ANALYSIS OF RD-14M TWO-PHASE THERMOSYPHONING EXPERIMENTS AND ASSOCIATED CATHENA SIMULATION RESULTS

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ABSTRACT

This paper presents some of the results of a detailed analysis of some of the two-phase thermosyphoning tests conducted in the RD-14M multiple channel figure-of-eight loop test facility. The tests were conducted to obtain a better understanding of two-phase thermosyphoning behaviour in a multiple-channel facility. The tests generally showed similar thermohydraulics phenomena as the loop inventory was reduced.

There is a basic difference between two-phase thermosyphoning behaviour in the tests conducted in the multiple-channel RD-14M and in the previous RD-14 single-channel per pass loop test facilities. In each of the RD-14M tests, the flow in some of the channels in each pass reversed direction and this new direction was sustained for a long time. This reversal generally was not observed in the tests conducted in the single-channel test facilities. This reversal played an important role in the subsequent RD-14M loop thermohydraulics behaviour. Specifically, the channel flow reversal reduced and in some tests stopped the thermosyphoning flow and caused the loop pressure to rise. The flow reversal and subsequent loop inventory drainings eventually caused the flow in some channels to decrease and stratify resulting in channel heatup. The report presents a physical interpretation for each of the major phenomena observed in the tests. A simple criterion for the onset of channel flow reversal similar to that proposed previously is given.

CATHENA was used to simulate a number of the RD-14M tests with the objective of obtaining a better understanding of the phenomena observed in the tests. CATHENA generally predicted all of the observed phenomena. The details of the predicted results depended on the choice of the steady state conditions and heat loss distribution around the loop. The paper also studies the results of

the CATHENA simulations of the tests to support the interpretation of the test results.

ACKNOWLEDGEMENT

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INTRODUCTION

This paper presents the results of a detailed analysis of some of the two-phase thermosyphoning experiments conducted in the RD-14M multiple-channel test facility. The analysis used both the raw experimental data and the results of CATHENA simulations of the experiments. Major physical phenomena observed in the experiments are identified and explained in terms of physical parameters of the system.

Previous analyses of two-phase thermosyphoning in the single-channel per pass RD-14 test facility (Reference 1), showed that reducing the loop inventory initially increased the thermosyphoning flow. (In this paper, thermosyphoning is defined as the flow of single-phase water or cocurrent steam and water over the top of the boiler U-tubes). These analyses also showed that when the two-phase mixture from the boiler hot leg reached the top of the U-tubes and extended into the cold leg, the thermosyphoning flow began to decrease. Eventually, at some reduced loop inventory, the thermosyphoning flow decreased sufficiently to cause the channel flow to stratify and the channel to heat up.

The RD-14M multiple-channel test facility was constructed to study the effect of multiple channels on two-phase thermosyphoning behaviour. A series of two-phase thermosyphoning tests were conducted in RD-14M and a preliminary analysis of the tests was performed (Reference 2). This paper presents a more detailed analysis of some of these tests.

RD-14M FACILITY

RD-14M (Figure 1) is a five-channel per pass loop test facility with its major components arranged in a figure-of-eight configuration similar to that in a CANDU heat transport system (HTS). The channels are located at various elevations. The feeder pipes connect the channels to horizontal headers. The feeders and end fittings are trace heated to compensate for heat losses. Nevertheless, significant heat losses have been identified in the loop. The RD-14M facility is extensively instrumented.

RD-14M STEADY TWO-PHASE THERMOSYPHONING TESTS

The steady two-phase thermosyphoning RD-14M tests were conducted at various powers, secondary side pressures and loop inventories. In these tests, single-phase thermosyphoning was established at the desired conditions in the pass power and primary and secondary side pressures. Subsequently, the primary fluid was drained intermittently from one of the outlet headers to obtain two-phase thermosyphoning conditions at a desired loop inventory level. The intermittent draining of the loop inventory was continued until a process trip, usually high heater element temperature of 600 degrees Celsius) occurred thereby terminating the test. In addition to the effects of power, secondary side pressure, and loop inventory, the tests also studied test repeatability and the effects of boiler feedwater temperature, trace heating, draining rate, and duration between consecutive draining operations.

TEST ANALYSIS RESULTS

A preliminary analysis and interpretation of all of the test results were performed previously (Reference 2). This paper provides some of the results of a more detailed analysis of the high power tests with the outlet header interconnect pipe and surge tank valved out.

Generally, the phenomena in the various tests were similar. Specifically, at some reduced loop inventory in each of the tests, the direction of the flow in some of the channels reversed from inlet-to-outlet to outlet-to-inlet and this new direction was maintained for a significant length of time. In this paper, this phenomenon is referred to as channel flow reversal. In the process of this flow reversal, the outlet feeder became water-filled and the inlet feeder became two-phase-filled. This flow reversal is distinguished from a temporary flow reversal that may occur during a large amplitude flow oscillation. Channel flow reversal eventually caused the tests to be terminated on high heater element temperature. As in Reference 2, it is proposed, with experimental justification, that, in the tests, a channel flow reversed when the inlet-to-outlet header pressure difference became sufficiently negative to overcome the net hydrostatic head in the inlet and outlet feeders of the channel. With oscillations in the flow and pressure difference the channel flow reversal may occur at lower negative values of the header pressure difference.

For a given power, the phenomena in the high and low pressure tests were somewhat similar but some of them occurred for different reasons. These phenomena are described in detail below for the two high power (160 kW) tests #T8808 and T8809 conducted at high (4.5 MPa) and low (1.0 MPa) secondary side pressure respectively. For each of the tests, the flow behaviour is decribed in only one of the two passes of RD-14M since it was similar in the other pass.

High Pressure Tests

With each draining of the loop inventory, the primary side pressure (Figure 2) decreased further towards the secondary side pressure. This pressure reduction caused the hot water in the outlet piping to flash and consequently the void in these pipes continued to increase. At some reduced loop inventory, the primary pressure began to increase. This pressure rise was caused by thermosyphoning breakdown and consequent insufficient heat removal by the boilers.

The behaviour of the phase distribution in the hot and cold legs of the boiler tubes had significant effect on the thermosyphoning and channel flow behaviour. This behaviour is deduced from the measured pressure difference between the inlet and outlet of each of the boilers (Figure 3). This pressure difference became more negative and reached a minimum as the loop inventory was drained. Further loop inventory draining caused this pressure difference to increase to a relatively high positive value. This behaviour in the pressure difference is explained as follows. After a few initial drainings, the boiler pressure difference decreased because the void in the boiler hot leg increased reducing the hydrostatic head in the hot leg. The friction pressure drop increased as the two-phase region in the hot leg increased. Initially, the friction pressure drop was small compared to the difference in the hydrostatic heads in the hot and cold legs. Therefore, the pressure difference across the boiler tubes decreased. When the void entered the cold leg, the net hydrostatic head began to decrease but the friction pressure drop continued to increase and became dominant causing the pressure difference across the boiler to become positive.

It is inferred (and confirmed by CATHENA simulations as described below) that when the void entered the cold leg, the boiler pressure difference also became oscillatory and the oscillations in the two passes were in-phase with each other. These oscillations are caused by an interaction between variations in the flow and the resulting friction pressure drop and in the net hydrostatic head. The change in the heat transfer to the secondary side has a small effect on this oscillation.

The behaviour in the header pressure difference between the inlet and outlet headers (Figure 4) was nearly similar in magnitude and opposite in sign to that in the boiler pressure difference as expected. In particular, when the boiler pressure difference became significantly positive, the header pressure difference became significantly negative.

The thermosyphoning flow (Figure 5) increased after each of the initial drainings and reached a maximum when the boiler pressure difference reached a minimum. Subsequently, the flow decreased and developed oscillations at the same time that the boiler pressure difference increased and became oscillatory. This flow behaviour is explained similarly to that in the boiler pressure difference. Later on, the thermosyphoning flow decreased again and eventually stopped, i.e., thermosyphoning broke down at about 80% loop inventory when the primary-to-secondary temperature difference was about 3 degrees Celsius. This decrease in the flow occurred partly because the net hydrostatic head in the inlet and outlet piping decreased after further draining increased the loop void in the boiler hot and cold legs. The resulting increase in the friction pressure drop also reduced the thermosyphoning flow. The flow decreased also because the flow reversed in some of the channels and these channel flows no longer contributed to the thermosyphoning flow. It is inferred that, following thermosyphoning breakdown, reflux condensation in the boiler hot legs removed some of the channel heat.

The flow behaviour in each of the channels prior to reversal was similar to that in the thermosyphoning flow and for similar reasons. The oscillations in the channel flows, thermosyphoning flow, and header and boiler pressure differences had various phases relative to each other. At some reduced loop inventory, the flows in the top channels, i.e., HS5 and HS10, reversed at about the same time.

The flow reversal in HS5 is explained similarly to that in Reference 2 and is as follows. Figures 6 and 7 show respectively the HS5 inlet flow and header-to-header pressure difference at about the time of the channel flow reversal. The flow was oscillatory with increasing amplitude. The oscillation amplitude was large relative to the mean flow. The header pressure difference was negative and oscillatory and the oscillations before channel flow reversal were nearly in-phase with those in HS5 flow. As the amplitude of the flow oscillations grew, the flow began to periodically stagnate and sometimes reverse momentarily (Figure 6). This momentary flow reversal sometimes caused void to momentarily appear in the inlet feeder (Figure 8). At the time of channel flow stagnation indicated by the arrow #1 in Figures 6, 7, and 9, the header pressure difference was significantly negative and for sufficiently long time to cause the flow to stagnate in some axial plane along the channel. From this axial plane, high quality fluid flowed towards the inlet and outlet feeders. This stagnation and bi-directional flow are inferred from the negative value of the channel flow (Figure 6) and the positive value of the pressure difference across the channel (Figure 9). Consequently, the void in the inlet (Figure 8) and outlet feeders (Figure 10) increased. Shortly afterwards, the header pressure difference began to decrease to -20 kPa at the time shown by the arrow #2 in Figure 7. This value of the header pressure difference was sufficiently negative to reverse the channel flow. At this time, indicated by the arrow #2 in Figure 10, the void in the outlet feeder collapsed.

From the above discussions, a simple criterion for a sustained channel flow reversal is as follows. A channel flow reverses when the inlet-to-outlet header pressure difference is sufficiently negative to overcome the difference between the hydrostatic heads in the inlet and outlet feeders. Thus, at the onset of channel flow reversal,

$$\Delta p = - g.h.(\varrho_i - \varrho_o)$$

where h = the elevation difference between the headers and the channel, g = gravitational acceleration, ϱi = inlet feeder fluid density, and ϱo = outlet feeder fluid density. To relate the above criterion to the loop themohydraulics conditions, Δp, ϱ_i, and ϱ_o must be evaluated in terms of these conditions. The values of ϱ_i and ϱ_o depend on the amount and distribution of void in the feeders. This void, in turn, depends on the channel flow history and oscillation characteristics. An upper and a lower bound values for Δp are readily given. One of these values is obtained for Δp = water density and Δp = steam density. This value is appropriate for the case of test T8808 described above where the flow stagnates before reversing since then the outlet feeder void is quite high. For the top channel and for test T8808, this upper bound value of Δp is about -30 kPa compared to the value of -20 kPa in the test (Figure 7). The lower bound value of Δp is obtained for Δp = subcooled water density and Δp = saturated water density. This lower bound value is between 2 and 5 kPa. This value is appropriate for the case where the oscillation amplitude is sufficiently large to collapse the void in the outlet feeder prior to channel flow reversal as described below.

With further draining in the test T8808, the header pressure difference (Figure 7) became more negative (about -23 kPa) and the flow reversed in a mid-elevation channel for reasons similar to those in the top channels.

From measured fluid temperature and void above the inlet headers, the followings are inferred. The hot fluid entering the inlet headers from the channels with reversed flows eventually heated the inlet header fluid to the saturation temperature just after the thermosyphoning broke down. Subsequently steam rose up from the inlet headers and accumulated in the pump casing due to limited condensation there. This steam accumulation and limited heat removal by the reflux condensation caused the loop to pressurize. This pressurization forced back the water in the U-shaped piping between the pump inlet and the boiler outlet until it reached the inclined boiler outlet pipe. This steam then bubbled up through the pipe and condensed in the boiler cold leg.

Following thermosyphoning breakdown, void (Figure 11) appeared in the inlet feeders of some of the channels with forward flows and the flows in these channels decreased and stratified causing the upper fuel element simulators to heat up (Figure 12). These phenomena are explained as follows. Reduced thermosyphoning and channel flows caused the steam and water phases in the inlet header to separate with the steam in the upper parts and water in the lower parts of the inlet header. Subsequent thermosyphoning breakdown caused water level in the inlet header to fall exposing the feeder nozzles at the header to steam. These feeder nozzles, therefore, began to receive steam. This steam replaced the water in the inlet feeders as the water drained into the channels. This phenomenon is referred to as feeder draining. Feeder draining reduced the hydrostatic head of the water in the inlet feeders and, therefore, the flow. Therefore, the channel flow eventually stratified and the upper heater element temperature began to increase (Figure 12).

<u>Low Pressure Tests</u>

The phenomena in the low pressure test T8809 were generally similar to those in the high pressure tests. However, the primary circuit parameters were highly oscillatory. The behaviour of the loop pressure as the loop inventory was drained was similar to that in the high pressure tests. The boiler and header pressure differences were oscillatory about nearly zero time-averaged (i.e., mean) values unlike that in the high pressure test T8808.

The thermosyphoning flow was oscillatory and the oscillation amplitude increased with each draining of the loop inventory. The flow oscillations in the two passes were out-of-phase with one another. The pass-to-pass out-of-phase oscillations in a figure-of-eight such as RD-14M under two-phase conditions have been studied experimentally and analytically elswhere (References 3 and 4). The mean value of the flow increased after each draining of the loop inventory. The continued increase in the flow after each draining indicated that the extent of the void in the hot legs increased and no significant void entered the cold legs. It is relevant to note that, in the test T8809, the minimum difference in the fluid temperature between the primary and secondary sides was about 13 degrees Celsius. Following each channel flow reversal, the thermosyphoning flow abruptly decreased. In T8809, thermosyphoning did not break down and no void appeared above the inlet headers. Following each reduction in the thermosyphoning flow, the loop pressure increased. In another low pressure test, thermosyphoning broke down and the subsequent above-header behaviour was similar to that in T8808.

In T8809, the flow in each channel was oscillatory about a positive time-averaged value. This value increased as the loop inventory was reduced. The oscillations in the different channels had generally different characteristics. These oscillations have been observed (Reference 5) and are governed by a feedback between the flow and the outlet void and, therefore, the difference in the hydrostatic heads in the inlet and outlet feeders modified by the oscillations in the header-to-header pressure difference.

Between 92% and 90% loop inventory, the flows in HS8 and HS12 reversed. The mechanism for the flow reversal in the channels, where the oscillations in the flow and header-to-header pressure difference were nearly in-phase prior to the reversal, is similar to that in T8808. In the other channels in T8809, the void in the outlet feeders collapsed during a high flow period of the large amplitude oscillations in the channel flows. With the outlet feeder water-filled, the flow in the channel reversed when, subsequently, the header-to-header pressure difference rapidly became negative.

In T8809, the reversed flows in HS8 and HS12 began to decrease from the start of a subsequent draining and the resulting loop depresssurization. Subsequently, the fuel element simulators in HS8 began to heat up. Eventually, the test was terminated on high fuel element simulator temperature in HS8 at about 90% loop inventory. From other observations in the tests, it is inferred that the reduction in the flows in HS8 and HS12 was caused by void generation in the outlet feeders of HS8 and HS12. This void was generated by flashing of the water in the outlet feeders of these channels as the loop pressure decreased due to the draining.

In another low pressure test, both feeder draining, due to the inlet header phase separation, and water flashing in the outlet feeder, due to the loop depressurization, caused the fuel element simulators to heat up. This test was terminated on the resulting high heater element temperature in the channels with forward and reverse flows.

CATHENA TEST SIMULATION RESULTS

CATHENA was used to simulate some of the tests and in particular tests T8808 and T8809. The code generally predicted the phenomena observed in the tests. The details of the simulation of a particular test depended on the choice of the initial steady state conditions in the range of uncertainties of the measured parameters, modelling of heat loss magnitude and distribution, choice of component models (such as separator or no separator model in the headers), number of nodes, etc.

For the high pressure test T8808, the simulation predicted, among other things, :

i. The significant increase and decrease in the pressure difference across each of the boilers and inlet and outlet headers (Figure 13) respectively when significant void entered the cold legs (Figures 14 and 15).

ii. The decrease in the thermosyphoning flow (Figure 16) when significant void entered the boiler cold legs and subsequent in-phase flow oscillations.

iii. The decrease in the thermosyphoning flow (Figure 16) following each channel flow reversal and eventual thermosyphoning breakdown.

iv. The flow reversal in the top channel (Figure 17) earlier than that in the test. It predicted flow reversal in one of the middle channels but not the one in the test.

v. Feeder draining and resulting flow stratification in the bottom channel (Figure 18) following thermosyphoning breakdown.

CATHENA predicted channel flow reversal for reasons similar to those inferred from the test data. The discrepancy between the particular channel where the flow reversal is predicted and observed can be explained by noting that CATHENA predicted different oscillation characteristics in the flows and pressure differences than that in the test.

For the low pressure test T8809, CATHENA predicted the observed behaviour in the thermosyphoning and channel flows prior to any of the observed channel flow reversals. The code did not predict any of the observed channel flow reversals. This prediction can again be explained from the observation that CATHENA did not predict oscillation characteristics identical to that in the test. It is possible that with different initial steady state conditions and or at a lower loop inventory level and different modelling assumptions, CATHENA would predict channel flow reversal. In fact, in the simulation of the test T9002 which is a repeat of T8809 but with the outlet header interconnect pipe valved in, CATHENA predicted flow reversal in the top channel. This channel was not the same as that in which the flow reversed in the test.

It may be concluded that, under highly oscillatory loop conditions, it is unlikely that a code or model can predict all the complexities of the oscillation characteristics and, therefore, all possible channel flow reversals.

SUMMARY

This paper presents some of the results of a detailed analysis of some of the two-phase thermosyphoning tests conducted in the RD-14M multiple-channel test facility. The sustained channel flow reversal observed in each of the tests reduced the thermosyphoning flow and eventually led to channel heatup. The channel flow reversal reduced the thermosyphoning flow. At high pressure, the thermosyphoning broke down after the void entered the boiler cold legs. This breakdown caused the water in the inlet feeders to drain into the channels thereby reducing and stratifying the channel flows. This stratification caused the upper fuel element simulators to heat up. Similar phenomena also occurred in one of the low pressure tests. In other low pressure tests, the flows reduced and stratified in the channel where the flow had previously reversed because the water in the outlet feeders of these channels flashed due to a loop draining and the resulting loop depressurization. This stratification caused these channels to heat up.

It is proposed, with experimental evidence, as in Reference 2, that a channel flow reversed when the inlet-to-outlet header pressure difference became sufficiently negative to overcome the net hydrostatic head in the inlet and outlet feeders of the channel. Oscillations in the channel flow and pressure difference tended to reduce the net hydrostatic head thereby facilitating the flow reversal. A simple criterion for this flow reversal similar to that in Reference 2 is presented.

CATHENA was used to simulate some of the tests. For the high pressure tests, CATHENA predicted the observed phenomena and for reasons similar to those inferred from the test data. For some of the low pressure tests, CATHENA did not predict and, for other low pressure tests, CATHENA did predict the observed channel flow reversals because CATHENA generally did not predict oscillation characteristics identical to those in the tests. The details of the simulations depended on the choice of the initial steady state conditions, heat losses distribution, and modelling assumptions.

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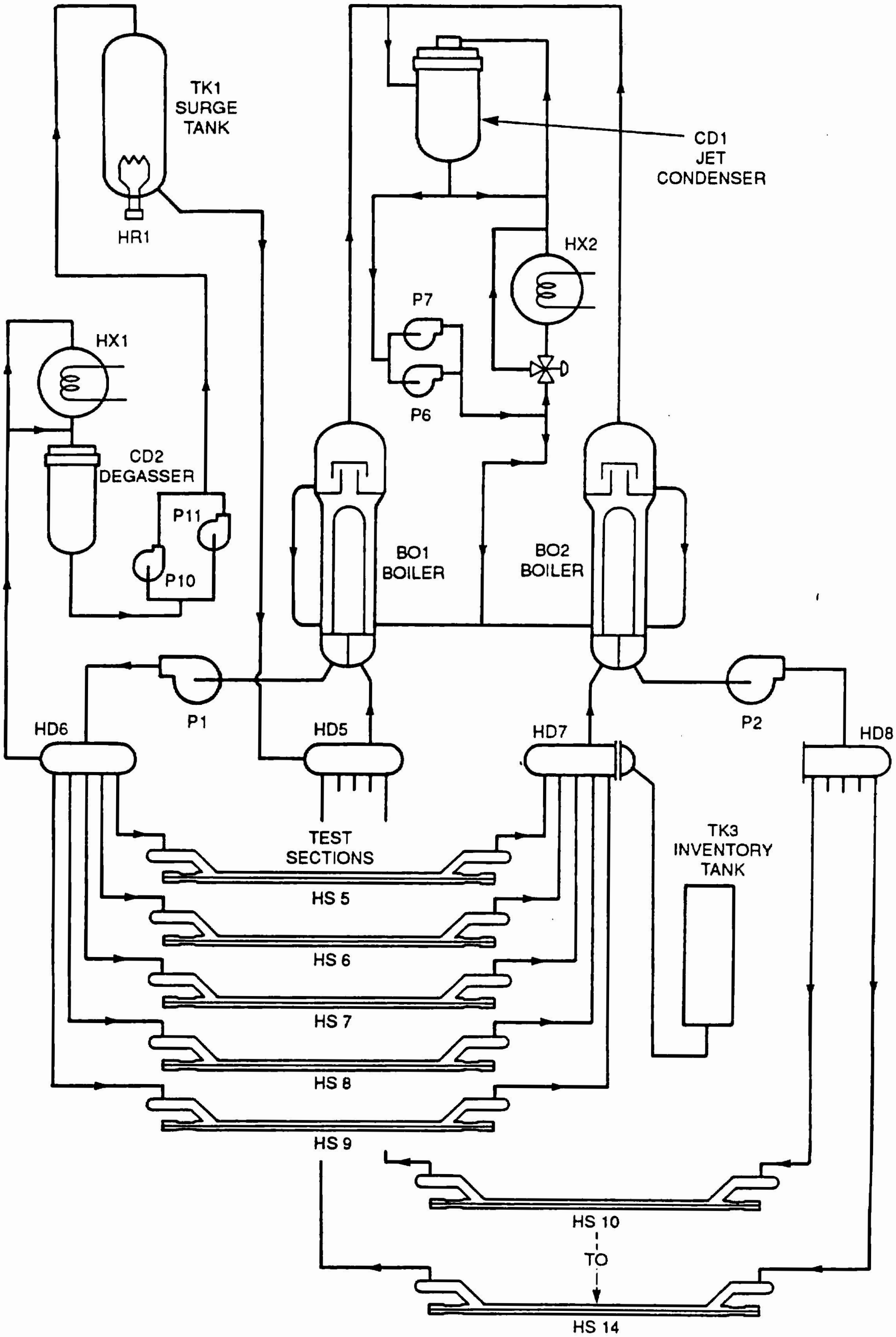

FIGURE 1 RD-14M TEST FACILITY SCHEMATIC

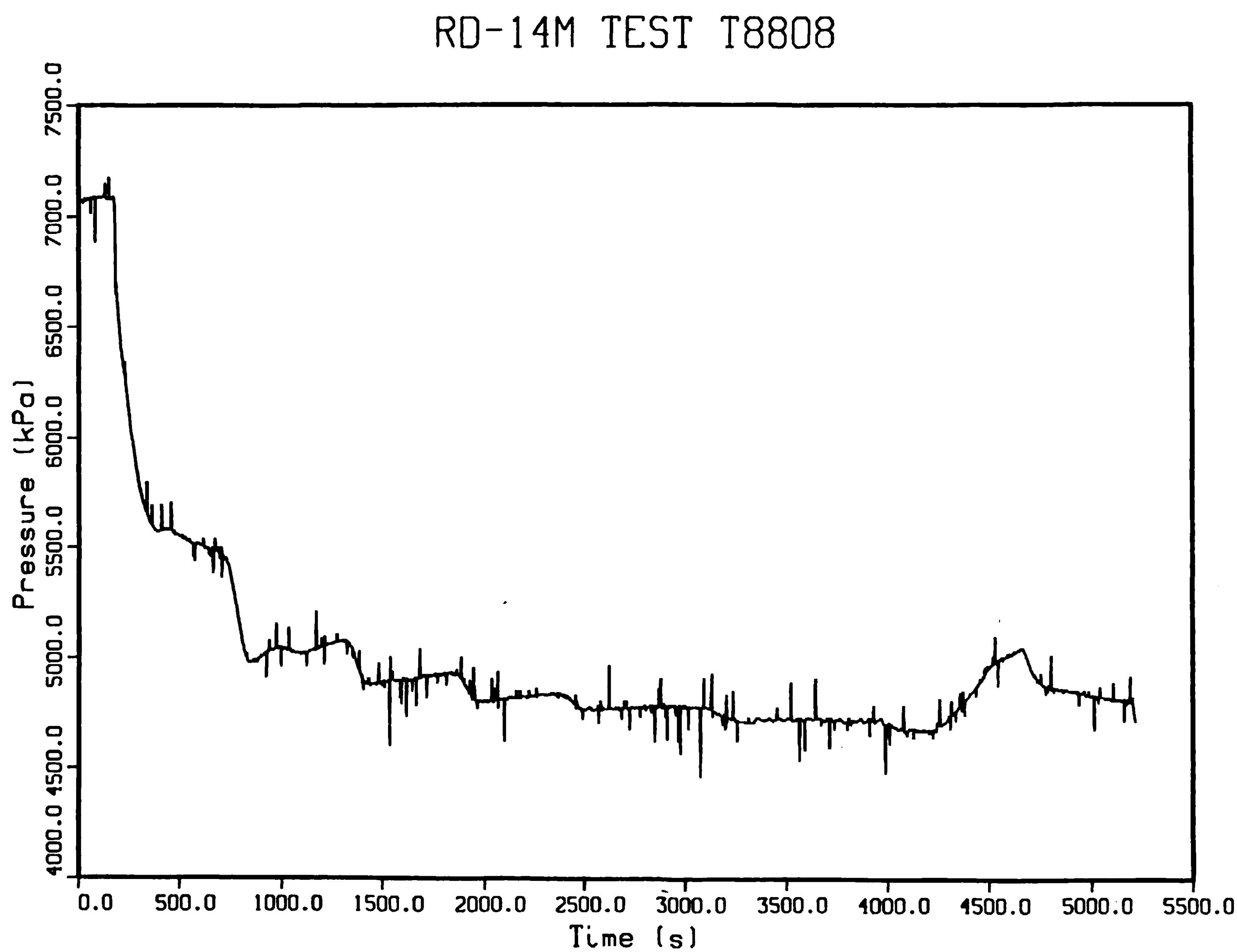

FIGURE 2 : Header #6 Pressure Transient

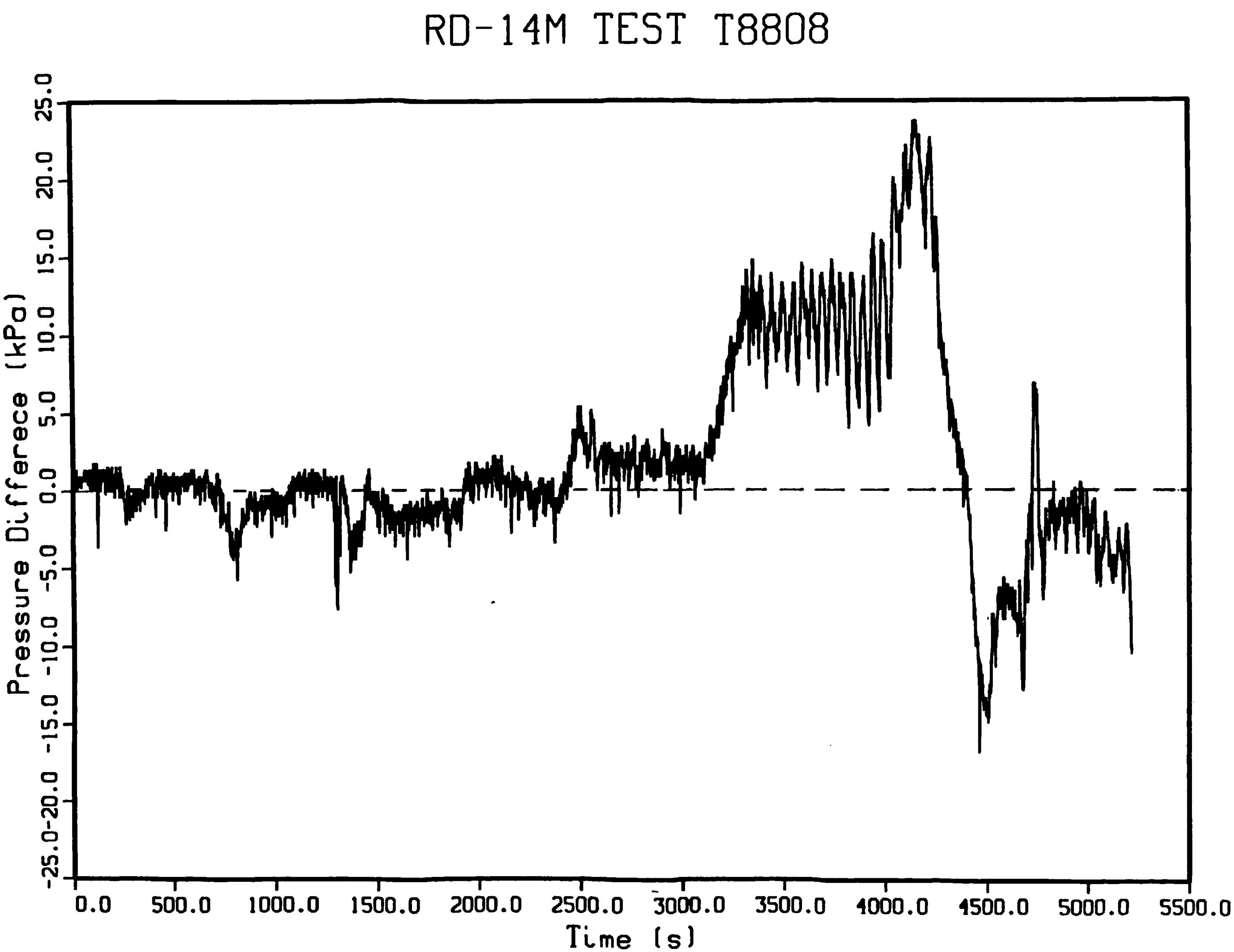

FIGURE 3 : Pressure Difference Transient Between Inlet and Outlet of Boiler #1

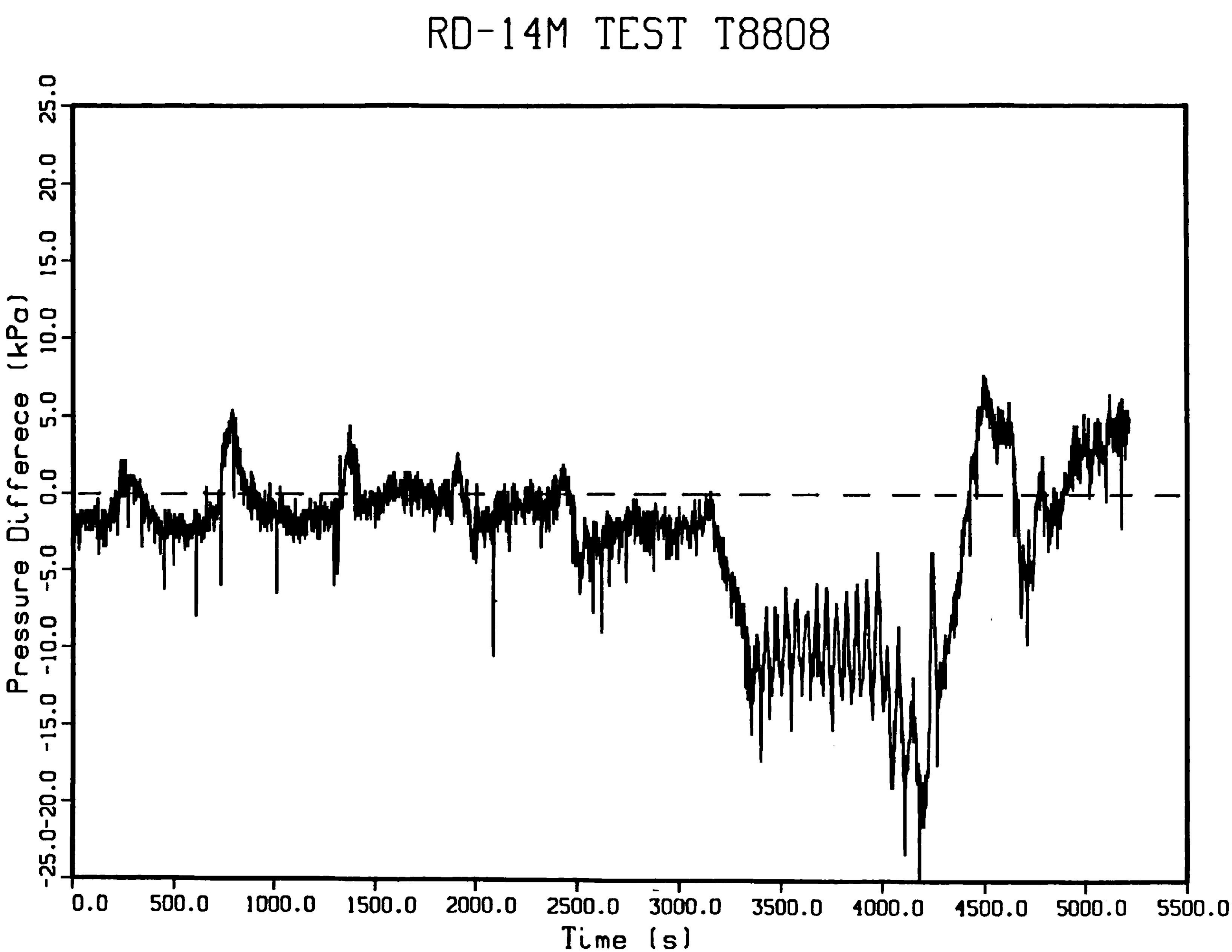

FIGURE 4 : Pressure Difference Transient Between Headers 6 and 7

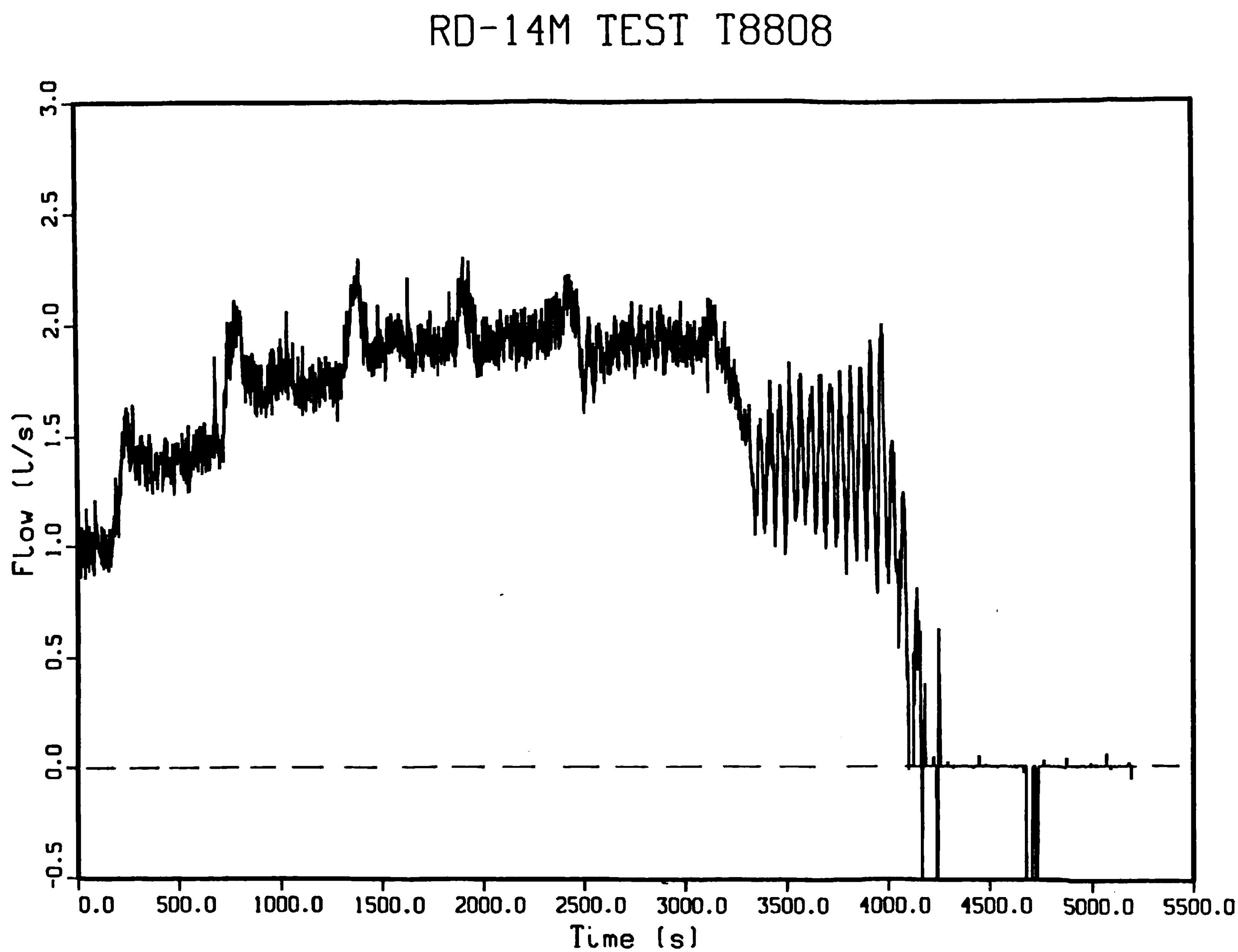

FIGURE 5 : Pump #1 Outlet Flow Transient

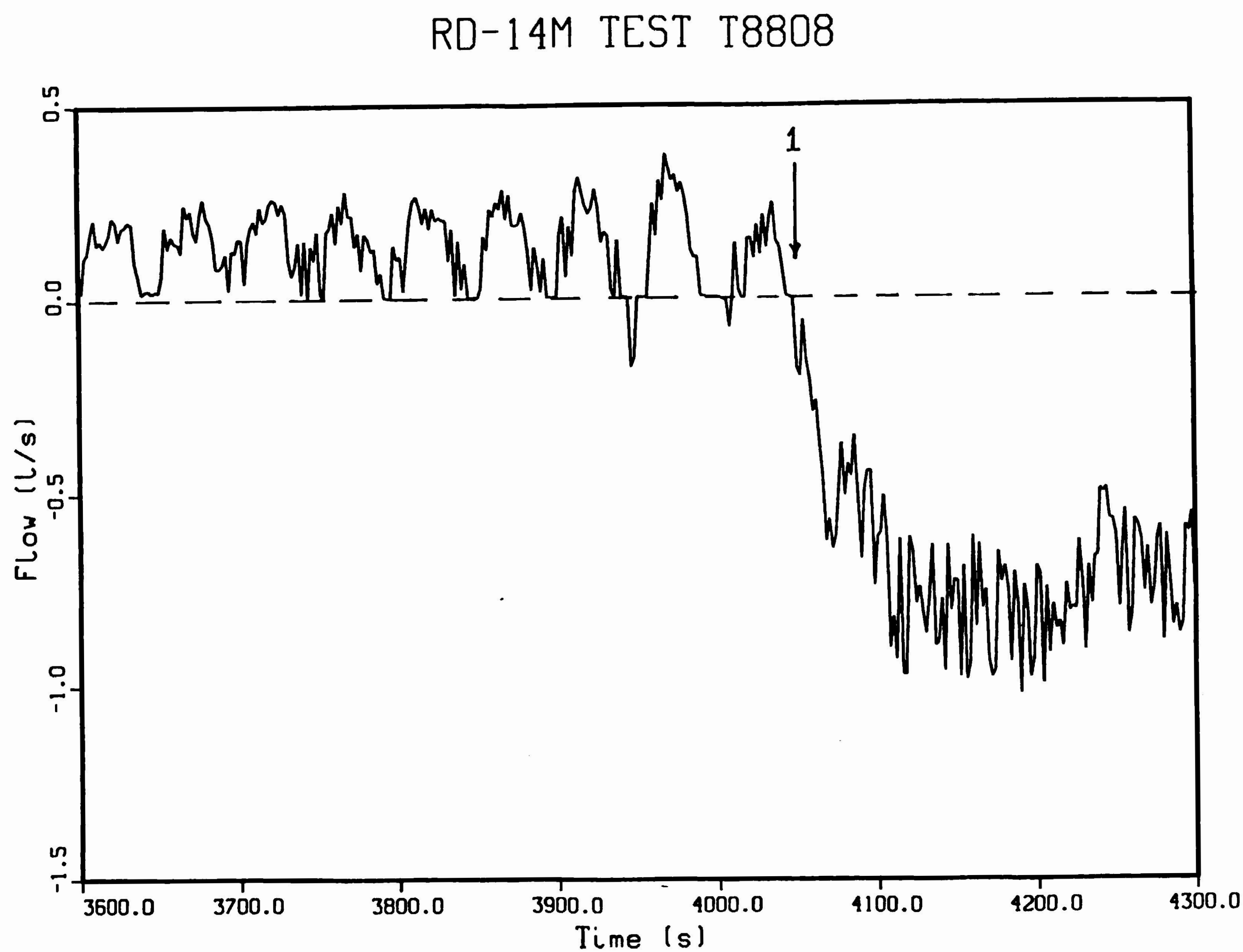

FIGURE 6 : HS5 Inlet Flow Transient

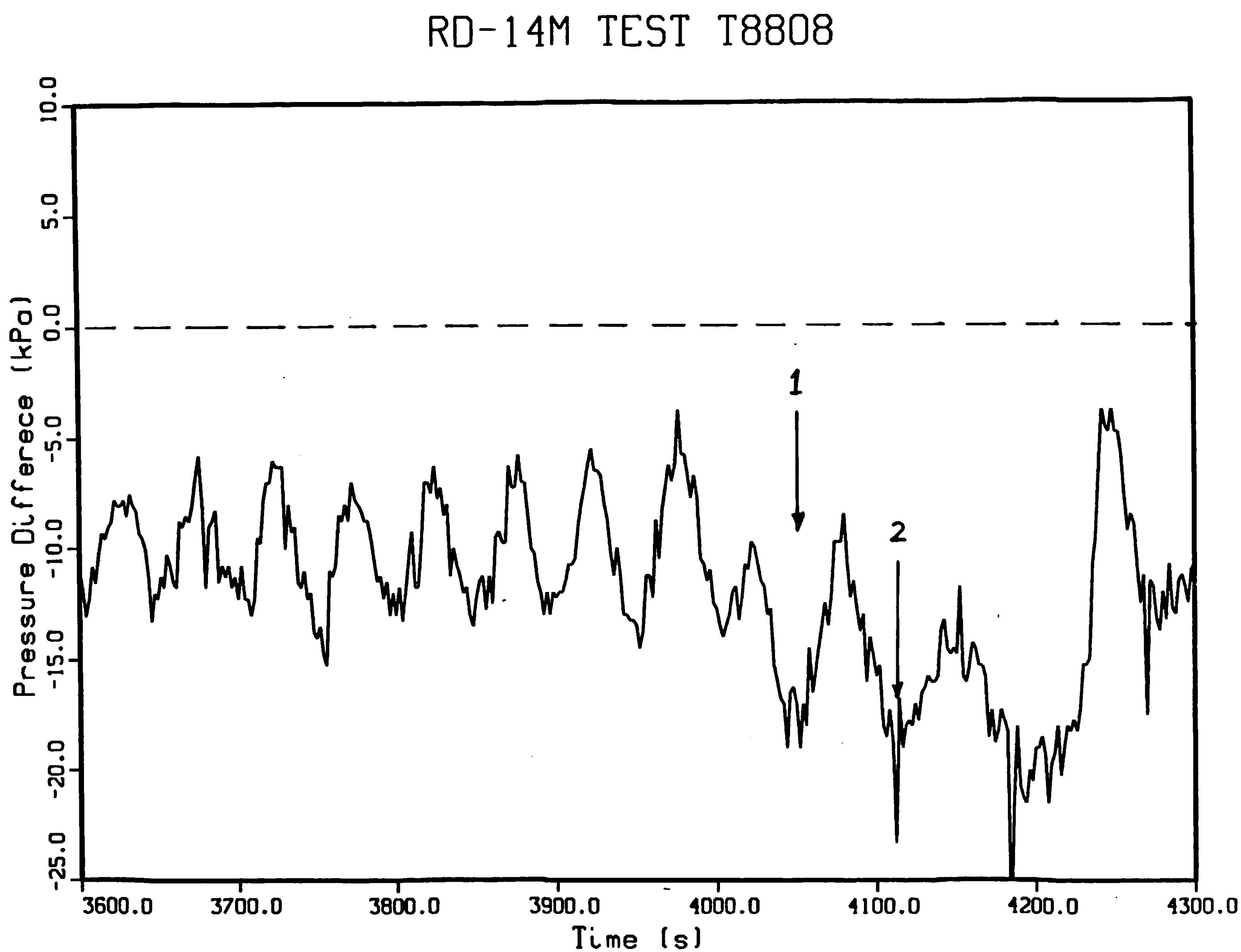

FIGURE 7 : Pressure Difference Transient Between Headers 6 and 7

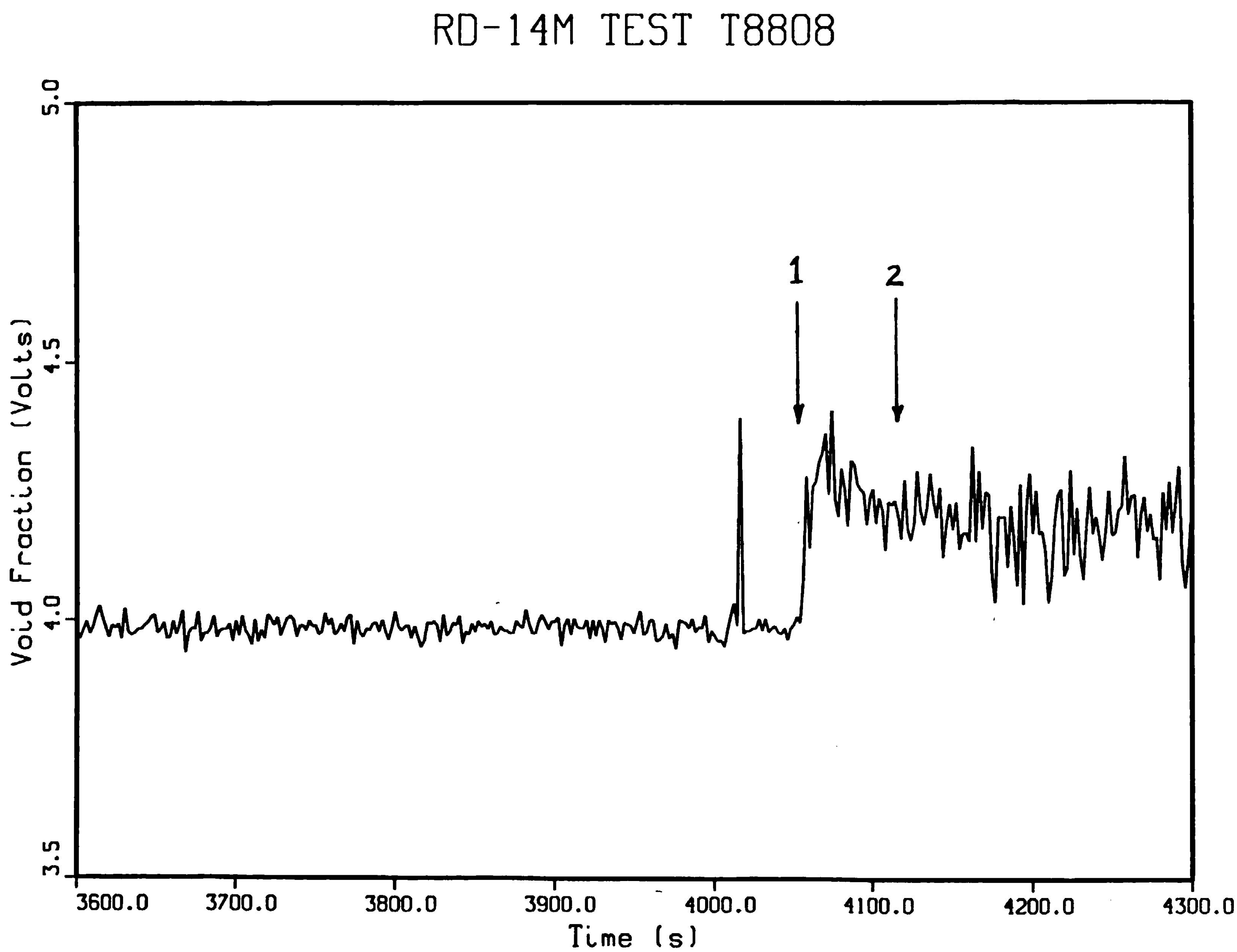

FIGURE 8 : HS5 Inlet Void Fraction Transient

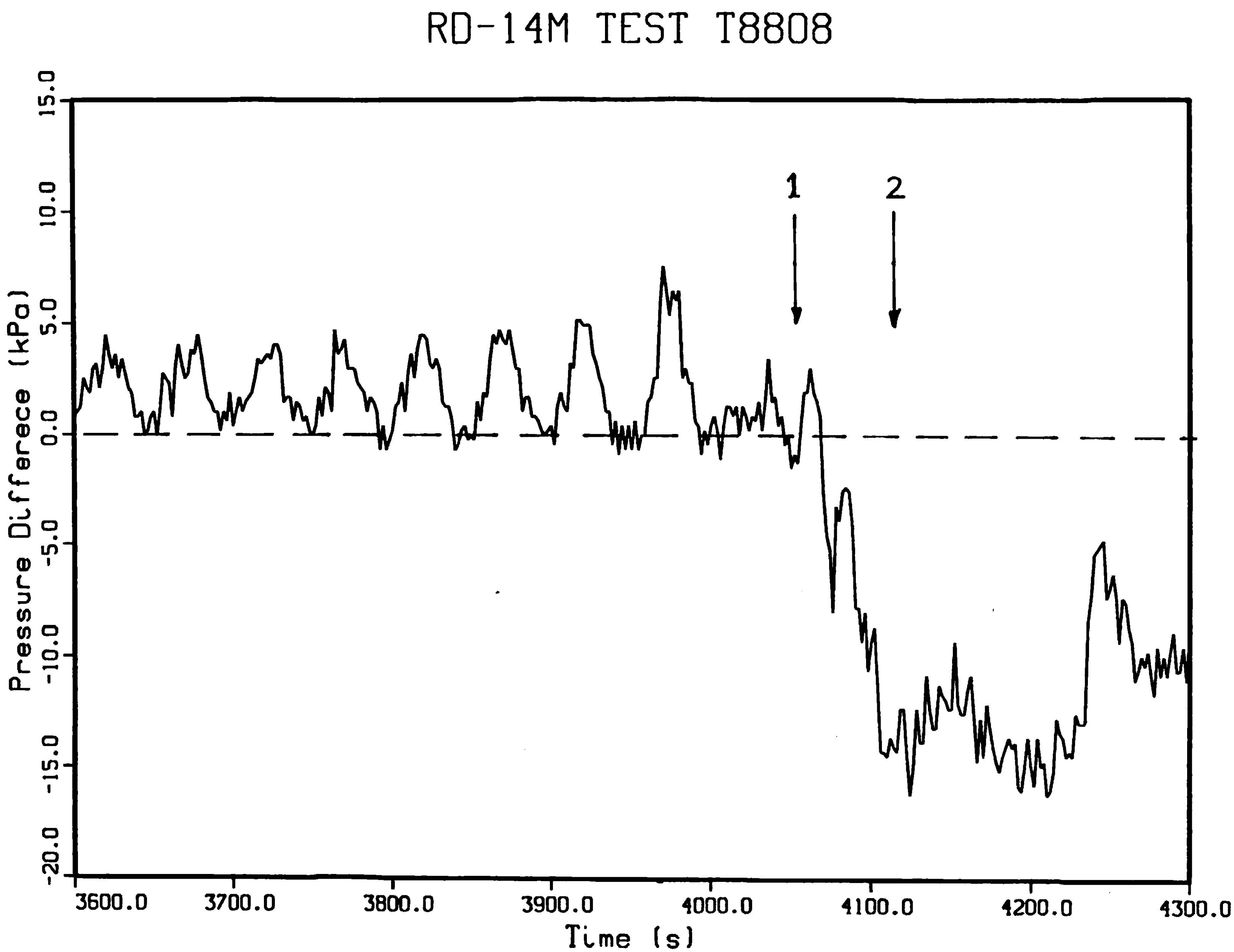

FIGURE 9 : HS5 Pressure Difference Transient

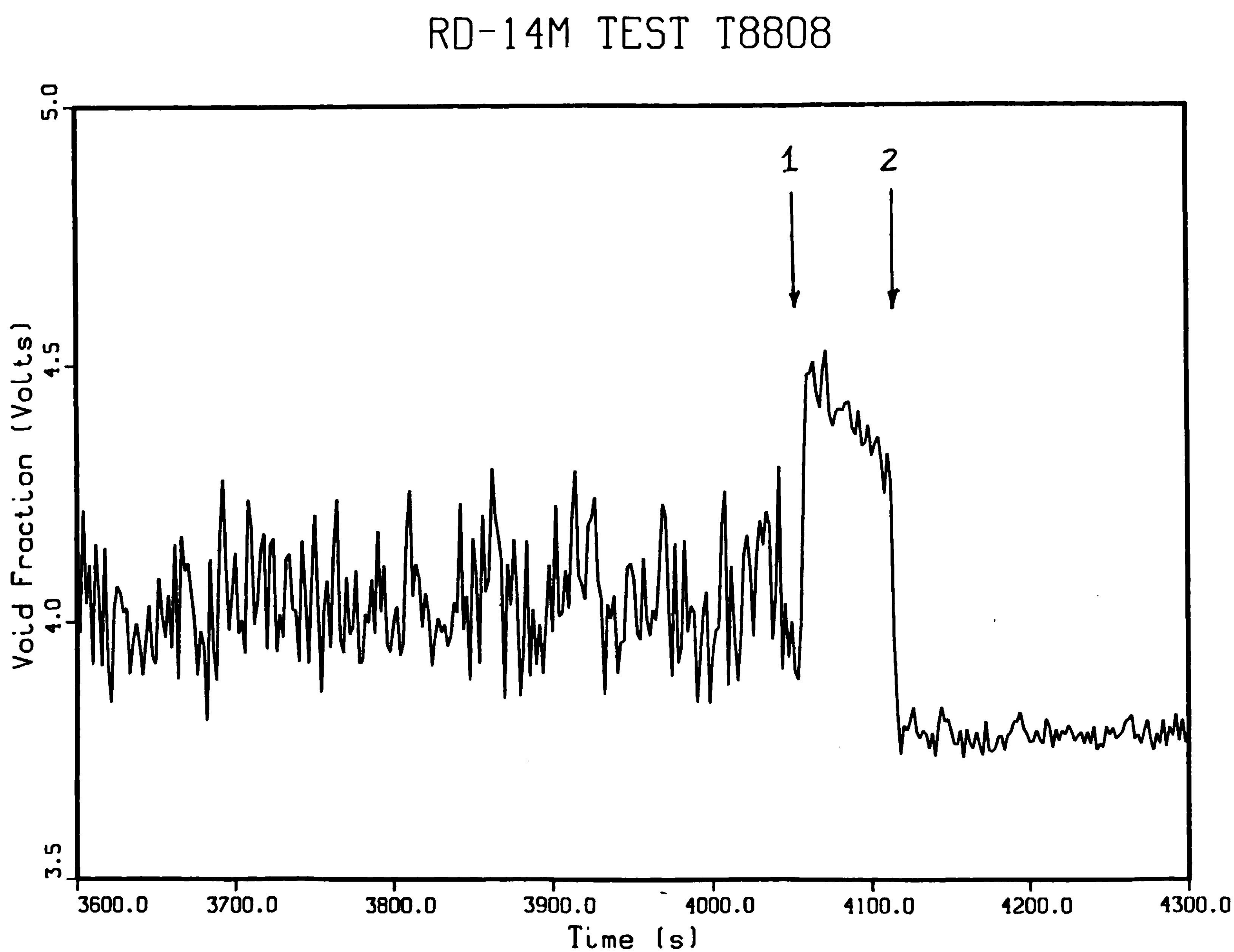

FIGURE 10 : HS5 Outlet Void Fraction Transient

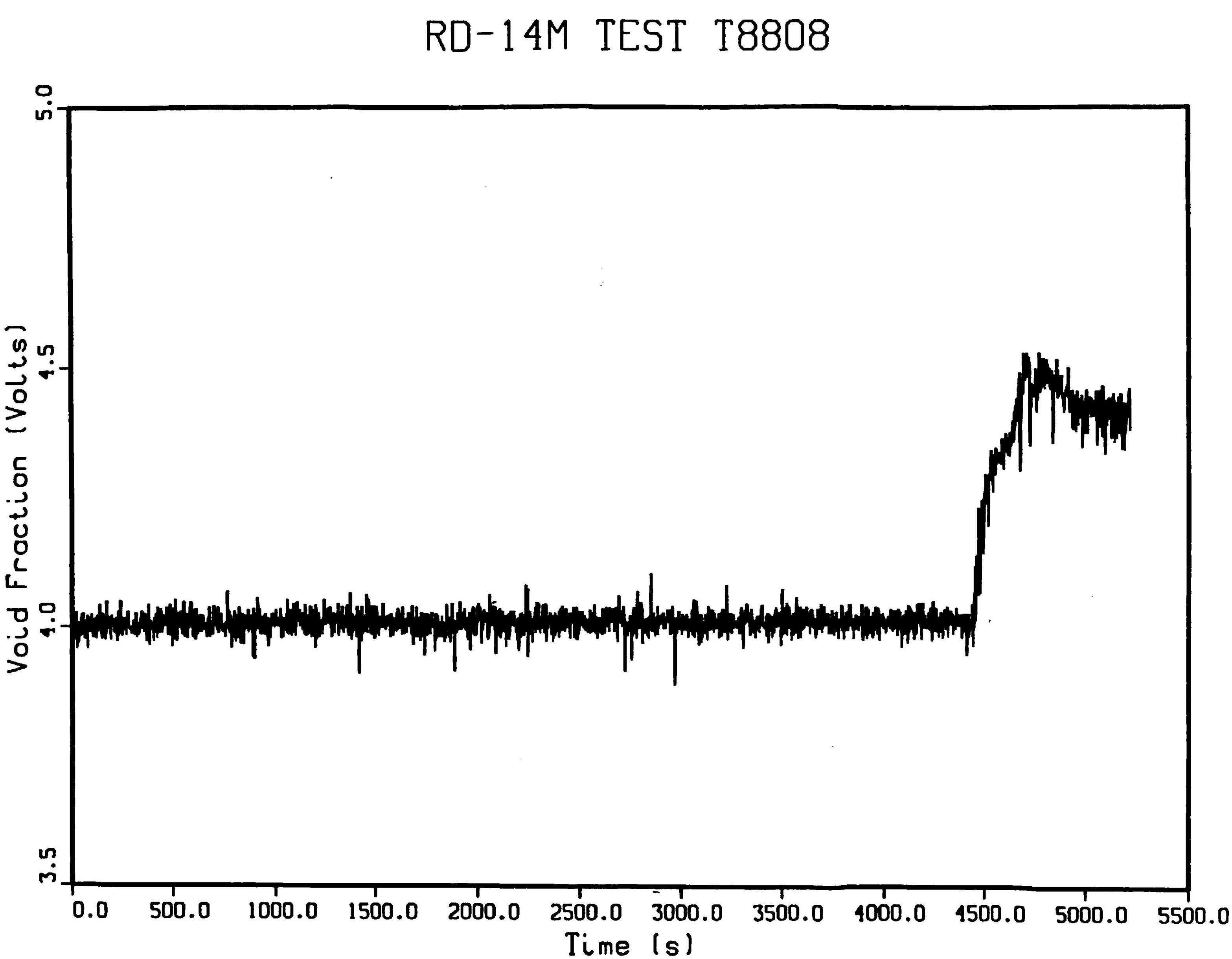

FIGURE 11 : HS9 Inlet Void Fraction Transient

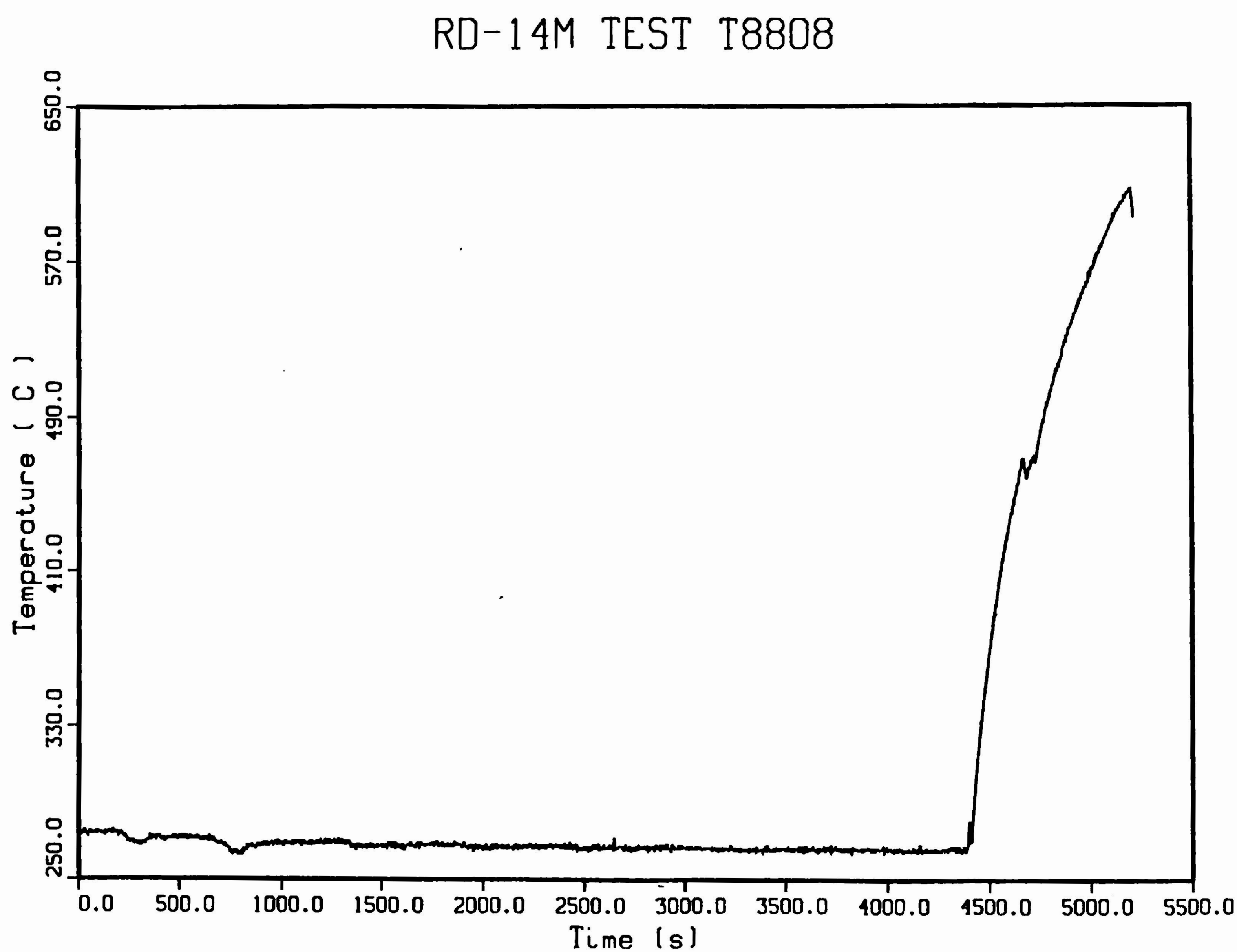

FIGURE 12 : Temperature Transient At Outlet End Of Top Heater Element (1-7N-2)In HS9

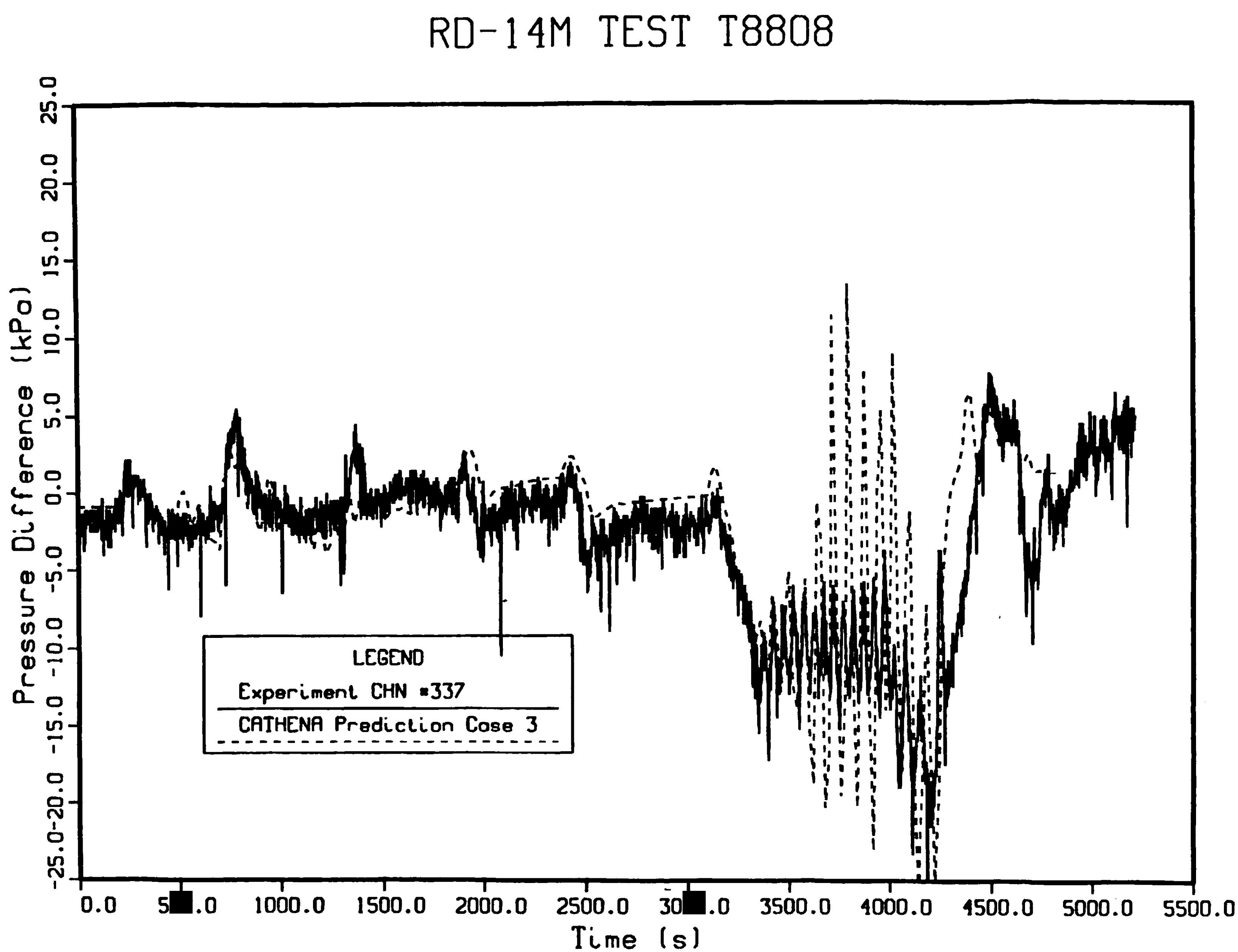

FIGURE 13 : Comparison of Measured and CATHENA MOD-3.3h Predicted Pressure Difference Transients Between Header #6 and 7

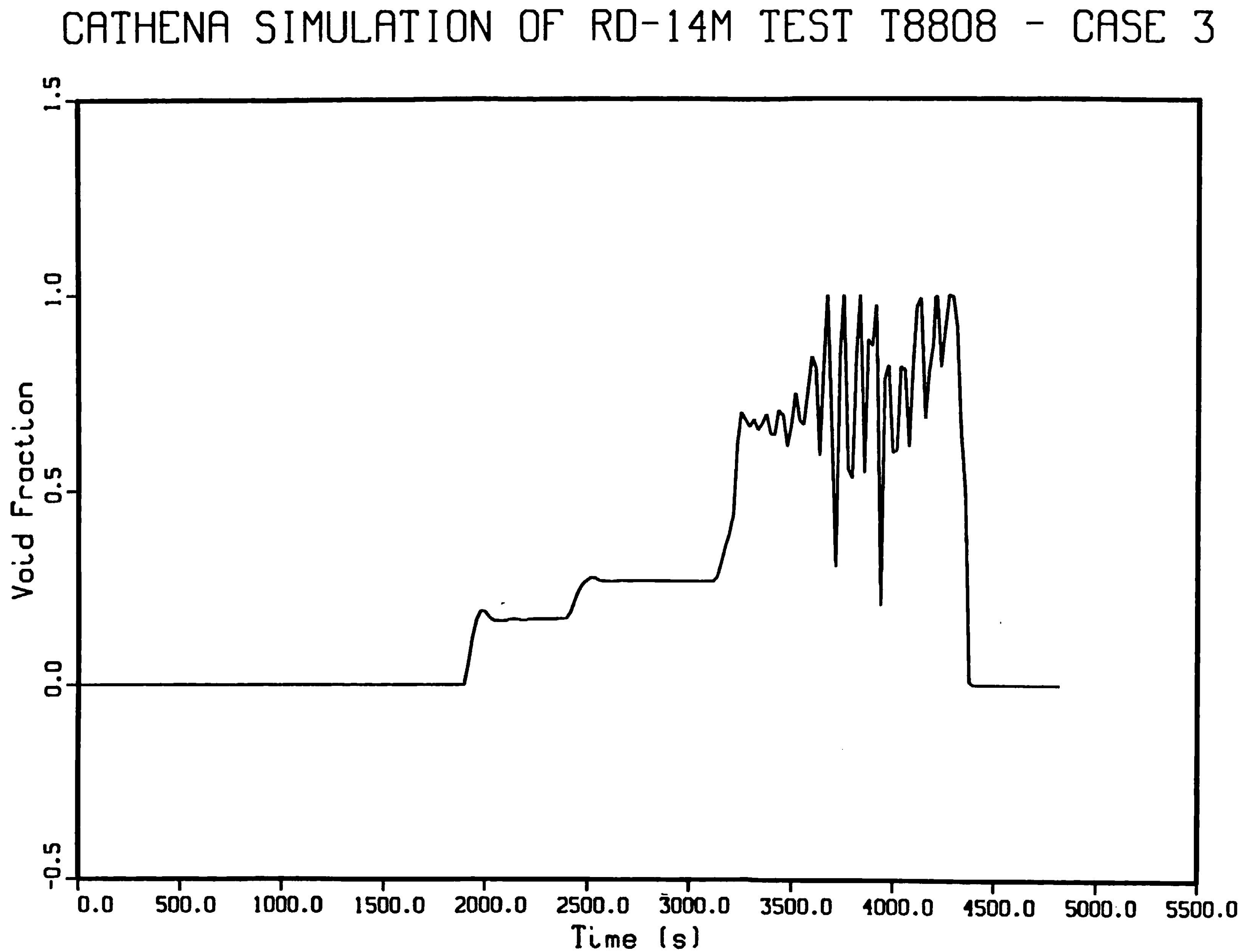

FIGURE 14 : Void Fraction Transient at Top of Boiler #1

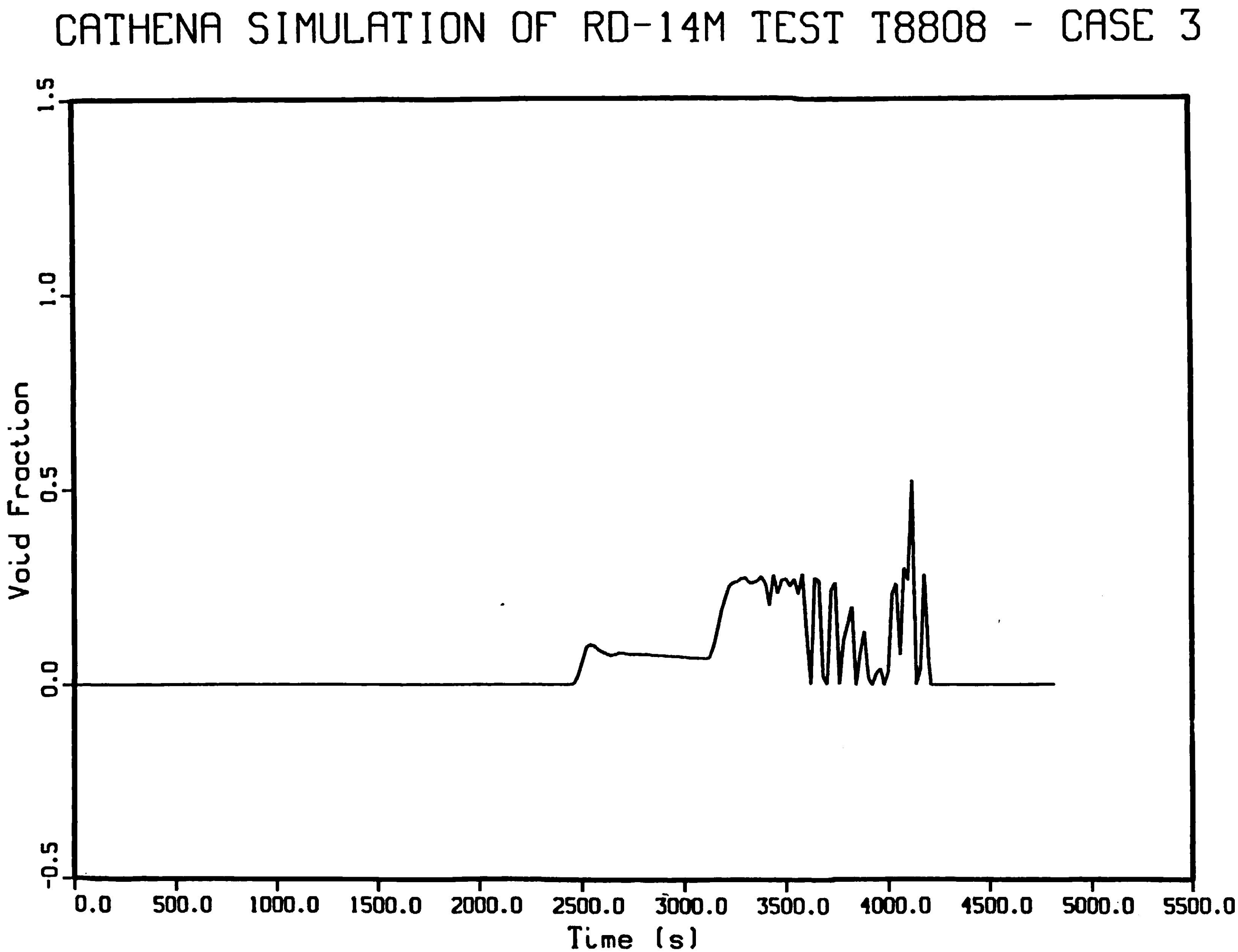

FIGURE 15 : Void Fraction Transient at Mid-Elevation of Cold Leg of Boiler #1

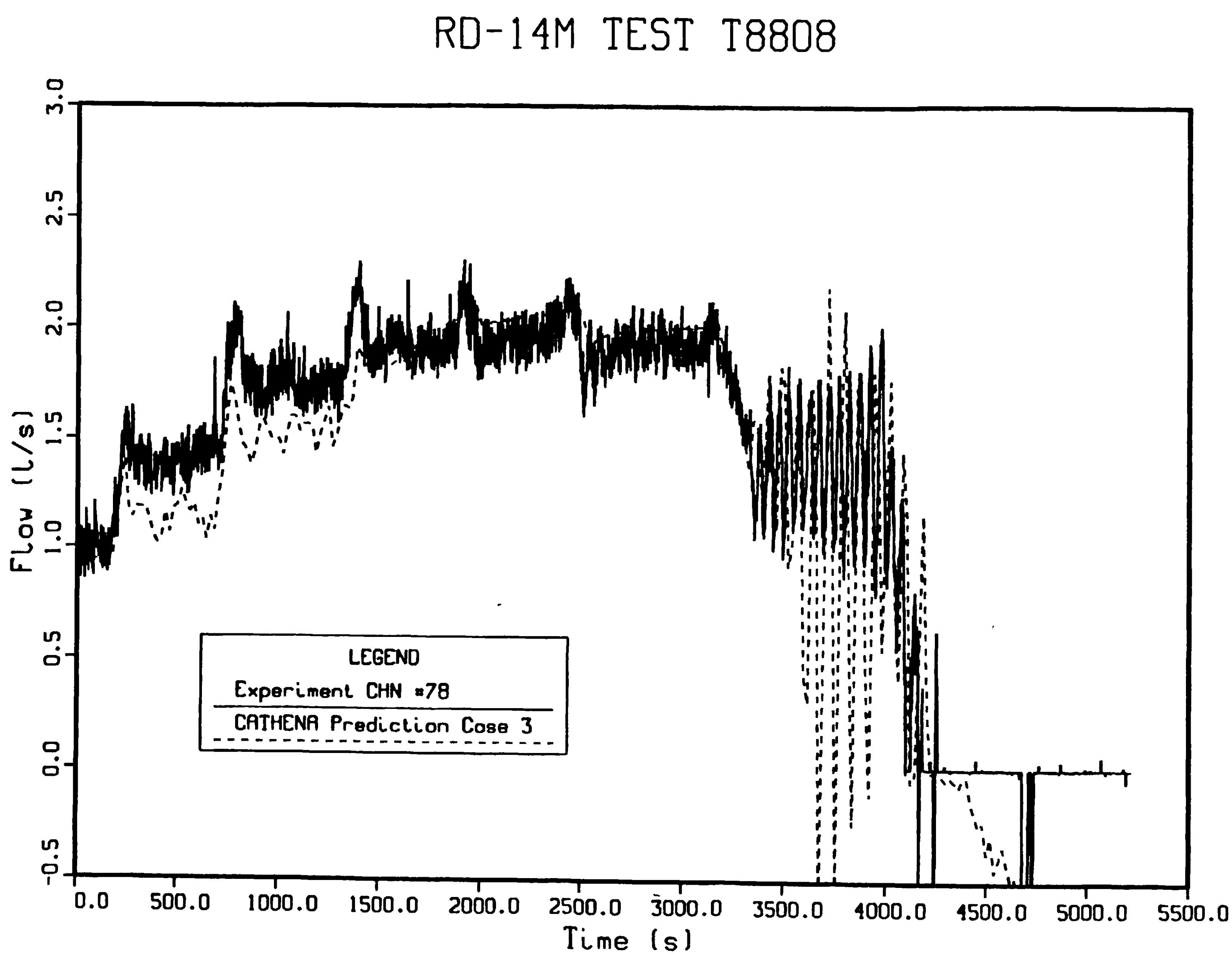

FIGURE 16 : Comparison of Measured and CATHENA MOD-3.3h Predicted Pump #1 Outlet Flowrate Transients

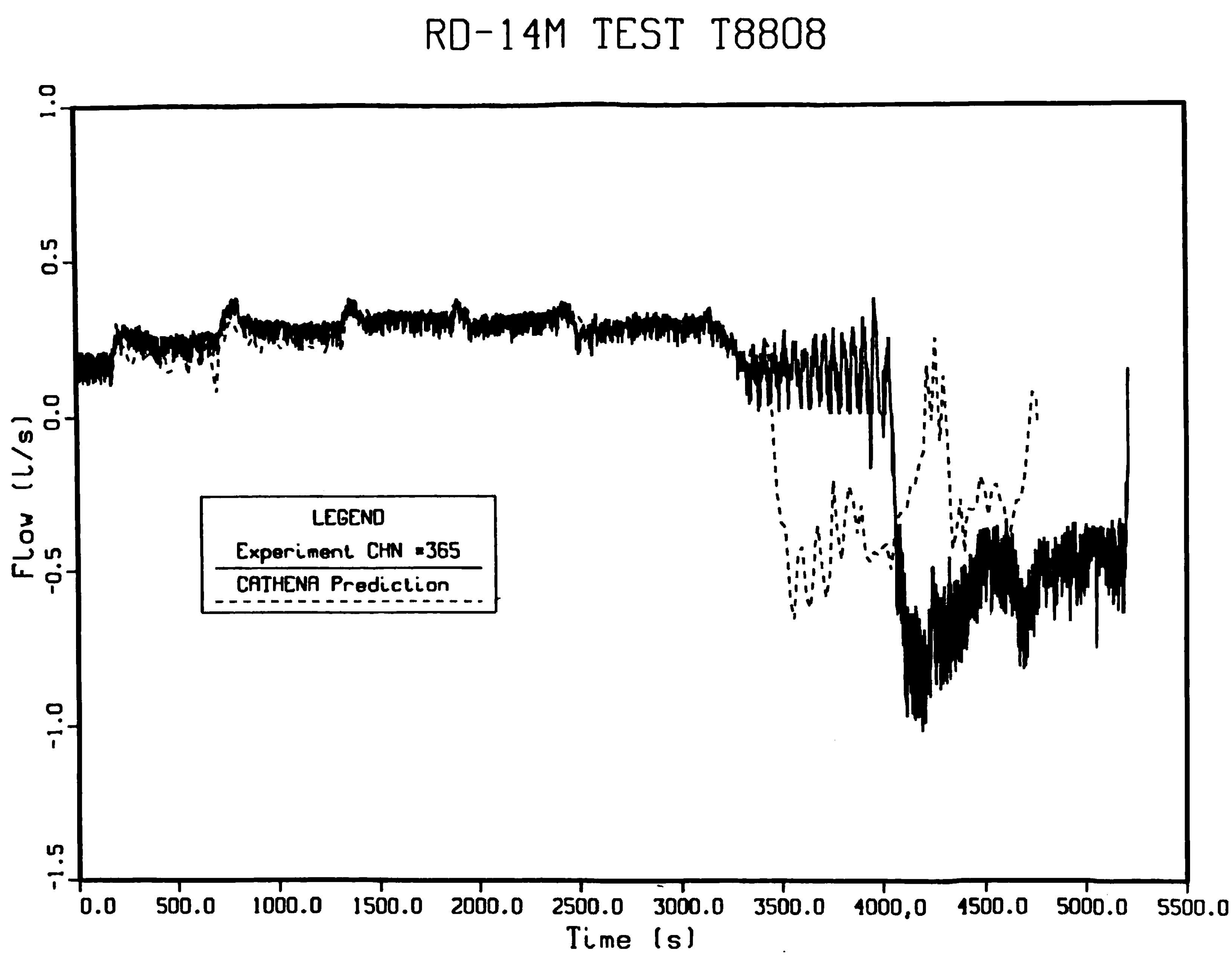

FIGURE 17 : Comparison of Measured and CATHENA MOD-3.3h Predicted HS5 Inlet Flowrate Transients

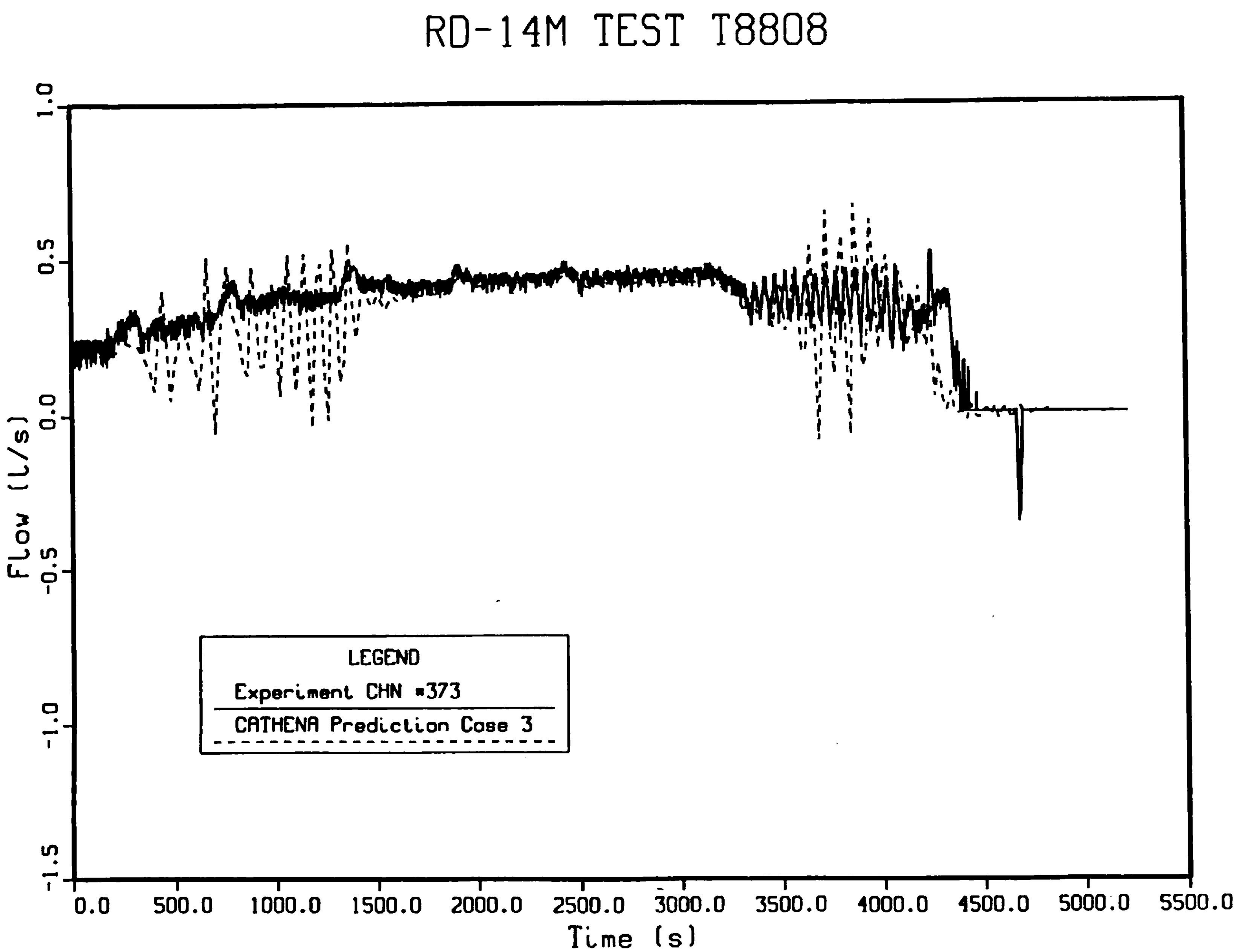

FIGURE 18 : Comparison of Measured and CATHENA MOD-3.3h Predicted HS9 Inlet Flowrate Transients