4A Once-Through
Steam Generator

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APPENDIX 4A

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APPENDIX 4A

B&W ONCE-THROUGH STEAM GENERATOR DEVELOPMENT PROGRAM

1 INTRODUCTION

The once-through steam generator is a result of continuing efforts by The Babcock & Wilcox Company to develop a steam generator of improved design for application in a nuclear power station. Technological advances in boiling heat transfer, combined with the unique operating characteristics of a pressurized water reactor system, contribute to improved efficiency and to reliable performance of the once-through steam generator.

2 HEAT TRANSFER CHARACTERISTICS

Boiling water research, which contributed to the development of the PWR once-through steam generator, started in the middle 1950's. To illustrate the results of this work, in Figure 4A-1 a curve of DNB (Departure from Nucleate Boiling) as a function of mixture velocity is plotted. DNB is defined as the quality where nucleate boiling changes to film boiling. Nucleate boiling is boiling from a wetted surface in which steam bubbles form around nucleation centers with a characteristic high heat transfer coefficient. In film boiling a film of superheated steam insulates the bulk of the water from the heat transfer surface. Film boiling is characterized by low heat transfer coefficient.

In Figure 4A-1, the abscissa shows the quality in per cent steam by weight. This varies from zero, which is all liquid, to 100 per cent, which is all steam. The ordinate is mixture velocity. This curve indicates the quality at which DNB occurs for a given pressure, heat flux, and geometry. Typical operating conditions for PWR steam generators are 1,000 psi and a mean boiling heat flux of 50,000 Btu/hr-ft^2. At very low velocities, as shown on the curve as Zone "A", boiling occurs similar to the boiling in a pot or teakettle. One hundred per cent quality steam is reached before nucleate boiling is lost.

As mixture velocities are increased, the DNB quality slowly decreases. As mixture velocities increase, the effect of steam slip or slip velocity to promote continuation of nucleate boiling diminishes. "Slip velocity" is the phenomenon in which the steam in a two-phase system moves at a greater velocity than the water. As higher mixture velocities are reached, the dropoff in quality increases per increment of mixture velocity. With only a slight increase in velocity, the DNB curve breaks sharply to the left. The DNB quality reaches a minimum then reverses and increases with velocity until it reaches a maximum and goes straight upward.

Prior to the advent of the once-through steam generator, combustible fuel boiler designs concentrated in the area (Zone "B") of the curve shown in the lower left-hand corner. Mass flow requirements for natural circulation steam generators are generally low to provide low pressure drop in the vapor generating section, while at the same time a relatively high circulation ratio (ratio of pounds of mixture flowing to pounds of steam produced) prevails to ensure adequate flow throughout the high temperature, high heat absorbing zones. Thus, for a natural circulation boiler with a circulation ratio of 5:1, a corresponding mixture quality of 20

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per cent leaves the vapor generating section. This is far below the DNB quality; hence, nucleate boiling is maintained throughout the boiling section of a natural circulation boiler. This prevents "burnout", which can occur at the point of DNB in a boiler with a high temperature heat source and a low circulation ratio.

With the advent of PWR plants, with a limited temperature heat source, similar recirculation ratios are required. Although the problem of burnout does not exist, "dryout" at the point of DNB can deposit chemicals on the tube and cause "hideout". This condition may create problems with secondary water chemistry control. Film boiling also lowers heat transfer coefficients. With the advent of combustible fuel, once-through steam generators, B&W became interested in boiling water research in Zone "C" of the curve. A considerable research effort was conducted in the B&W Research Center, Alliance, Ohio, and later on in other laboratories, to establish the shape of the curve in Zone "C". It is necessary to achieve high velocities in a high temperature source to minimize tube metal fluctuations at the point of DNB by maintaining relatively high heat transfer coefficients in the film boiling region. This places the operating conditions in the upper portion of the curve.

During the late 1950's, when this early research work was being done, an interesting trend in the boiling water curve was observed. Test data indicated that for a given subcritical pressure and heat flux, an inverse ratio of velocity to steam quality at DNB occurred at low mass flows. This characteristic did not permit application for combustible fuel, once-through steam generators because of the high temperature "burnout" problem. It was recognized by B&W, however, that this trend could be important in once-through steam generator applications where the tube wall temperature fluctuations at the location of DNB are low enough to permit the design of a boiler with low mass flows. (See Zone "D".) The pressurized water reactor offered possibilities for the useful application of this desirable boiling water heat transfer characteristic.

To further explore the heat transfer characteristics of boiling water at low mass flows, test work was performed in the B&W Research Center. In Figure 4A-2, a schematic of the high pressure boiling water heat transfer apparatus shows the equipment used in performing these investigations.

A single tube, electrically heated to achieve desired heat fluxes in a 6 ft test section, contained closely spaced thermocouples to observe tube metal temperatures. The once-through steam generator and bypass arrangement were used to control the steam quality entering the test section. Mixture velocities were varied to investigate DNB characteristics over a wide range of conditions.

To investigate DNB characteristics for PWR operating conditions, testing was performed at a pressure of 500 psi and 1,000 psi with heat fluxes from 20,000 to 100,000 Btu/hr-ft^2. Two tube diameters were used to determine the effect of geometry. This work supplemented our knowledge of Zone "D" of the boiling water curve and produced results that were even more desirable than had been postulated from slip velocity theory. The break in the curve occurred at higher velocities than expected.

Additional information was obtained while performing stability characteristics tests on a recirculating PWR steam generator. In Figure 4A-3 a schematic diagram of the steam generator stability test facility is shown. The steam generator has a vertical U-tube bundle with fifty-five 1/2-in. OD tubes with a separate steam drum, separate riser, and separate downcomer. The riser and downcomer each contain a valve so that studies can be made of the effect of circulation ratio on stability. To test the once-through steam generator principle, valving was modified to introduce feedwater directly into the bottom of the unit. Instrumentation and controls on the facility did not permit B&W to obtain extensive operating data. However, the observed heat transfer characteristics confirmed previous test data, and, operationally, the unit was extremely stable.

3 LABORATORY TESTS

During August 1964, steps were taken to design and construct a facility to operate a full-scale section of the PWR once-through steam generator. An existing hot water loop at the Research Center was used as the basis for this facility. The objective of this test program was to investigate operational characteristics in regard to stability, heat transfer, and controllability.

In Figure 4A-4 a drawing of the test unit arrangement is shown. It contained seven tubes duplicating the tube length, tube diameter, and material of the full-size steam generator. Shell-side flow area per tube duplicates the full-size steam generator. The superheater section is arranged with concentric baffles to simulate the pressure drop and heat transfer characteristics of the full-size steam generator. An external downcomer is provided with a flow area duplicating the annulus area of the full-size steam generator. The external mixer is arranged with a feedwater nozzle sized to reproduce design feedwater spray velocity into the downcomer. The unit was tested at conditions of pressure, temperature, and mass flows duplicating conditions in the proposed full-size unit. The stability and heat transfer characteristics were investigated over a wide range of secondary pressures, flows, and feedwater temperatures with several arrangements of feedwater heating. The dynamic response characteristics of the boiler were determined. Performance was investigated with various arrangements of automatic control, using steam generator-following and turbine-following modes of operation.

Test results indicated that the concept of a straight-tube, once-through steam generator with shell-side boiling operates stably, that the heat transfer is in agreement with the calculated values on which the design was based, and that controls were able to accommodate all anticipated operating conditions of load changes and steady state requirements. Control is essentially on the traditional, three-element feedwater control concept. Feedwater is kept in step with steam flow with a final correction made from pressure error. This pressure error is equivalent to an error in water level in the traditional drum-type recirculating boiler. The use of pressure error in a high capacity steam generator of this type has been shown to be an excellent index of secondary inventory in the unit.

B&W efforts to obtain detailed information on once-through nuclear steam generators with shell-side boiling are continuing. A 37-tube steam generator, which has been fabricated and erected in the new 12.5 x 10^6 Btu/hr hot water test facility in the Research Center, is presently being tested. Structural characteristics of the 37-tube unit duplicate those of the previously tested 7-tube unit. Tube lengths, diameter, materials, type of baffling have been duplicated. An external mixer and downcomer arrangement is used.

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Figure 4A-5 shows how a 37-tube steam generator compares in shell-side characteristics with other sizes. The plotted curve has the total number of tubes for the abscissa and a ratio representing the number of centrally located tubes to the total number of tubes for the ordinate. In a 7-tube unit, one out of the seven tubes is centrally located, e.g., completely surrounded by adjacent tubes. This ratio is approximately 0.14. A 19-tube unit, which is the number making the next largest uniform pattern of tubes, has seven centrally located tubes. This ratio is approximately 0.37. The 37-tube steam generator has 19 centrally located tubes. This ratio is approximately 0.52. The corresponding ratio for a 15,000-tube central station steam generator is 0.97. This shows that the 37-tube test unit will have shell-side characteristics approaching those of a full-size central station steam generator. Operation of the 37-tube facility will provide additional information on steam generator control optimization. The 7-tube tests demonstrated the capability of the system to operate in either the steam generator-following or turbine-following mode throughout the normal load range. For central station plants there is an additional incentive to apply the integrated master control system. This system is primarily suited to controlling mw generation to a demand signal. Another characteristic of the integrated system is the ability to hold pressure variations to a minimum.

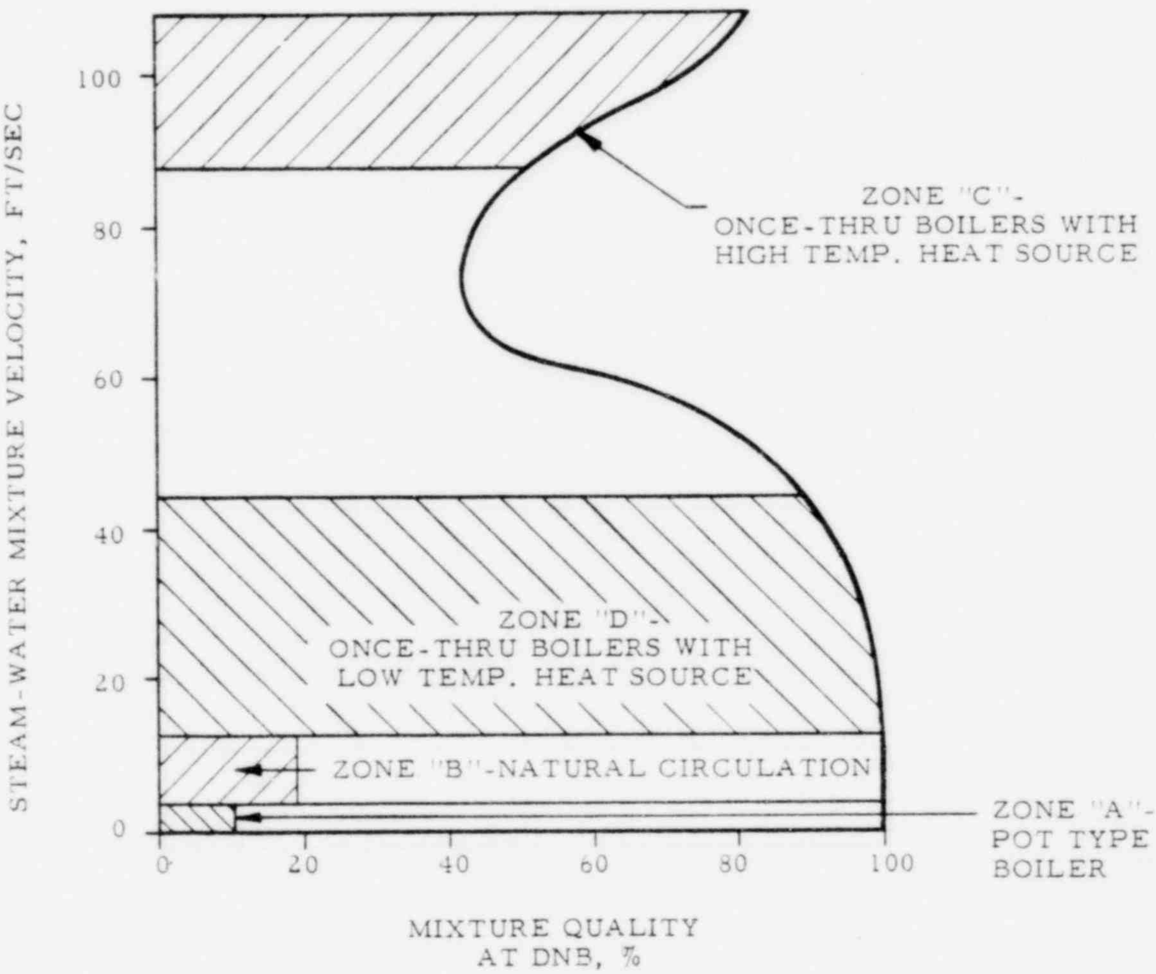
4 CURRENT RESEARCH AND DEVELOPMENT PROGRAMS

4.1 VIBRATION

Analysis of the natural frequency of the tubes of the once-through steam generator has shown that the lowest frequency in the steam generator tube bundle is approximately 33 cps. Experience has shown that natural frequencies of 33 cps or higher have been no problem in service. In addition to the theoretical investigation of the design of the once-through steam generator, it is planned to vibrate the 37-tube model once-through steam generator during the testing program at the Research Center. By imposing mechanical vibrations on the steam generator from an external source, and by varying the frequency of the source of vibration, it will be possible to determine accurately the natural frequency of the tubes and other parts of the steam generator. After completion of the testing program, the steam generator will be destructively examined for evidence of tubes hitting each other or structural parts, and for evidence of wear.

4.2 FEEDWATER SPRAY NOZZLE PROGRAM

The once-through steam generator mixes the incoming feedwater with steam drawn from the steam generator tube bundle to heat the feedwater to approximately saturation temperature before it enters the tube bundle. A test program is underway to develop a feedwater spray arrangement which will provide for atomizing the water to small enough droplets to assure that the feedwater will be at saturation temperature before entering the tube bundle. Testing has begun on a spray nozzle to demonstrate the spray pattern and droplet size. It is planned to investigate the spraying of water both into air and into a steam atmosphere. The length of time or distance required for the subcooled water to be heated nearly to saturation temperature will be determined. A study of the dynamics of the steam and water flow within the tube bundle and feedwater heating annulus is in progress.



STEAM-WATER MIXTURE VELOCITY VERSUS
HEAT TRANSFER DNB

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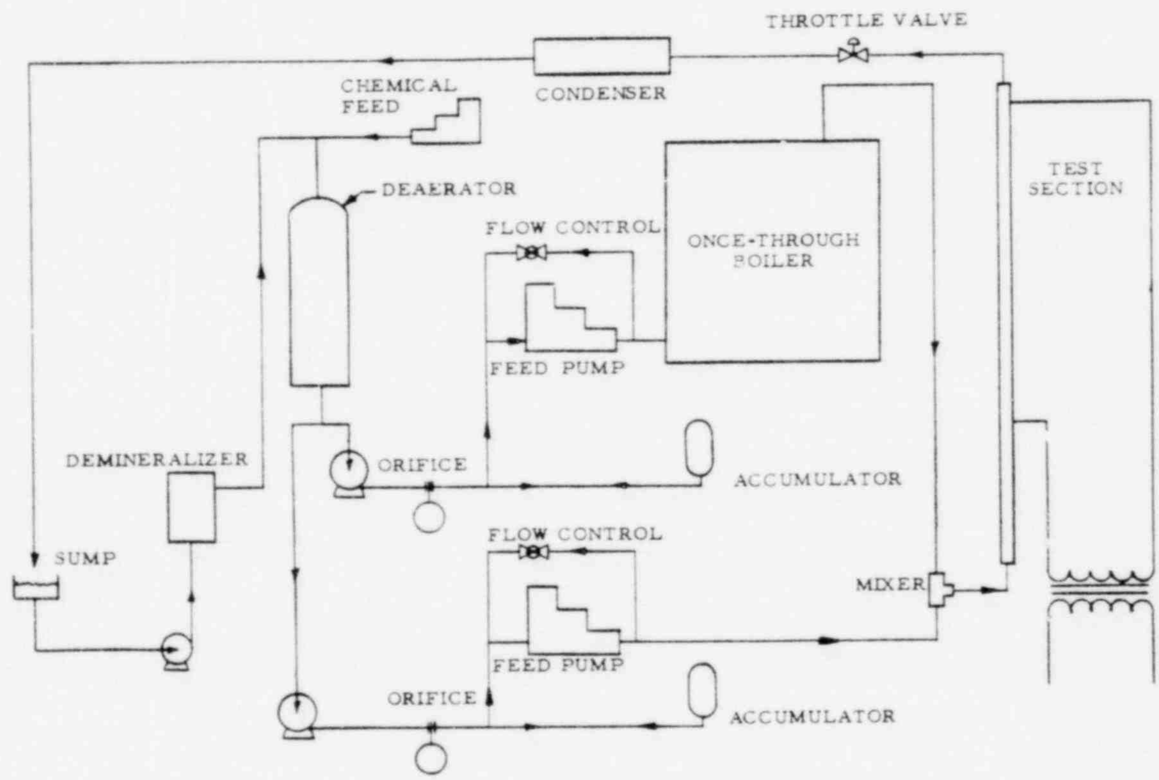
OCONEE NUCLEAR STATION

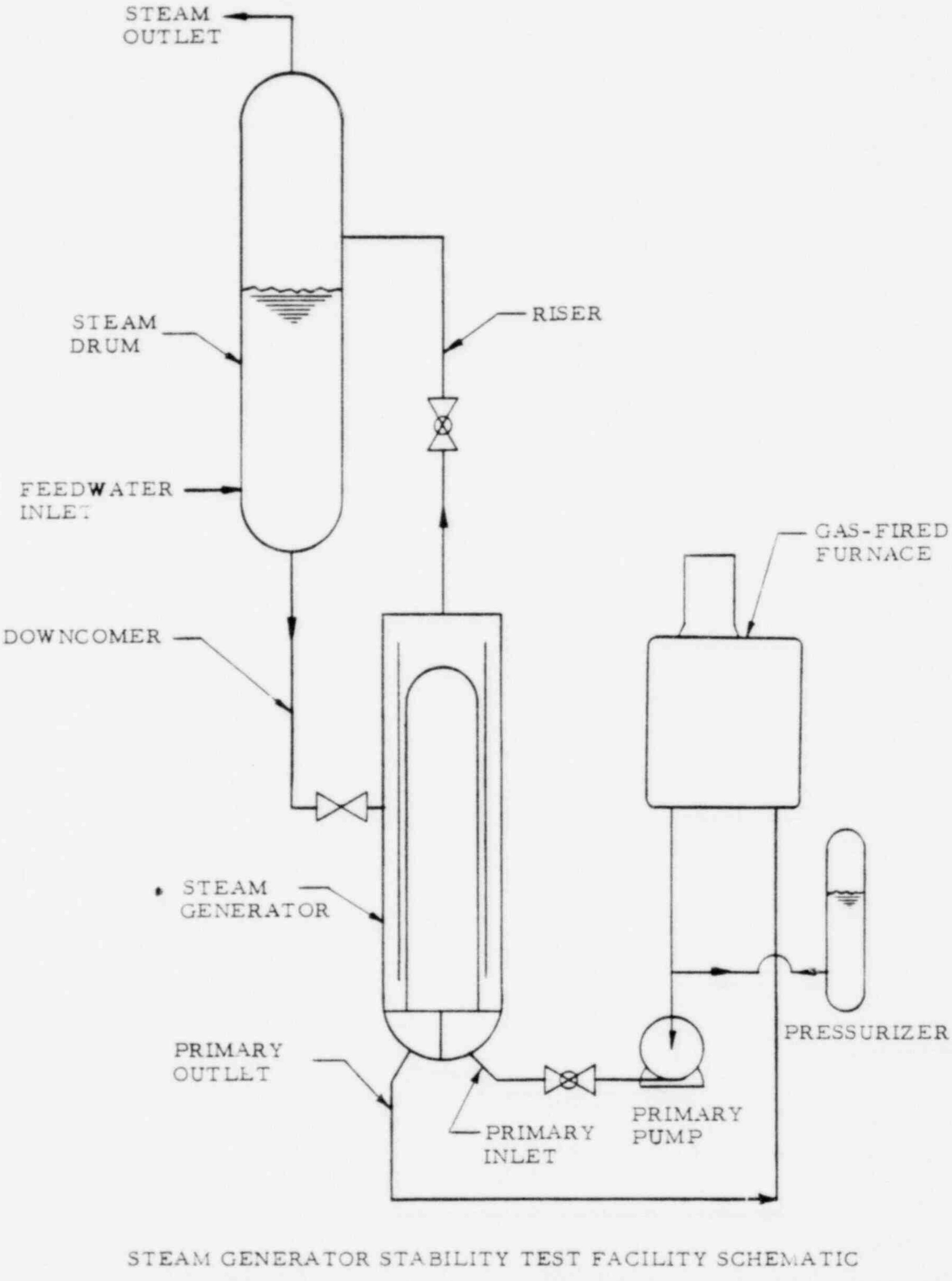
FIGURE 4A-1



HIGH PRESSURE HEAT TRANSFER TEST FACILITY SCHEMATIC

OCONEE NUCLEAR STATION

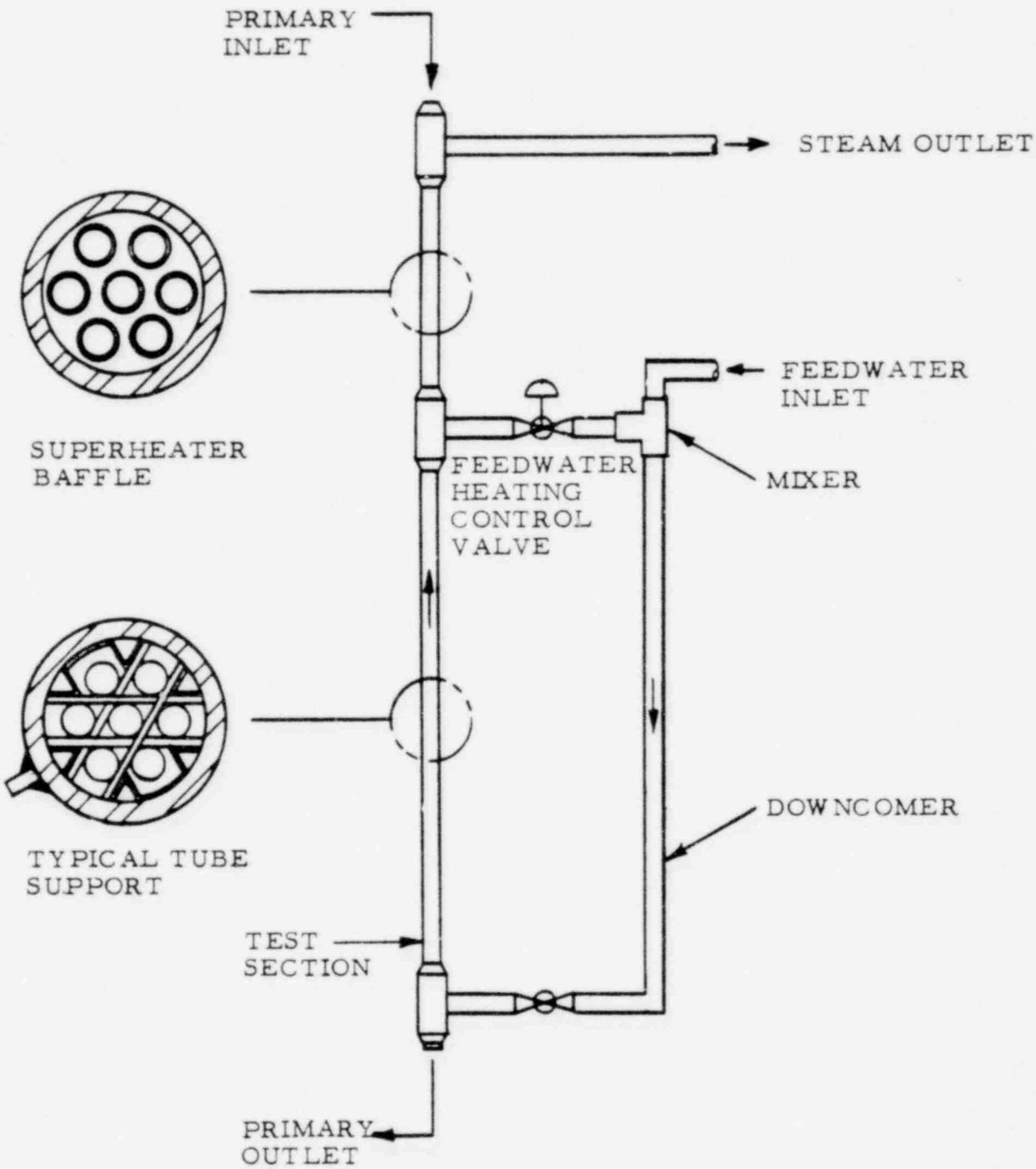
FIGURE 4A-2



STEAM GENERATOR STABILITY TEST FACILITY SCHEMATIC

OCONEE NUCLEAR STATION

FIGURE 4A-3



ONCE-THROUGH STEAM GENERATOR TEST ARRANGEMENT

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FIGURE 4A-4

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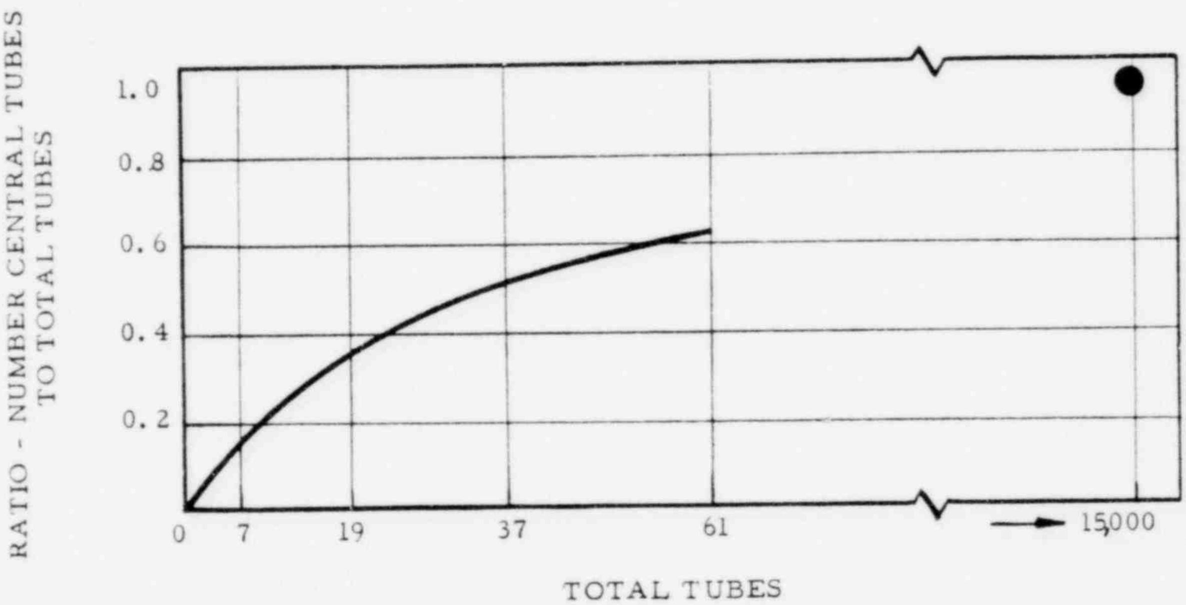

CENTRAL TUBE RATIO VERSUS TOTAL TUBES
RE SHELL-SIDE CHARACTERISTICS OF ONCE-THROUGH
NUCLEAR STEAM GENERATORS

OCONEE NUCLEAR STATION

FIGURE 4A-5