IAEA-SR-218/98

BYPASS LINES TO REDUCE REACTOR COOLING-DOWN RATE DURING NATURAL CIRCULATION EMERGENCY CORE COOLING

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Abstract

This paper describes the main characteristics of a Natural Circulation Loop (NCL) and presents the first results of temperature and flow distribution when bypass lines that connect the cold source outlet with the hot source outlet are opened. The NCL was designed to study the hot-leg temperature effects caused by the opening of bypass lines connecting different hot-leg vertical positions. NCL is a thermal-hydraulic loop with a vertical electric heater and an immersion heat exchanger similar to those of advanced nuclear reactors. The heat exchanger outlet flow is measured with a magnetic flow meter. The bypass line flow is estimated through heat balance calculations. The first result, presented in this paper, shows that the flow direction in the bypass line is from the cold leg to the hot leg when the lower bypass line is opened and is in the opposite direction when the higher bypass line is opened. The paper also shows that the bypass line flow in the cold- to hot-leg direction is almost 10% of the total flow, which is enough to produce a substantial rise in the heater outlet temperature. This process can be used to reduce the cooling-down rate during natural circulation emergency core cooling, permitting a faster reactor restart.

Keywords: natural circulation, advanced reactors, thermal-hydraulics.

1. INTRODUCTION

Advanced nuclear power plant concepts cover different types of designs. The Advanced PWR is an interesting concept that uses natural circulation to remove the core residual heat. The emergency core cooling system is the system that achieves this residual heat removal. It is well known how necessary it is to build and operate a prototype or demonstration plant to bring a concept with much innovation to commercial maturity. It is also evident that there is the opportunity of introducing innovative features that require few development efforts but can produce substantial positive effects. These types of improvement need research, engineering and confirmatory testing before their use in a given plant.

Passive emergency core cooling systems of advanced PWR produces variable cooling-down rates depending on the residual heat rate. Occasionally, in the beginning of the cooling down process, when the residual heat decays substantially, reducing this cooling rate to restart the reactor in less time would be interesting.

In 1998 IPEN started a research project to study the effects of bypass lines in the hot-leg temperature of a system when operating in natural circulation. A Natural Circulation Loop (NCL) [1,2,3,4] was conceived and built for this purpose. In this thermal hydraulic loop the bypass lines connect the cold source outlet with the hot source outlet. Depending on the bypass to hot-leg vertical position connection, the bypass line flow can be either from the cold leg to the hot-leg or from the hot-leg to the cold leg. If the Main Bypass line flow follows the cold-to-hot direction, the net flow through the heater will be smaller. The heat exchanger flow will be the sum of the heater flow with the bypass line flow. The heater outlet temperature will be higher compared with the temperature without bypass flow.

This paper consists of four sections. The first section is this introduction. The second section describes the main characteristics of NCL. The third section describes the experiments and shows the first results of the temperature and flow distribution when the bypass lines that connect the cold source outlet with the hot source outlet are opened. The fourth section presents the conclusions and discusses future works.

2. NATURAL CIRCULATION LOOP DESCRIPTION

Fig. 1 presents a schematic layout of the Natural Circulation Loop (NCL) which resembles an Advanced Pressurized Water Reactor Decay Heat Removal System. The NCL has an electric heater that it is the hot source of the system, and a heat exchanger, that is the heat sink. Cold water coming from an elevated water reservoir is supplied to the water tank by gravity. The NCL has a water circulating pump installed to allow specific operations for calibration and measurement of the hydraulic characteristics of the system. A magnetic type flow meter is installed in the main circuit line. The magnetic flow meter was chosen to measure water flow rates below 0.1 kg/s, without flow interference. A globe valve controls the secondary cooling water flow with the aid of a variable area flow meter. As NCL was designed to study the hot-leg temperature effects caused by the opening of bypass lines connected in different hot-leg vertical positions, it was provided with a main bypass line with a motor operated valve (bypass valve). This main bypass line is connected with the hot-leg in two different positions: a High bypass connection and a Low bypass connection. The main NCL circuit pipe consists of copper with 22 mm O. D. and 0.6 mm thickness. All connections are welded and the main components are fitted with 3/4 in threaded connections.

To avoid unnecessary loss of head, the valves in the main loop lines are ball type. Fig. 1 shows the 24 thermocouples distributed in the experimental loop. There are nineteen 0.5 mm K Type thermocouples and five 1.5 mm T Type thermocouples.

The electric heater has three "U" type electrically heated elements of stainless steel clad and a non heated central rod, making a hexagonal array with a heat transfer area of 0.474255 m^2. The heating elements are of 14.8 mm in diameter and 1.7 m in length. The shell diameter is 2 ½ inches. The heater design power is 10 kW but its maximum operating power was limited to 3.3 kW in the natural circulation tests. A specially designed rectifier receives a 0-10 DCV control signal from any kind of external font and controls the electric power. The power control signal, flow meter signal and thermocouples' signals are connected to a AT-MIO-16E National Instruments Data Acquisition Board [5] installed in an Intel Pentium type P.C. (Fig. 2). The 26 signals are multiplexed and registered in intervals of 16 seconds of the data acquisition period.

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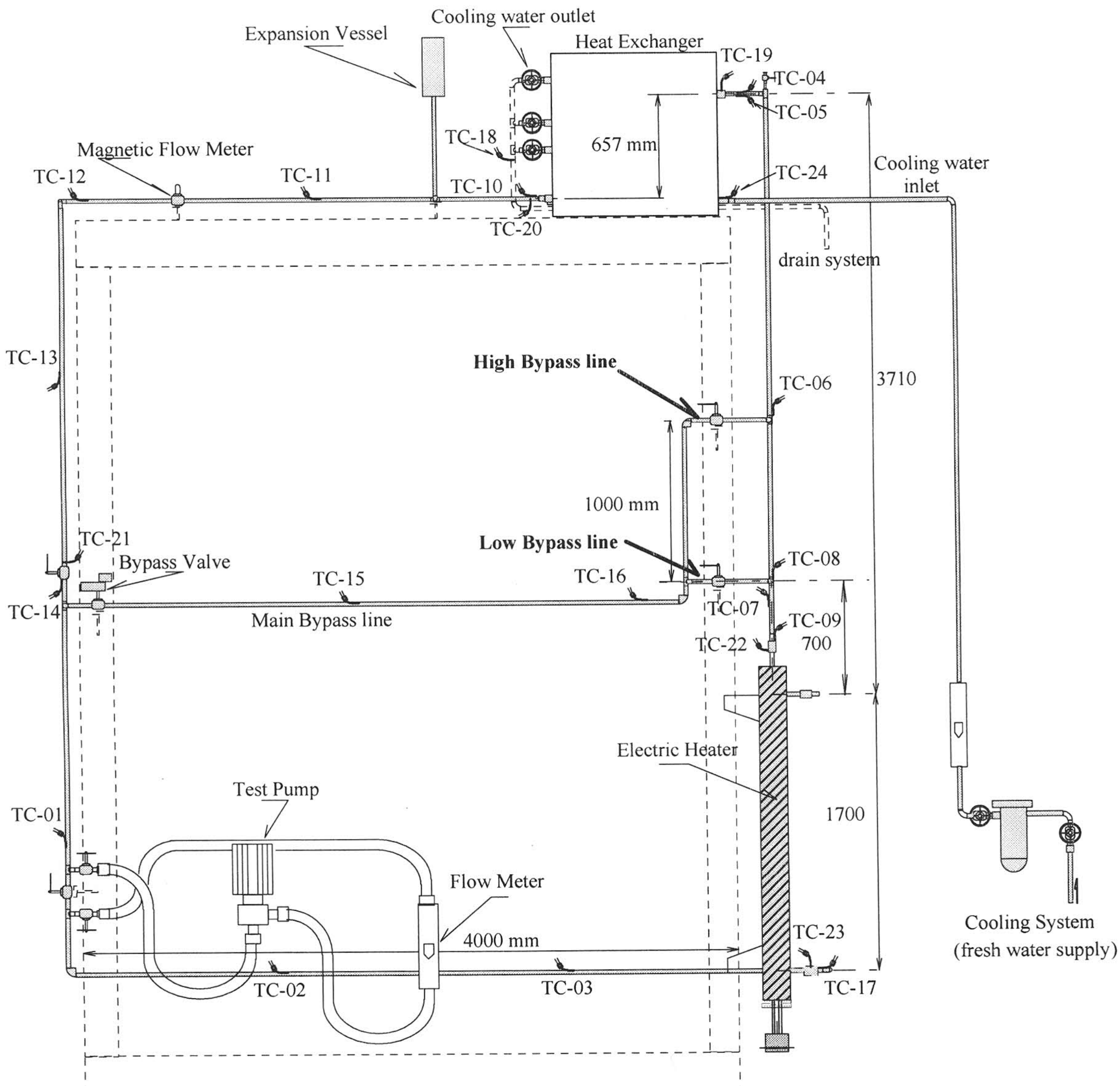

FIG.1. Natural Circulation Loop layout.

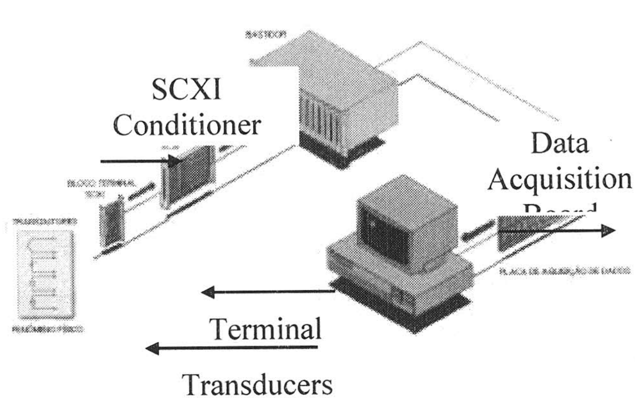

FIG. 2. Data Acquisition System.

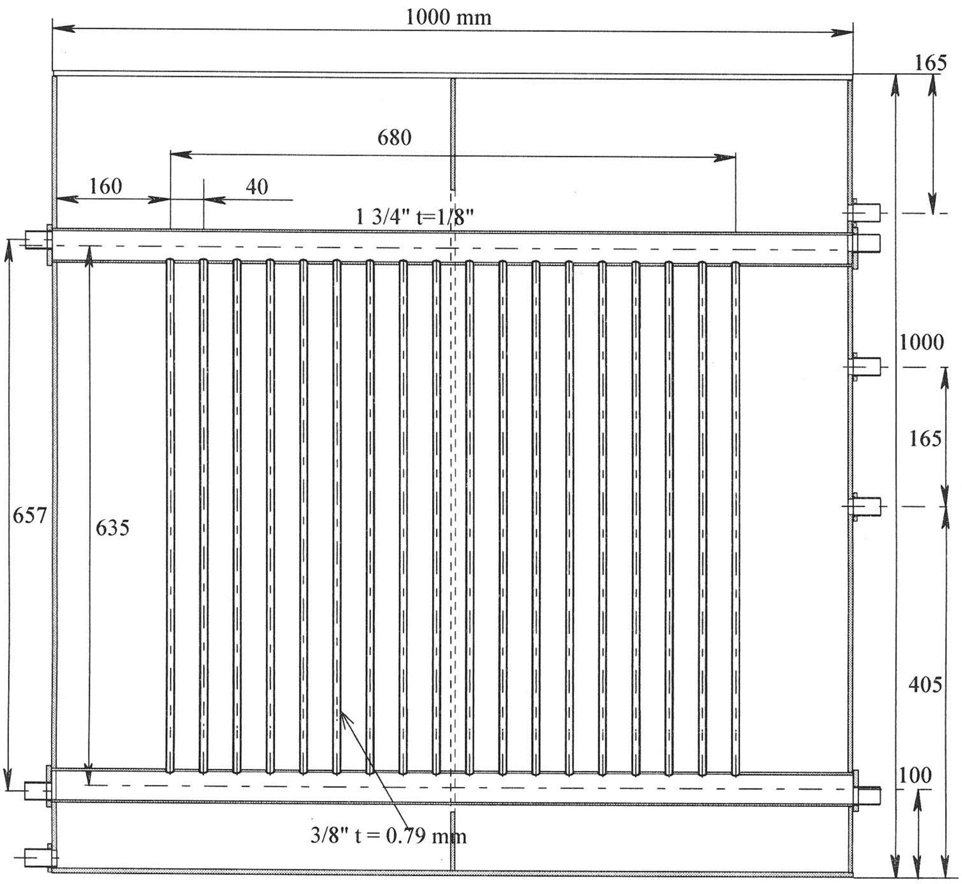

FIG. 3. Heat Exchanger Cross Section.

The heat exchanger (Fig. 3) is a reservoir of 0.202 m^3, rectangular, and made of copper. It has two 1.75 inches in diameter headers and eighteen 3/8 inch vertical tubes. The total heat transfer area, based on the external diameters is 0.621 m^2. The heat exchanger was designed based on naval and on AP-600 designs [6].

3. NATURAL CIRCULATION EXPERIMENTS

This section describes the first set of experiments with the bypass lines opening. In the first one of these experiments, the low bypass line was opened twenty-two minutes after the start of power operation. The second experiment followed the first one by the closure of the low bypass line and with the high bypass line opening. The results of the first experiment are compared with another experiment with the external loop steady state operation without bypass flow. To allow this comparison the results were superposed in the time scale. The second experiment initial time was set immediately after the end of the first one.

The data acquisition during the first experiment was initiated a few minutes before the heater was on in a partial power of 1250 W. After twenty-two minutes the bypass line was opened. Ten minutes later the power was increased to ≈ 2300 W. The electric power and mass flow rates registered are shown in Fig. 4. The heat exchanger mass flow rate was measured with the magnetic flow meter. The heater and bypass line mass flow rates were estimated through mass and heat balance as explained through Fig.5 and equations below:

$$m_{Ht}h_{Ht} + m_{Bp}h_{Bp} = m_{HE}h_{HE} \quad (1)$$

$$m_{Ht} + m_{Bp} = m_{HE} \quad (2)$$

where m_{Ht} is the heater mass flow rate, m_{Bp} the bypass line flow rate, m_{HE} the heat exchanger mass flow rate, h_{Ht} is the heater outlet enthalpy, h_{Bp} is the bypass line enthalpy and, h_{HE} is the heat-exchanger inlet enthalpy.

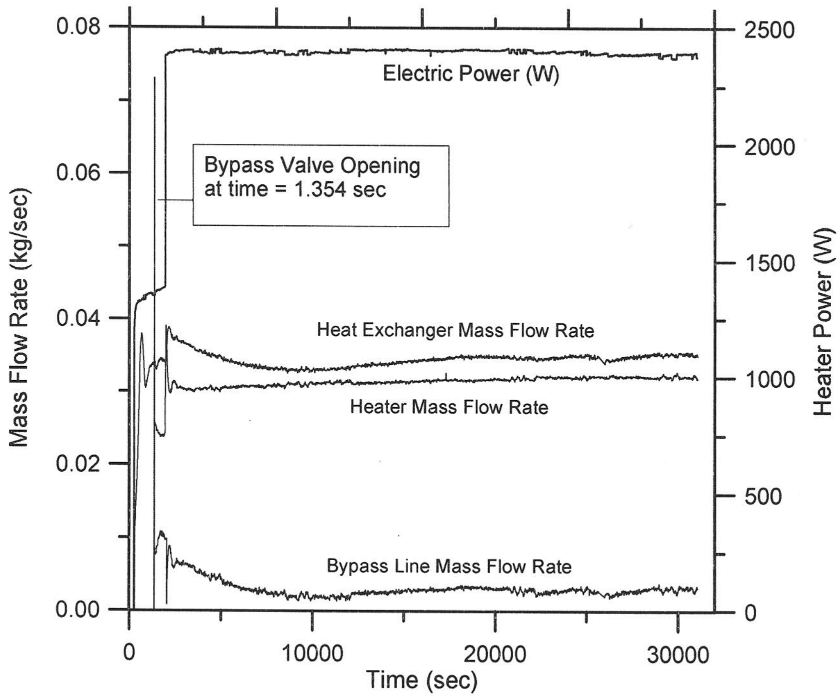

FIG. 4. Heater Power and Mass Flow Rates - First Experiment.

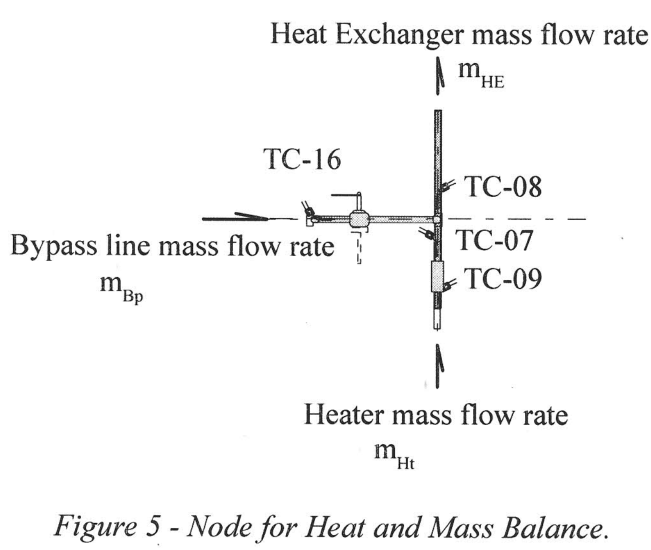

Figure 5 - Node for Heat and Mass Balance.

Due to the natural circulation processes characteristic of the NCL loop, the temperature and mass flow rates changes are very slow, then the errors associated with heat and mass balances due to the transient conditions are small. Because of this one can assume that the bypass mass flow rate estimate will be close to the real one. Fig. 6 shows the bypass mass flow rate of Fig. 4 as a percentage of the total flow, the heat exchanger mass flow rate. It can be observed that, as the initial bypass line temperature is small, the initial bypass flow grows quickly to 30% of total flow, then falls to approximately 10%. This low fraction of mass flow is enough to produce a 15-degree C temperature rise in the heater outlet as can be seen in Fig. 7, where the temperature result of this transient is superposed to the results of an equivalent transient without the bypass line opening. The power-step amplitude and timing in the two experiments were not the same but the steady state power was the same. In the experiment one, the bypass line was opened 1354 seconds after the start of data recording causing a perturbation in the outlet heater temperature.

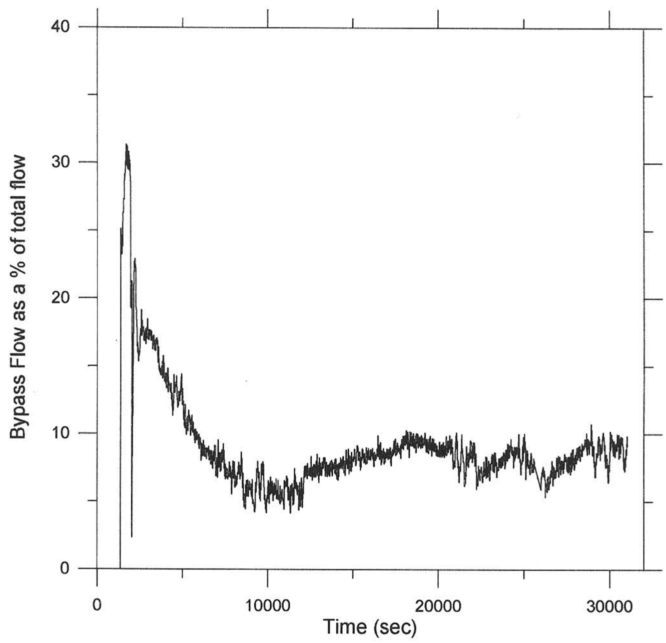

FIG. 6. Bypass Flow Rate as a Percentage of Heat Exchanger Mass Flow.

The second experiment was in sequence of the first one and lasted 14:46 hours. Fig. 8 shows the electric power and mass flow rates registered during this time. In this experiment the high bypass line was opened at time = 250 seconds. Because this experiment followed the first one, the temperature rapidly reached the steady state condition, but the experimental setup was kept in operation to observe the NCL power and water supply stability, this can be observed in the heat exchanger temperatures of Fig. 9. Fig. 8 shows that the total flow rate is through the heater instead of the heat exchanger. Now the bypass line flow rate is stipulated to be negative. Fig. 9 shows that the experiment was very stable. The first hour of this experiment bounds the greatest changes in flow and temperatures. Fig. 10 shows the temperature behavior around the bypass line and Fig. 11 shows the bypass percentage of mass flow rate, which reaches a mean value of 18% in the first hour. The most important observation in this experiment was that, as the heater mass flow rate was almost not affected by the bypass opening, the heater outlet temperature did not change. The heat exchanger outlet temperature had changed but the heater inlet temperature was compensated with the bypass water mixture. Here the main component affected was the heat exchanger.

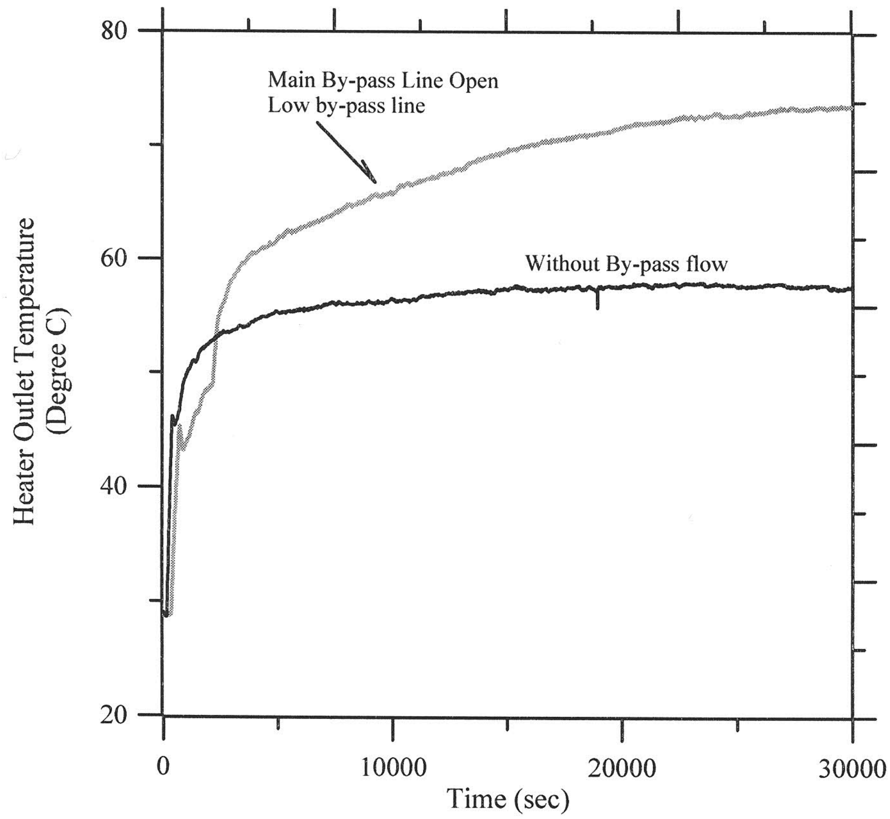

FIG. 7. Heater Outlet Temperature Results.

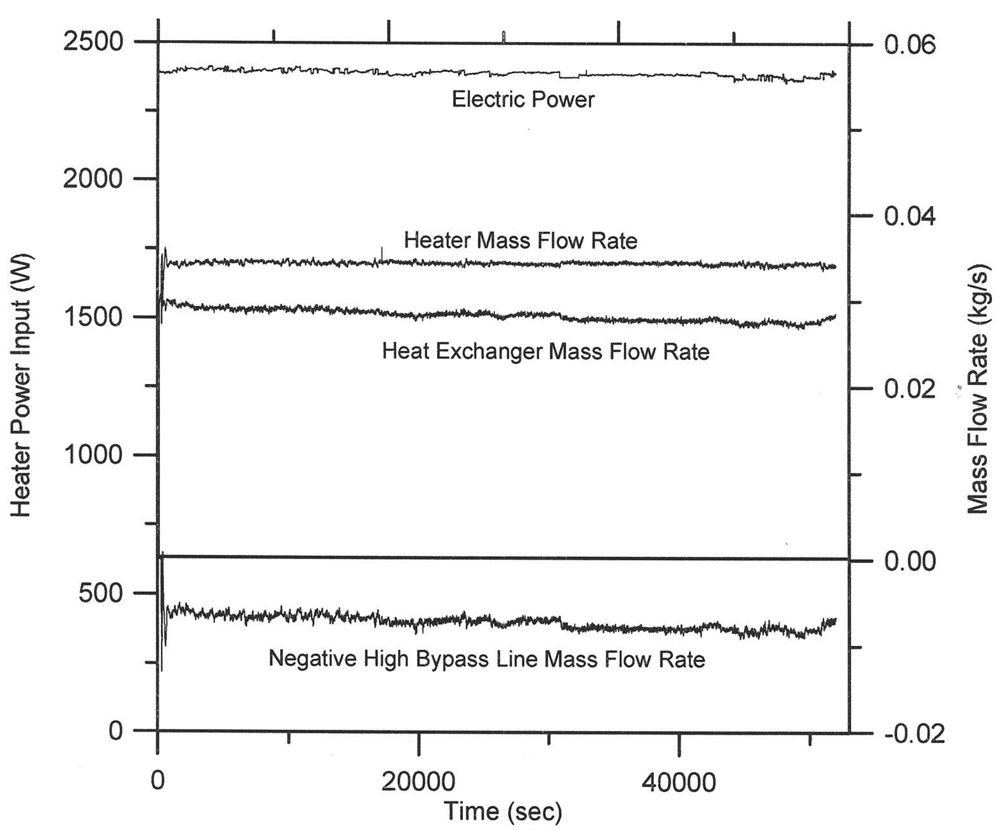

FIG. 8. Heater Power and Mass Flow Rates - Second Experiment.

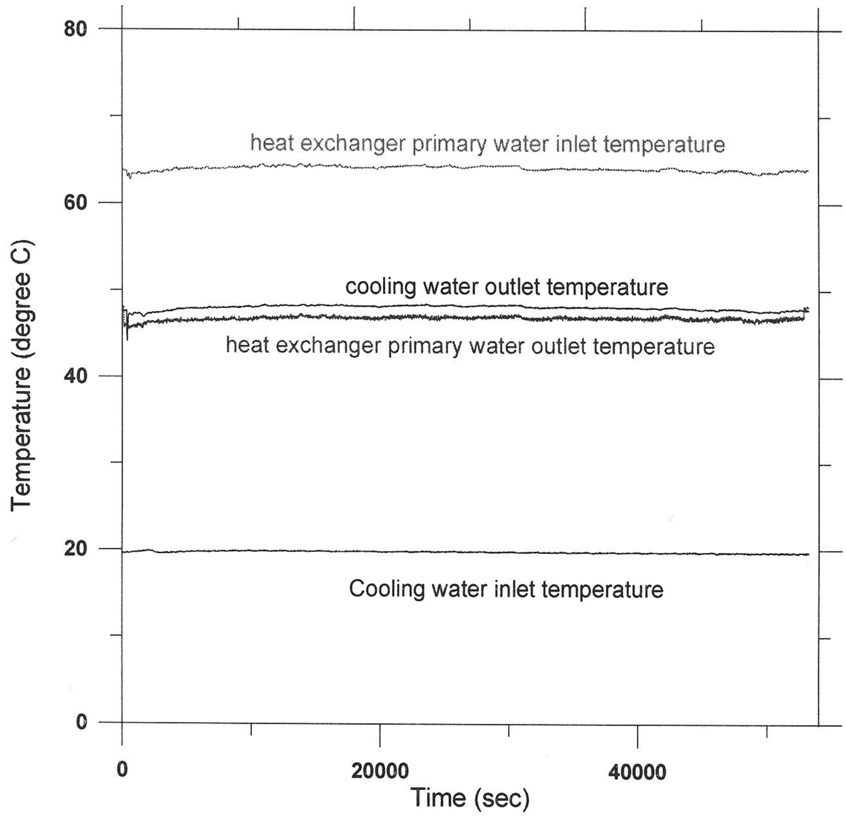

FIG. 9. Main components temperature behavior.

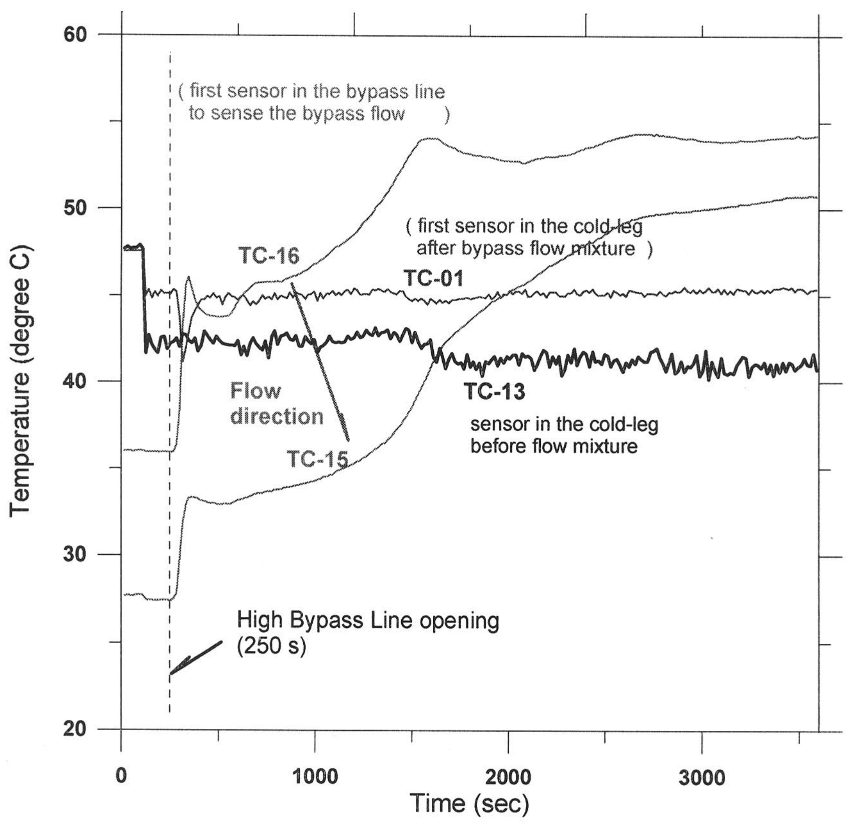

FIG. 10. Bypass line temperatures behavior.

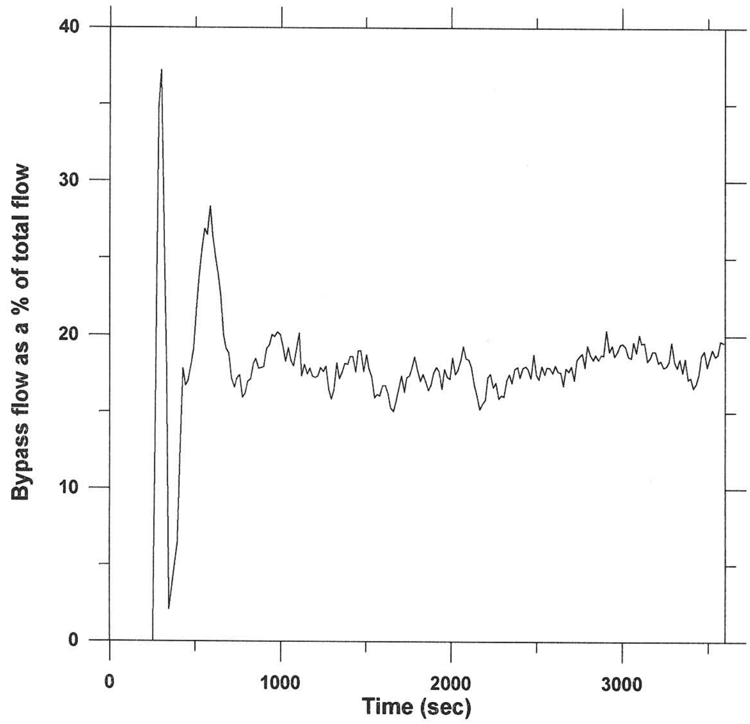

FIG. 11. Bypass line percentage of flow.

CONCLUSIONS

The first sets of experiments with the opening of bypass lines in the Natural Circulation Loop (NCL) were analyzed and show that bypass lines can be used to control the outlet temperature of the hot source in a natural circulation system.

The results presented in this paper, shows that the flow direction in the bypass line is from the cold leg to the hot leg when the lower bypass line is opened and is in the opposite direction when the higher bypass line is opened.

It was observed that the bypass line flow in the cold- to hot-leg direction is almost 10% of the total flow, which is enough to produce a substantial rise in the heater outlet temperature. This process can be used to reduce the cooling-down rate of a reactor vessel during natural circulation emergency core cooling, permitting a faster reactor restart. The temperature changes will be higher in the emergency cooling system.

Depending on the bypass to hot-leg vertical position connection, the bypass line flow can be changed to the hot-leg to the cold leg direction. If the main bypass line flow follows the cold-to-hot direction, the net flow through the heater will be smaller; the heat exchanger flow will be the sum of the heater flow with the bypass line flow. The heater outlet temperature will be higher compared with the temperature without bypass flow. If the vertical connection position of the bypass line with the hot-leg is higher, the flow changes its direction and, even if this flow is bigger than that observed in the other case, the heater conditions will not suffer great changes. In the second experiment presented, a bypass flow equivalent to 18% of the total flow was observed.

In the future experiments initial and boundary conditions will be controlled to be the most similar as possible. The convenience of application of power steps will be carefully analyzed before starting any other experiment. It was not commented before but, an uncertainty of 16% in the flow measurements was observed, while the expectation was only 10% uncertainty.

A numerical model is going to be developed to aid the experiments planning. This model will be used in future works to find the vertical connection position of the bypass line with the hot-leg where the flow direction changes.

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