AN EXPERIMENTAL STUDY OF A FLASHING-DRIVEN CANDU MODERATOR COOLING SYSTEM

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ABSTRACT

The results of an experimental study to investigate the feasibility of using a passive flashing-driven natural-circulation loop for CANDU-reactor moderator heat rejection are presented. A scaled loop was constructed and tested at conditions approximating those of a CANDU calandria cooling system. The results showed that stable loop operation was possible at simulated powers approaching normal full power. At lower powers, flow oscillations occurred as the flow in the hot-leg periodically changed from two-phase to single-phase. The results from earlier numerical predictions using the CATHENA thermalhydraulics code showed good qualitative agreement with the experimental results.

INTRODUCTION

CANDU* moderator heat-rejection systems normally use pumps to circulate the heavy water to heat exchangers cooled by pumped service water. However, heat rejection by natural circulation has advantages, and a system to reject the heat passively using a flashing-driven natural-circulation loop is being developed.

An obvious advantage of a natural-circulation system is that the pumps can be eliminated with cost savings and improvements in reliability. Another advantage lies in the role of the moderator as an emergency core-cooling system. Elimination of the need for emergency power supplies would improve the diversity between the two emergency core-cooling systems: the moderator and the emergency coolant-injection system. Postulated severe-accident frequencies, which are dominated by common failures in pumps and their power supplies, can be greatly reduced.

A flashing-driven natural-circulation loop works best if the calandria runs at a temperature near the boiling point. For conventional fuel channels, considerable moderator subcooling is required to avoid dryout on the calandria side of the calandria tube during low-frequency events, when the moderator has to act as a heat sink. However, this requirement can be overcome by optimising the contact conductance when a hot pressure tube distorts into contact with its calandria tube. A calandria tube roughened or ridged on its inside diameter to optimize this conductance is under development [1].

The passive moderator cooling system (PMCS) is part of an integrated emergency heat-rejection concept being developed for CANDU [2]. In an emergency, heat is transferred from the heavy-water to a light-water system,

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*CANDU: CANada Deuterium Uranium. Registered trademark.

which also circulates by natural convection.

In the PMCS design, the moderator is maintained close to saturation at the calandria pressure, and heat is transported from the calandria to an elevated passive heat exchanger in a natural-circulation loop [3]. Under normal operating conditions, heat has to be continuously removed from the moderator. This is done in existing plants by using a forced convection loop. An attractive feature of the PMCS (see Figure 1) is that flashing (vapour generation caused by decreased pressure as the moderator flows upward in the hot-leg) occurs close to the calandria exit. This provides a large driving force, because of the large density difference between the cold-leg subcooled liquid and the hot-leg two-phase mixture. This design feature makes it possible to remove moderator heat under both normal and accident conditions using natural-convection flow. Furthermore, having the moderator temperature close to saturation provides the option of utilizing the moderator heat for feedwater heating, which improves plant efficiency [3].

The main feature of the PMCS design is that vapour is generated by flashing. Because flashing-driven natural circulation at low pressure is not a common mode of operation in existing systems, it has not been experimentally investigated. Preliminary simulations using the CATHENA [4] code have shown that a flashing-driven natural-circulation loop can be used to remove normal moderator heat without any flow instabilities [3]. The tests described in this paper investigated the feasibility of the flashing-driven natural-circulation concept at experimental conditions that simulated those of a CANDU calandria, specifically the CANDU-3 calandria.

SCALING OF THE EXPERIMENTAL LOOP

Because of the large moderator heat load (≈ 66.4 MW for CANDU-3), a scaled model of the design reported in [3] was constructed. A full-height scaling methodology [5] was used, in which the loop height was preserved and the volume reduced by a factor of 60. The only exception to the factor of 60 scaling was the calandria, which was scaled by a factor of 600.

CATHENA PRE-TEST SIMULATION OF THE SCALED EXPERIMENTAL LOOP

CATHENA simulations of the scaled experimental loop were performed to help develop an experimental run plan. The loop parameters (flow resistance coefficients and heat transfer coefficients) were estimated using handbook correlations. The results of the simulations showed that for a given calandria inlet temperature the loop is unstable at lower powers, but becomes stable at higher powers. A sample simulation is shown in Figure 2, where power was increased from 150 kW to 400 kW. The initial conditions prior to the power increases were as follows:

power = 150 kW
flowrate = 1.74 kg/s (single-phase natural circulation)
calandria inlet temperature = 75.6°C
calandria outlet temperature = 96.1°C

Figure 3 shows the CATHENA void fraction prediction at the top of the hot-leg for this simulation. It shows that for powers up to 250 kW, there is a periodic change from two-phase to single-phase flow in the hot-leg, as evidenced by the periodic zero void fractions. The flowrate at these powers is characterized by large amplitude oscillations, as shown in Figure 2. As the power increases to 350 kW, the flow begins to stabilize (flowrate amplitude becomes smaller) and the two-phase region in the hot-leg does not disappear, as Figures 2 and 3 show at approximately 1500 s. As the power increases to 400 kW, the flow becomes stable, as Figures 2 and 3 show at approximately 1900 s.

EXPERIMENTAL APPARATUS AND PROCEDURE

Loop Description

Figure 4 shows a schematic of the scaled loop. The calandria was simulated using a cylinder with four electrically heated bundles. Each bundle consisted of 49 heaters, providing a total heated surface area of 4.03 m^2. The bundles were arranged so that a total power of up to 1.2 MW could be generated in the simulated calandria. To allow visualization of the flashing flow, the 8.54-m-long hot-leg was constructed using glass piping with a nominal inner diameter of 10 cm. The hot-leg was connected to an accumulator tank. A condenser (operating at atmospheric pressure) was incorporated into the top of the tank, as shown in Figure 4. The bottom of the tank was connected to a plate heat exchanger, which was then connected to the cold-leg. The cold-leg was constructed using stainless-steel piping with an inner diameter of 7.4 cm. A turbine flowmeter and a valve (to vary cold-leg flow resistance) were incorporated into the cold-leg.

Instrumentation

The measurements consisted of total calandria power, flowrate into the calandria, average void (7.92 m from the calandria exit), and temperatures and pressure drops at various locations (see Figure 4). The flowrate was measured using a turbine flowmeter with a range of 1.8 to 36.5 kg/s. The average void was measured using a gamma-densitometer system with a fanned beam operating in the current mode [6]. Temperature and pressure drop measurements were also obtained at various locations (see Figure 4), to help interpret any oscillatory data.

Procedure

The water in the loop was first heated and degassed for about three hours before testing. At the end of the heating and degassing period, the water temperature in the whole loop was very close to saturation at the condenser pressure (≈100°C). Because pre-test CATHENA simulations showed that loop instabilities would be encountered in the early stages of the test as the power was increased, the tests comprised of two parts: low-power and high-power tests. The low-power tests were conducted using the condenser only (the heat exchanger was not used). The inlet temperature to the calandria in the low-power tests was close to 100°C (saturation temperature at the condenser pressure). At this high calandria inlet temperature, we were able to investigate the validity of the flashing-driven natural-circulation concept with minimum heat input. The high-power tests were conducted after the low-power tests, to approximate the full-power conditions in the CANDU-3 calandria (1.1 MW for the scaled loop).

In all tests, the basic run procedure was to increase the power until flashing was observed in the glass pipe, which simulated the hot-leg. An experimental constraint was that the calandria outlet temperature was not to exceed the saturation temperature at the calandria pressure (approximately 117°C). This constraint was met by manipulating the power (low-power tests) and the power and heat exchanger cooling (high-power tests).

EXPERIMENTAL RESULTS

Low-Power Tests

Figure 5 shows the power and flowrate time histories for the low-power tests. Figures 6 and 7 show the calandria inlet and outlet temperatures and the void fraction for the same time period. At powers up to 200 kW, the flow oscillation amplitude is large, as shown in Figure 5. Visual observations at these powers indicated periodic change from two-phase to single-phase flow in the glass hot-leg. This is consistent with the void measurements shown in Figure 7, where the void fraction drops to zero periodically at powers up to 200 kW. At powers above 200 kW, two-phase flow occurred at all times in the hot-leg and the flow began to stabilize. Stable flow was finally achieved at 350 kW and higher powers (see Figure 5), with flashing occurring in the top half of the hot-leg. The residual fluctuations in flow at these powers are believed to be caused by subcooled boiling in the calandria, as void bubbles were clearly seen collapsing in the subcooled water above the calandria outlet. Subcooled void existed in the calandria because of its reduced size (and consequently reduced heater surface area), which was ten times smaller than the exact scaling value. In the actual CANDU calandria, subcooled boiling would not be expected to occur.

As a check on the stability of the loop, two transients were performed: 1) fast power increase from 0 to 400 kW, and 2) partial valve closure in the cold leg. The purpose of these transients was to determine whether the loop conditions would be restored following a significant amount of perturbation in the loop conditions. Figure 8 shows the results of the fast power increase transient. In this test, power was reduced to zero from the 400 kW steady operating point shown in Figure 5. After the two-phase flow disappeared from the hot-leg, but with a small residual single-phase flow caused by the density difference between the cold-leg and hot-leg, the power was increased to 400 kW over a period of approximately 30 seconds. The calandria outlet temperature increased until flashing occurred in the hot-leg and the flow increased significantly, as shown in Figure 8. The flow then quickly stabilized to the 400 kW steady-operation conditions. Figure 9 shows the partial valve closure transient results. Starting with steady flow at 400 kW, the valve located close to the calandria inlet (see Figure 4) was partially closed and then opened, to cause a perturbation in flow. As Figure 9 shows (starting at time ≈ 15700 s), the flow initially decreased and then increased when the valve was opened, and then quickly stabilized to the original steady operation at 400 kW in approximately 50 seconds. Theses transient tests showed that a unique stable operation was obtained at these conditions.

High-Power Tests

In the high-power tests, the calandria inlet temperature was decreased (by manipulating the heat exchanger secondary-side flow) and the power increased to 1000 kW. Figure 10 shows the calandria inlet temperature reduction, which was accompanied by the power increase. Figure 11 shows relatively stable loop flow at 900 and 1000 kW, with increased noise because of increased subcooled boiling in the calandria (increasing subcooled void was clearly seen exiting the calandria as the power was increased). No attempts were made to increase the power because of the increasing amount of subcooled void in the calandria, as we felt that 1000 kW was close enough to the target power of 1100 kW, which simulated the CANDU-3 moderator heat load. Again, the subcooled boiling in the calandria was caused by the significantly reduced size of the scaled calandria, and should not occur in an actual CANDU calandria.

DISCUSSION

The above results show that a low-pressure, flashing-driven natural-circulation loop operates in a stable manner at conditions approximating those of a CANDU-3 calandria. The results of the test agree qualitatively with earlier CATHENA predictions, based on approximate loop parameters. A more detailed comparison between the CATHENA predictions (Figures 2 and 3) and the experimental results was not made at this stage, because the CATHENA predictions were based on approximate loop parameters. However, the behaviour of the loop at lower powers (unstable flow) and higher powers (stable flow) was very well predicted by CATHENA. Refined CATHENA analyses are planned after accurate loop parameters are obtained from future tests.

At lower powers, the periodic change from single-phase to two-phase flow in the hot-leg causes large-amplitude flow oscillations, as shown by the CATHENA predictions (Figures 2 and 3) and test results (Figures 5 and 7). As the power increases, the two-phase region is maintained and the flow begins to stabilize.

While most of the loop components were closely scaled to simulate a CANDU-3 natural circulation loop, the calandria was undersized by a factor of 10. This resulted in a smaller heated surface area, and the heat flux was therefore much larger than would be expected in an actual CANDU calandria. The increased heat flux caused subcooled boiling in the experimental simulations, which may have caused residual fluctuations in the flowrate.

Subcooled boiling is not expected in an actual CANDU calandria because the heat flux is significantly smaller.

CONCLUSIONS

The tests reported in this paper have demonstrated that a flashing-driven natural-circulation concept is feasible and can be used to remove moderator heat at conditions approximating those of a CANDU reactor. Stable operation was obtained at a range of 350 to 1000 kW, which approaches full power in CANDU-3 and would scale to approximately full power in any CANDU reactor. At powers less than 350 kW, flow oscillations were obtained. The experimental results showed good qualitative agreement with earlier CATHENA predictions.

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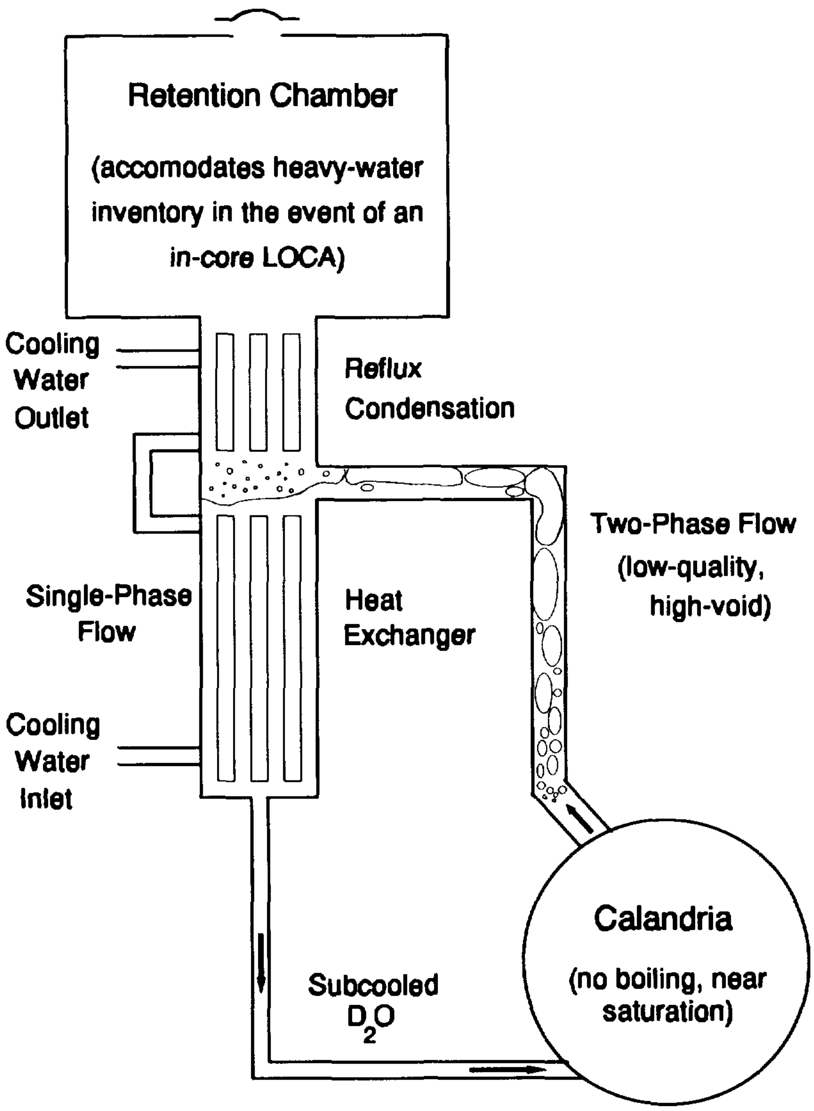

FIGURE 1 FLASHING-DRIVEN PMCS CONCEPT

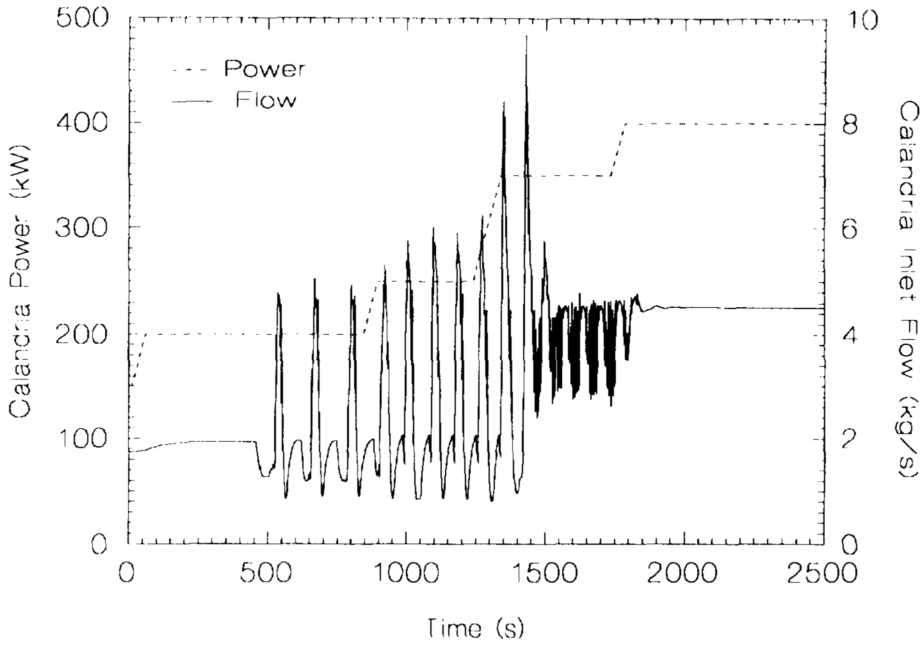

FIGURE 2 POWER AND FLOW TIME HISTORIES (CATHENA PREDICTIONS)

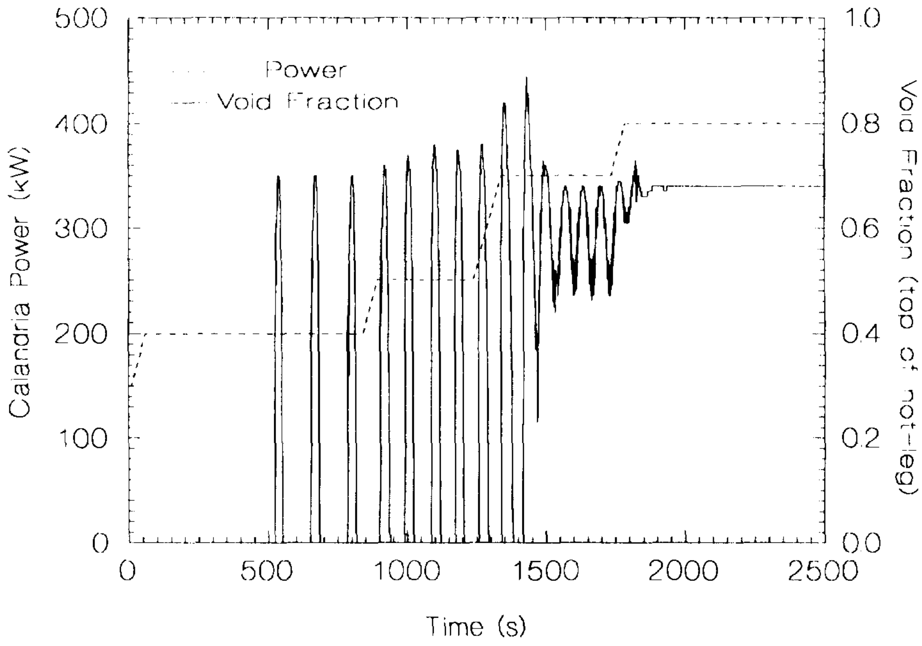

FIGURE 3 POWER AND VOID TIME HISTORIES (CATHENA PREDICTIONS)

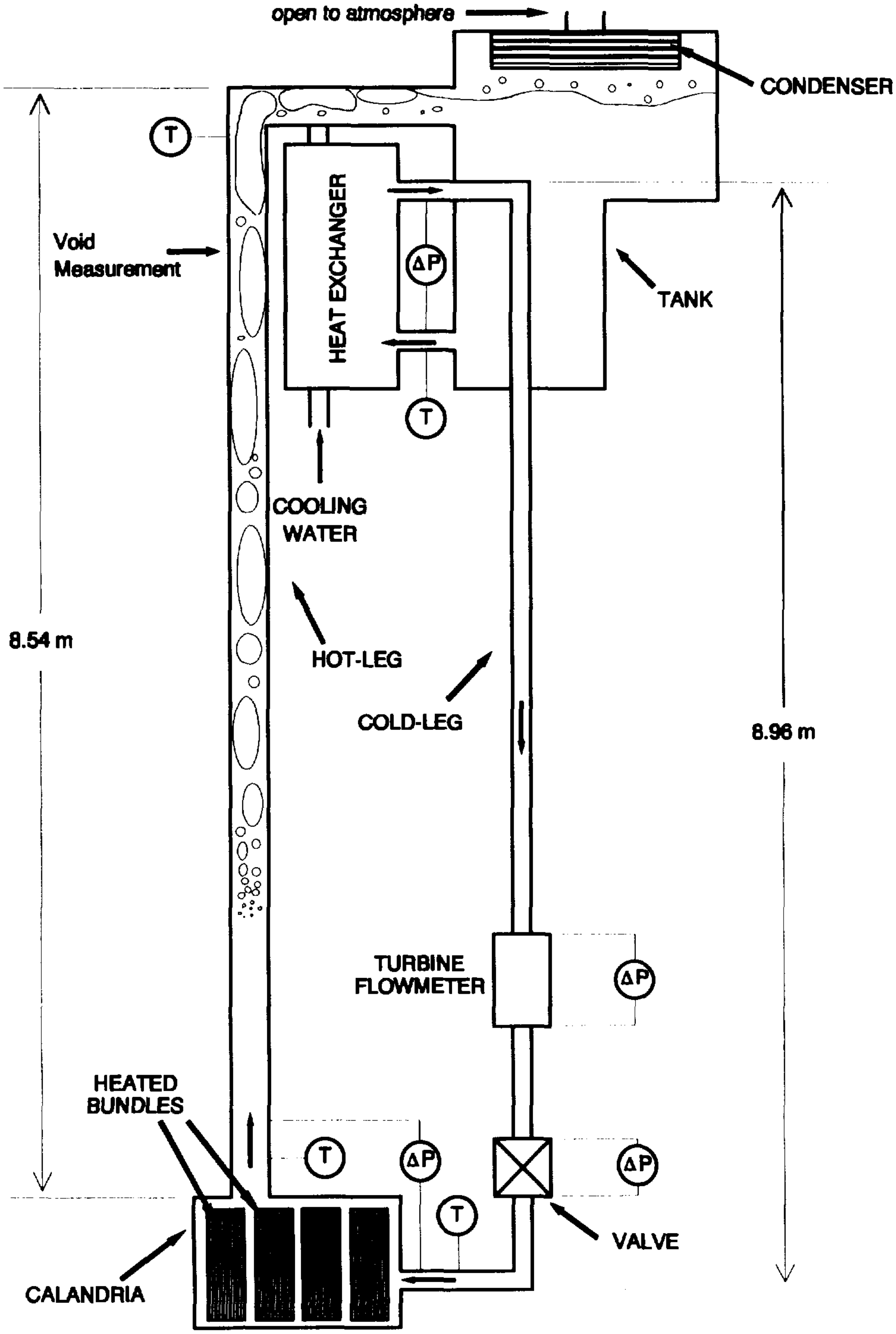

FIGURE 4 SCHEMATIC OF TEST LOOP

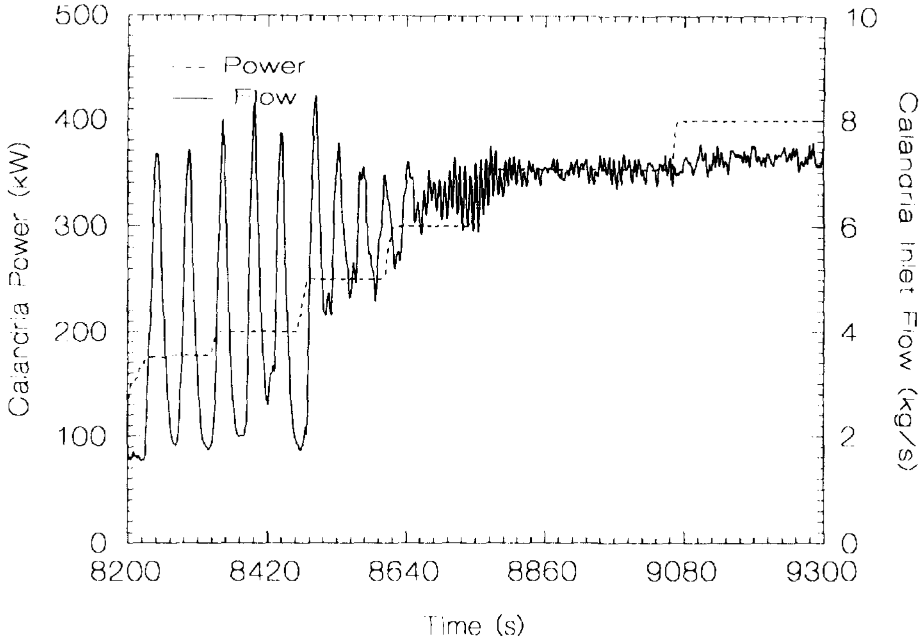

FIGURE 5 LOW-POWER TEST POWER AND FLOWRATE TIME HISTORIES

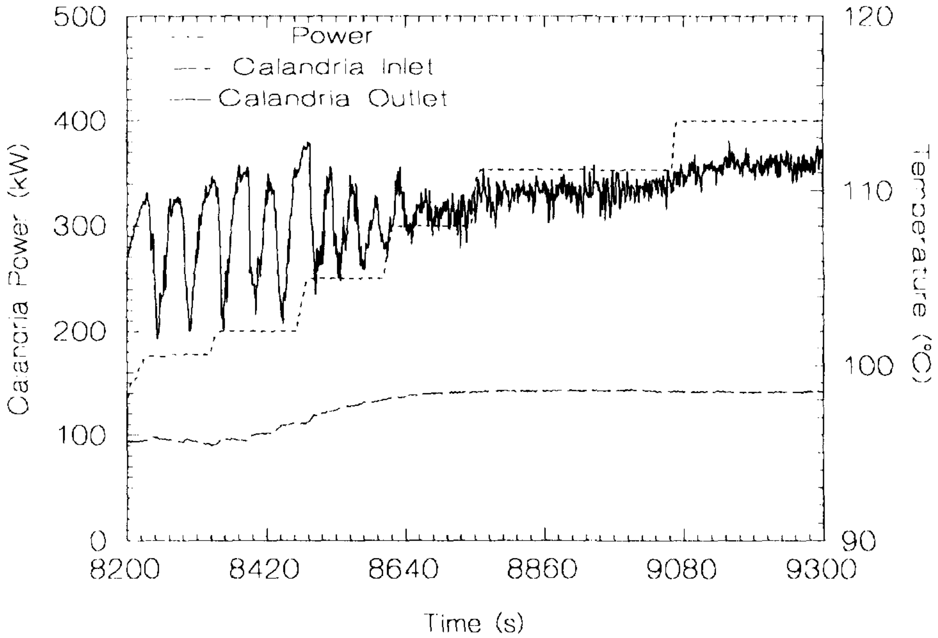

FIGURE 6 LOW-POWER TEST POWER AND TEMPERATURE TIME HISTORIES

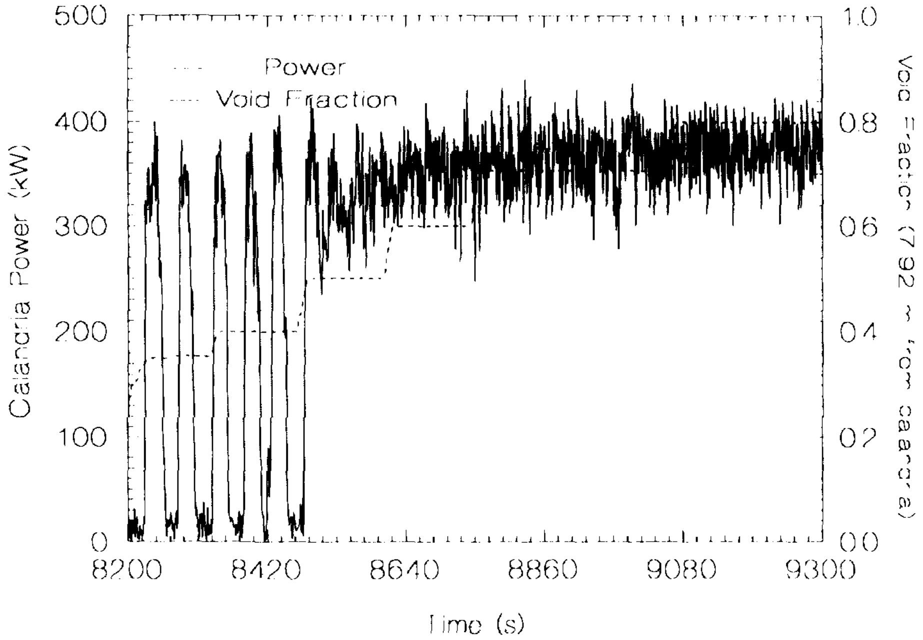

FIGURE 7 LOW-POWER TEST POWER AND VOID FRACTION TIME HISTORIES

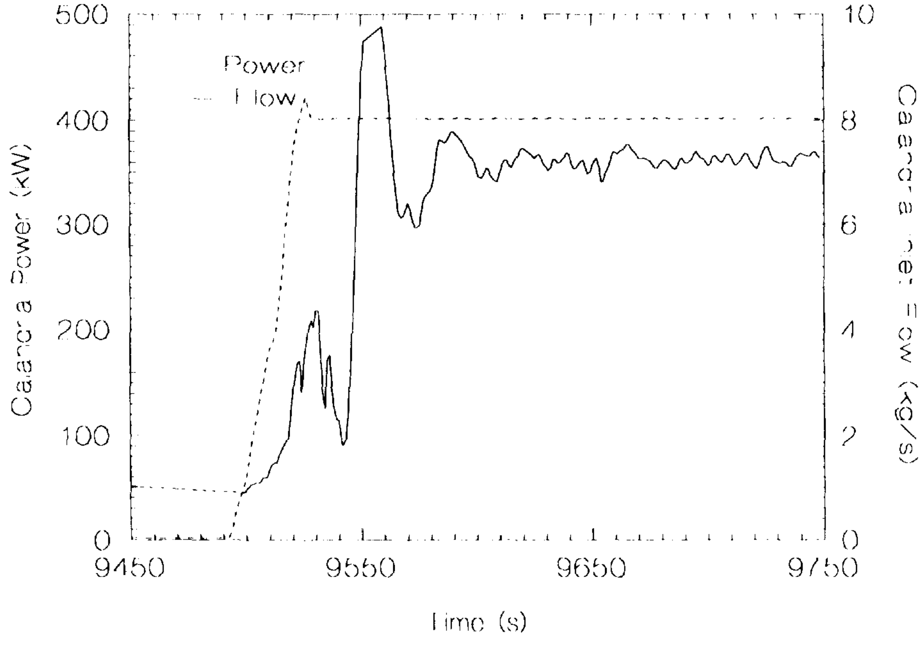

FIGURE 8 LOW-POWER TEST FAST POWER INCREASE TRANSIENT

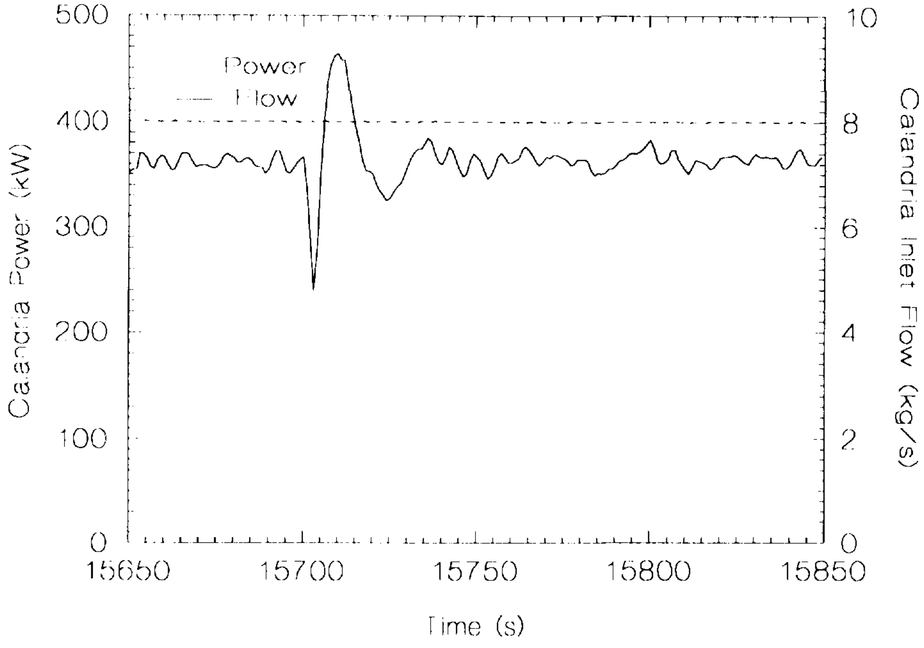

FIGURE 9 LOW-POWER TEST PARTIAL VALVE CLOSURE TRANSIENT

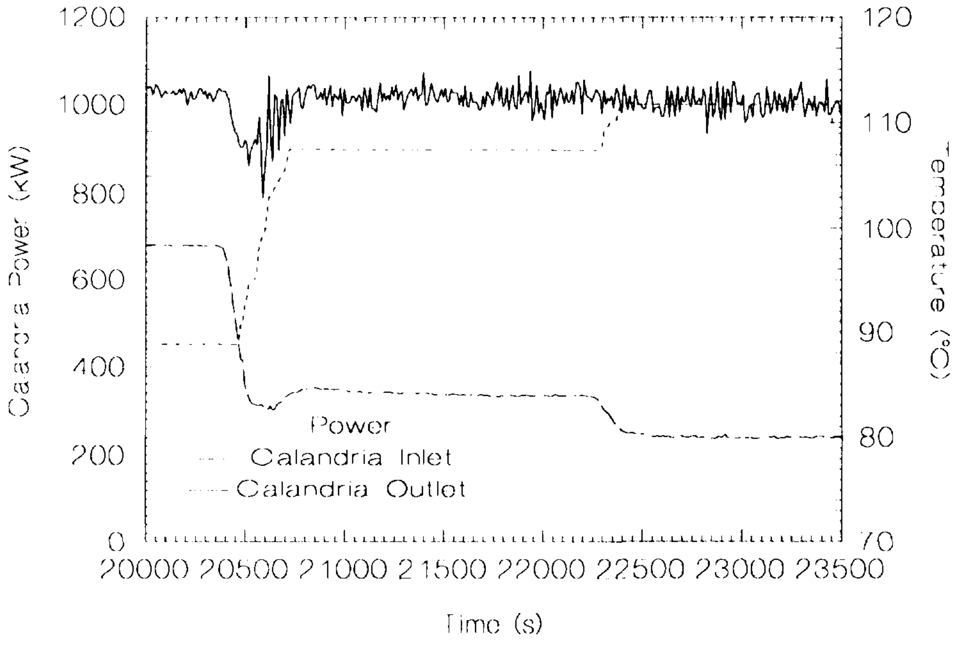

FIGURE 10 HIGH-POWER TEST POWER AND TEMPERATURE TIME HISTORIES

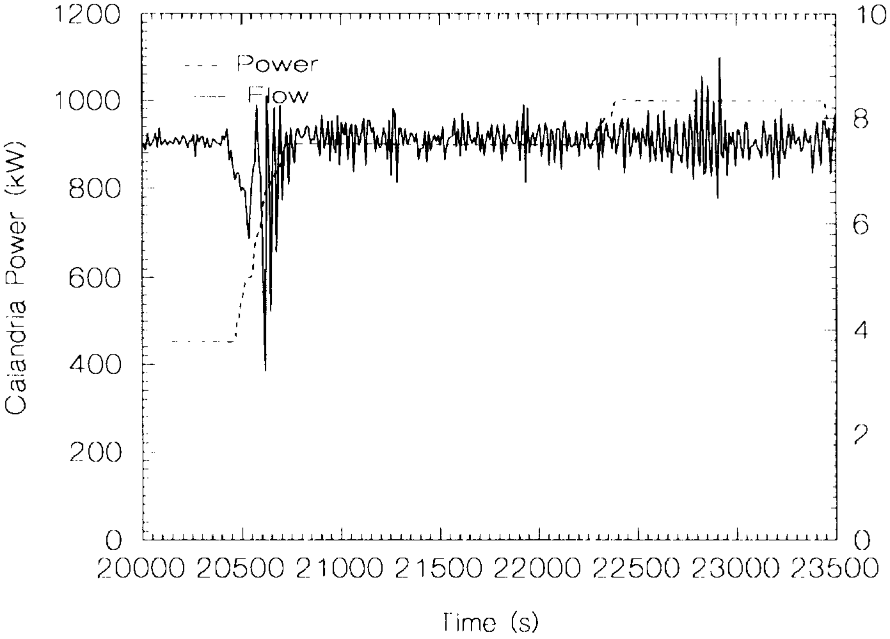

FIGURE 11 HIGH-POWER TEST POWER AND FLOWRATE TIME HISTORIES