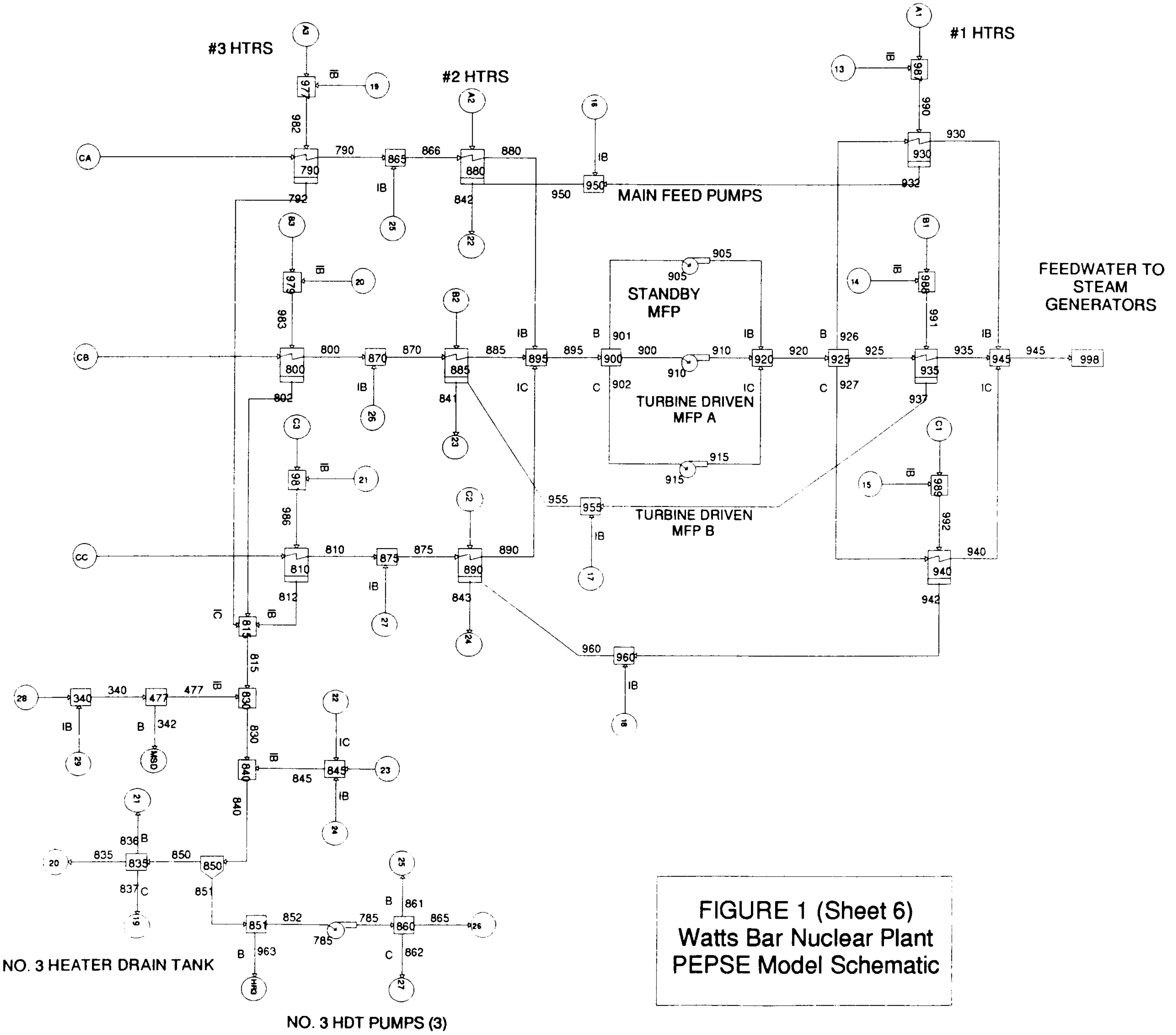

FIGURE 1 (Sheet 6)
Watts Bar Nuclear Plant
PEPSE Model Schematic