Some Ideas on Thermosyphoning in a Heat Transport Loop

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ABSTRACT

Analysis of the experimental results from RD-14M natural circulation tests have provided considerable insights into the conditions under which thermosyphoning can be an effective heat transport mechanism for the heat source. This paper focuses on the following aspects of heat transport under thermosyphoning conditions:

a. transition from forced circulation to thermosyphoning, and
b. transition from thermosyphoning to other natural circulation modes.

From analysis of transition-from-forced-circulation-to-thermosyphoning RD-14M experiments (*i.e.*, R-series tests), the transition period following the tripping of the primary heat transport pumps to the time when steady thermosyphoning conditions are established in the loop can be divided into three time phases: a pump rundown phase, a flow-power adjustment phase, and a phase during which a thermosyphoning density driving head is established. A physically reasonable criterion for the onset of local temperature excursions in the transition period is proposed.

From analysis of transition-from-thermosyphoning-to-other-natural-circulation-mode RD-14M experiments (*i.e.*, T-series tests), departure from two-phase thermosyphoning is characterized by the onset of flow reversals in some of the heated sections. A physically reasonable criterion for the onset of flow reversal in the heated sections has previously been proposed. It is shown that this criterion can be used to classify RD-14M T-series tests into three categories: tests with flow reversals under relatively steady conditions, tests with flow reversals under highly oscillatory conditions, and tests with hybrid flow reversals. A detailed discussion of the first and second categories of T-series tests is presented. Experimental observations and results are explained in terms of this flow reversal criterion.

INTRODUCTION

In a heat transport loop with the heat source located at the lowest elevation and the heat sink located at the highest elevation, a particular form of natural circulation cooling, known as thermosyphoning, can be an effective means of cooling the heat source in the absence of any forced circulation. Thermosyphoning is defined to be unidirectional coolant flow around the loop driven by the density differences of the coolant in a hot leg and a cold leg of the loop. The flow may be steady or oscillatory but unidirectional.

The primary heat transport system of a CANDU reactor (with the reactor core located at the lowest elevation and the steam generators or boilers located at the highest elevation) is an example of an arrangement that is conducive to the occurrence of thermosyphoning following a loss of forced circulation. To investigate the effectiveness of

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thermosyphoning cooling in a CANDU-typical figure-of-eight heat transport loop, natural circulation experiments have been performed in the RD-14M experimental facility over a number of years. RD-14M is the only large-scale pressurized-water, multi-channel, figure-of-eight loop with full-elevation change representation and components scaled to yield fluid conditions representative of those in CANDU reactors. A schematic of the RD-14M loop is shown in Figure 1.

Analysis of the experimental results from these natural circulation tests have provided considerable insights into the conditions under which thermosyphoning can be an effective heat transport mechanism for the heat source. This paper focuses on the following aspects of heat transport under thermosyphoning conditions:
a. transition from forced circulation to thermosyphoning, and
b. transition from thermosyphoning to other natural circulation modes.

TRANSITION FROM FORCED CIRCULATION TO THERMOSYPHONING

Under normal operating conditions, the reactor fuel is well cooled by forced circulation driven by the primary heat transport pumps. If the power supply to the primary heat transport pumps is lost, they will run down. Shortly after the loss of power, the reactor is shutdown and the reactor power is reduced to decay power levels. Results from analysis, experiments and actual reactor operating experience show that following a loss of forced circulation, thermosyphoning is capable of removing the core decay heat for a wide range of system conditions. Furthermore, once a heat transport system enters into the thermosyphoning mode of cooling, the system parameters can be maintained in a steady-state mode as long as the system is not significantly perturbed.

Some issues that need to be addressed when considering the effectiveness of thermosyphoning are: Following a loss of forced circulation, how smooth is the transition from forced circulation to thermosyphoning? Will local temperature excursions occur during the transition period?

To study the transition to natural circulation, a number of experiments (known as R-series tests) were performed in the RD-14M facility. Table 1 shows the initial conditions in test R8901 [1]. The test procedure was as follows: The loop was warmed at moderate power and low pump speed. Input power and pump speed were then adjusted to bring the loop to the desired steady-state single-phase initial conditions. The loop was allowed to stabilize at these conditions for about two hours. Once steady conditions were established, the primary pumps were exponentially ramped down starting around 90 s into the test. The surge tank remained connected to the loop throughout the test.

Table 1. Initial Conditions for Test R8901

	R8901
Primary System	
outlet header pressure MPa(g)	0.53
nominal power per pass kW	100
pass 1 pump flow L/s	13.8
pass 2 pump flow L/s	13.6
initial pump speed %	50
inlet trace heating kW	4
outlet trace heating kW	10
Secondary System	
steam drum pressure MPa(g)	0.1
feedwater temperature °C	80

The transition period following the tripping of the primary heat transport pumps to the time when steady thermosyphoning conditions are established in the loop can be divided into three time phases:

a. a pump rundown phase: during the pump rundown phase, the flows through the heated sections are controlled by the rundown characteristics of the pump. In this test, the pumps were turned off around 220 s into the test (*i.e.*, about 130 s after the start of the pump rundown). Prior to the pump rundown, the coolant temperature distribution around the loop is fairly uniform under decay-power forced-convection conditions. During the pump rundown phase, the loop flow is constantly decreasing, with a resultant change in the coolant temperature distribution around the loop.

b. a flow-power adjustment phase: At the end of pump rundown, the HT (heat transport) pumps are no longer the dominant factor driving flow around the loop. Instead, the driving force is provided by coolant density differences in the vertical piping sections connected to the ends of the heated sections. In many R-series RD-14M tests, the flow generated by the coolant density differences around the loop at the end of pump rundown were not high enough to keep the FES (fuel element simulators) at a constant temperature. Consequently, local heat-up of the FES could occur. Local heating of the coolant in the heated sections results in the formation of lower density coolant (either in the form of higher temperature coolant, or a two-phase mixture) in the heated sections and in the outlet piping.

c. a phase during which a thermosyphoning density driving head is established: This phase is characterized by the discharge of lower density coolant from the heated sections to the outlet feeders. Discharge occurs to the outlet feeders because forward flow is maintained during the flow-power-adjustment period. Following the discharge of lower density fluid to the outlet feeders, the flow generated by the coolant density differences is sufficient to remove all of the generated and stored heat from the heated sections, and the system enters a state of steady thermosyphoning.

Figures 2 and 3 show the measured loop flows at pump P1 and pump P2 in test R8901. After the complete rundown of the pumps, the flows were recorded as zero for a period of time. This is attributed to the stalling of the turbine flow meters at very low flow. Figures 4 and 5 show the inlet and outlet header temperatures (headers 6 and 7 respectively) in test R8901. Figures 6 to 8 show the top-pin sheath temperatures measured at the inlet, centre and outlet of heated section 11 in test R8901.

<u>A Criterion For Onset of Temperature Excursions During the Transition Period</u>

Based on the above understanding of the processes at work during the transition from forced to natural circulation, a physically reasonable criterion for the onset of local temperature excursions in the transition period is as follows:

$$\Delta\rho_{PUMP\text{-}RUNDOWN} < \Delta\rho_{THERMOSYPHON} \qquad \text{Eq. 1}$$

$\Delta\rho_{PUMP\text{-}RUNDOWN}$ is the density difference between the fluid in the hot and cold legs of the loop at the end of pump rundown. In general, $\Delta\rho_{PUMP\text{-}RUNDOWN}$ depends on a number of factors including:

a. the coolant distribution prior to the pump rundown,

b. the detailed rundown characteristics of the HT pumps,

c. the power history of the heated sections prior to and during the pump rundown period.

$\Delta\rho_{THERMOSYPHON}$ is the equilibrium density difference between the fluid in the hot and cold legs required to sustain steady thermosyphoning conditions for a given power in the loop. In general, $\Delta\rho_{THERMOSYPHON}$ depends on a number of factors including:

a. power input to the coolant,

b. heat losses from the loop, and

c. flow resistances around the loop.

The above criterion essentially states that when the density difference between the fluid in the hot and cold legs of the loop at the end of the pump rundown period becomes less than that required for equilibrium thermosyphoning conditions, local temperature heat-up of the coolant will occur to increase the density difference driving thermosyphoning. An upper bound estimate of the peak sheath temperature that might be attained during the transition period can be obtained using Ontario Hydro's CCAFF [2,3] methodology which assumes a sustained interruption of flow through the heated section.

TRANSITION FROM THERMOSYPHONING TO OTHER NATURAL CIRCULATION MODES

Once a heat transport system enters into the thermosyphoning mode of cooling, the system parameters can be maintained in a steady-state mode as long as the system is not perturbed.

In the case where the system conditions are perturbed, a departure from thermosyphoning cooling to other modes of natural circulation cooling can eventually occur. To investigate the departure from thermosyphoning to other modes of natural circulation cooling, a number of experiments (known as T-series tests) have been conducted in the RD-14M facility. The test procedure for these tests was typically as follows: Each experiment was started with the loop in single-phase thermosyphoning conditions. The surge tank was valved out. By controlled intermittent draining of the liquid inventory from the loop, two-phase natural circulation was established. Intermittent draining of the loop inventory continued until a process protection trip (usually high sheath temperature of ~600°C) occurred, thus terminating the experiment. In this paper, FES temperature excursions in excess 600°C are classified as significant temperature excursions.

The issues of interest from these tests are: Under what conditions would a departure from the thermosyphoning mode of cooling occur? And, what are the characteristics of the subsequent natural circulation mode?

Results from RD-14M natural circulation experiments show that the transition from two-phase thermosyphoning to other natural circulation modes is denoted by the onset of flow reversal in some of the heated sections (or the onset of bi-directional flow). Conceptually, the onset of flow reversal in one or more heated sections should result in a degradation in the heat rejection capability from that under thermosyphoning conditions, since an alternative pathway is created for circulating the coolant between a pair of headers entirely within the piping of the heated sections, the feeders and the headers. The heated coolant in this alternative pathway bypasses the dominant heat sinks (*i.e.,* steam generators). Since there are five heated sections per pass in the RD-14M loop, the onset of flow reversal in one heated section per pass corresponds to:

a. 80% of the heated sections flowing in the normal forward direction, and 20% of the heated sections flowing in the reverse direction, and
b. a potential reduction in the above-header flow (going through the steam generators) by a factor of 2/5 or 40%.

Experimentally, the onset of flow reversal in one heated section per pass was observed to result in a reduction in the flow rate through the steam generators and a slight increase in the overall coolant temperature to new steady-state levels. RD-14M experimental results also show that the onset of flow reversal in one heated section per pass did not coincide with the onset of significant temperature excursions in the heated sections. In all tests, the liquid inventory had to be further reduced, and more than one heated section per pass had to reverse before significant temperature excursions were encountered. These observations suggest that the degradation in the heat rejection capability following the onset of flow reversal in one heated section per pass is transient and short-lived. The effect of a reduction in the above-header flow following flow reversal appears to be off-set by the development of a larger primary-to-secondary temperature gradient. RD-14M test results suggest that following the onset of flow reversal in one heated section per pass, the system parameters (mainly temperature) are able to readjust themselves to new steady-state values and thereby restore the same overall heat rejection capability.

By analyzing the T-series RD-14M natural circulation experiments, the following criterion for the onset of flow reversal in a heated section (or channel) has been proposed [4]:

$$[\rho_{IF}(t) - \rho_{OF}(t)]\, g\, h < -[P_{IH}(t) - P_{OH}(t)] \qquad \text{Eq.2}$$

where $\rho_{IF}(t)$ is the average density of the coolant in the inlet feeder at time t,
$\rho_{OF}(t)$ is the average density of the coolant in the outlet feeder at time t,
$P_{IH}(t)$ is the inlet header pressure at time t,
$P_{OH}(t)$ is the outlet header pressure at time t,
g is the gravitational acceleration constant, and
h is the elevation difference from the header to the heated section.

This criterion is effectively a statement of force balance on the fluid in the heated section. Under thermosyphoning conditions, the feeder density difference term (on the left hand side of Eq.2) is positive. For the onset of flow reversal to occur, the above criterion states that the header-to-header pressure differential (on the right hand side of Eq. 2) must be negative and its magnitude must be greater than the feeder density difference term on the left hand side.

The above flow reversal criterion is useful for classifying the flow reversals observed in the RD-14M T-series of natural circulation experiments into three categories:

a. flow reversals under relatively steady conditions,
b. flow reversal under highly oscillatory conditions, and
c. hybrid flow reversals.

Flow Reversals Under Relatively Steady Conditions

In this category, the system response to the systematic reduction in the liquid inventory in the loop is relatively steady. While there may be minor fluctuations in the system parameters as a result of the perturbation (*i.e.,* the draining process), these fluctuations are relatively small so that the force balance of the terms in Eq. 2 at a particular time t is essentially the same as a force balance of the terms in Eq. 2 using time-averaged values. Under these conditions, a flow reversal occurs when the large feeder density gradient term (driving flow in the normal forward direction) is counterbalanced by an even larger negative header-to-header pressure gradient.

The above flow-reversal condition is consistent with the experimental observation that the highest-elevation and the lowest-power heated sections are the first ones to reverse because the feeder density difference term on the left hand side of Eq.2 is the smallest amongst the heated sections. In general, the feeder density difference term depends on the following factors:

a. the elevation difference from the header to the heated section,
b. the power input to the heated section.

These ideas are illustrated in Figure 9 showing the experimentally measured header-to-header pressure differential as well as that required to reverse heated section 5 (the highest-elevation and lowest-power heated section in one pass) in test T8805. The ΔP_{HH} required to reverse the flow in heated section 5 was estimated from gamma densitometer readings at the inlet and exit of the heated section. (See reference 4 for more details). In Figure 9 (and the subsequent figures as well), small arrows are used to denote the beginning and end of each drain, while large arrows are used to denote the occurrence of flow reversals in the heated sections.

In these T-series tests, the initial removal of inventory from the hot leg side actually enhances the two-phase thermosyphoning flow since the feeder density difference term in Eq. 2 is increased with the formation of void in the outlet feeders due to draining. For flow reversals to occur in this mode, the header-to-header pressure differential has to become sufficiently large and negative. The development of an increasingly negative header-to-header pressure differential with draining has been explained [5] by postulating:

a. that the two-phase region in the steam generators will eventually extend beyond the top of the U-bend of the steam generator tubes following draining, and
b. that flow through an increasing number of steam generator tubes will cease as the system inventory is reduced.

Eventually, the header-to-header pressure difference is sufficiently large and negative to overcome the feeder density difference term. For tests conducted at a power level of 160 kW/pass and a secondary side pressure of 4.5 MPa, this condition was typically achieved when the liquid inventory in the RD-14M loop had been reduced to about 85% of the initial inventory. The onset of flow reversal (or the departure from thermosyphoning) was followed by additional flow reversals in the heated sections, and rapid FES temperature excursions leading to the termination of the experiments following a further reduction in the primary coolant inventory.

Flow Reversal Under Highly Oscillatory Conditions

In this category, large oscillations in the system parameters (including those in the density gradient term and the header-to-header pressure gradient term in Eq. 2) are observed following the removal of a certain amount of inventory from the system. The timing and magnitude of these oscillations are such that for a short period of time the flow reversal criterion (Eq. 2) is satisfied. Figure 10 show the experimentally measured header-to-header pressure differential in test T8809. Figure 11 shows a flow reversal in heated section 8 occurring around 3000s in test T8809. Figure 12 shows a comparison of the experimentally measured header-to-header pressure differential versus that required to reverse the flow in heated section 8.

The above mechanism can be used to explain (in whole or in part) a number of experimental observations:

a. Onset of flow reversals can occur at relatively high liquid inventories (>90%). In this category, the onset of flow reversal depends on the stability characteristics of the loop. If the system response to the perturbation (*i.e.*, removal of inventory) becomes highly oscillatory at high liquid inventories, flow reversals can occur at high inventories. The stability characteristics of a figure-of-eight heat transport loop under thermosyphoning conditions have been investigated by a number of investigators [6-11].
b. There is much greater variability (in comparison to the flow reversals classified under the first category) with regards to which of the heated sections is the first to reverse. This result is consistent with the observation that the oscillations in the feeder density difference term and the header-to-header pressure differential term in Eq. 2 are not strongly coupled.
c. flow reversals in this category do not necessarily lead to significant temperature excursions. While flow reversals can occur with relative ease in this category, by the same token the flow in a reversed heated section can easily revert back to its original forward flow direction, *i.e.*, some flow reversals are temporary. This is particularly true when the onset of flow reversal occurs at a high liquid inventory. In RD-14M tests, no significant FES temperature excursions were observed to result from intermittent or first flow reversals in the heated sections.

Under certain conditions, a temporary flow reversal can become a sustained one. A sustained reversal of flow for a particular heated section can result in the sustained exposure of the inflow feeder to steam at its inflow header. This in turn can result in a sustained FES temperature excursion.

Such occurrences have been observed in tests T8809, T8810 and T9308. These tests are unique in that significant FES temperature excursions were observed to occur at high (>85%) loop inventories. It should be noted that six other tests conducted under nominal conditions that are the same as those in these three tests did not experience high FES temperatures until the inventory had been reduced to below 70%.

In all three tests (T8809, T8810 and T9308), no significant temperature excursion was observed following the onset of first flow reversal, *i.e.*, when the flow in only one heated section per pass has reversed. When additional heated sections in the same pass reversed their flow direction, significant temperature excursions were observed. The onset of flow reversal in two heated sections per pass in the RD-14M loop corresponds to:

a. 60% of the heated sections flowing in the normal forward direction, and 40% of the heated sections flowing in the reverse direction, and

b. a potential reduction of the above-header flow (going through the steam generators) by a factor of 4/5 or 80%.

Under this flow configuration, significant amounts of steam can accumulate in the inlet and outlet headers of that pass. The inflow feeders of some heated sections can become exposed to steam for a sustained period of time, resulting in a sustained temperature excursion. Some factors influencing which of the heated sections can become steam-exposed include:

a. the location and direction of flow in a feeder in relation to the location and direction of flow of the boiler intake or discharge piping,
b. the location and direction of flow in a feeder in relation to the location and direction of flow of the neighbouring feeders, and
c. the location of feeder connections in the header.

Some of these ideas can be illustrated using Figure 13, which is a schematic of inlet header 6 and outlet header 7. Under two-phase thermosyphoning conditions, the outlet header (*e.g.*, header 7) is two-phase "filled". Since the boiler intake piping is located at one end of the outlet header, the steam discharged from the five heated sections have to migrate towards the boiler intake piping, resulting in a void profile in the outlet header which should be highest around the boiler intake piping and lowest around the outlet feeder connections of heated sections 5 and 6. This geometrical arrangement at outlet header 7 suggests that heated sections 5 and 6 are not likely to be *steam-exposed* following a reversal of flow in either of these heated sections. At the same time, the inlet feeder connections of heated sections 5 and 6 to inlet header 6 are located directly beneath the pump discharge piping. This geometrical arrangement suggests that under forward flow conditions, both of these heated sections should be supplied with single-phase coolant, and in the event that a flow reversal occurs in one of them, any two-phase coolant emerging from heated section 5 or 6 is likely to be condensed by the subcooled coolant emerging from the pump discharge piping. Analysis of experimental results show that significant FES temperature excursion rarely occurred in heated sections 5 or 6. A similar line of reasoning suggests that heated section 9 has a higher probability of experiencing significant FES temperature excursions following a flow reversal. Experimental analysis shows that the number of heat-ups in heated section 9 is amongst the highest of all heated sections.

Ongoing analysis is being conducted to explain the experimental results observed in the other pass of the RD-14M loop regarding which of the heated sections in this pass has a higher frequency of becoming steam-exposed following the reversal of flow.

The magnitude of the FES temperature excursion in this mode has been shown to be conservatively modelled [12] by assuming the occurrence of feeder draining in the inflow feeder using Ontario Hydro's SLLOH methodology [13]. Figure 14 shows the pressure drop measurements across the inlet and outlet feeders of heated section 8 in T8809. The feeder pressure drop measurement can be used to provide a qualitative indication of the nature of the fluid inside the feeder. At the beginning of the test, the measured feeder pressure drops were set to yield close-to-zero values when the feeders were completely liquid filled. When a feeder became two-phase "filled", the feeder pressure drops would deviate from the close-to-zero values: the inlet feeder pressure drop would become more positive while the outlet feeder pressure drop would become more negative. Figure 14 shows that in T8809 the inlet feeder was initially liquid filled until the onset of flow reversal at about 3000 s, after which void was present for the remainder of the test. Figure 14 also shows that the outlet feeder was initially liquid filled until about 1200 s, after which evidence of void was intermittently detected. With the onset of flow reversal at 3000 s, the outlet feeder became and remained liquid filled until about 3760 s. The drop in outlet feeder ΔP after this time indicates that void was present in the outlet (inflow) feeder. Since void was not detected by the gamma densitometer near the entrance to the heated section until about 4200 s (see Figure 15), this suggests the occurrence of feeder draining. Around 4300 s, a second flow reversal occurred in heated section 6, resulting in significant voiding in both the inlet and outlet feeders of heated section 8 (see Figures 14 and 15). Figure 16 shows the corresponding measured peak FES temperature in heated section 8. It should be noted that the measured peak FES temperature in heated section 8 was levelling off towards the end of the test. This levelling-off of the peak FES temperature excursions was observed in all three tests (T8809, T8810 and

T9308). This trend is consistent with the temperatures computed using the SLLOH methodology [12]. Currently, additional RD-14M tests are being conducted to investigate the limits of FES temperature excursions.

Hybrid Flow Reversals

Flow reversals in this category are hybrids of those of the first and second categories. Flow reversals occur partly due to the development of an adverse header-to-header pressure gradient that partially offsets the forward density gradient term in Eq. 2, and partly due to the establishment of system fluctuations whose timing and magnitude are such that the header-to-header pressure gradient term is sufficiently large and negative to partially offset the density gradient term in Eq. 2. The combined influence of the above two factors is sufficient to cause flow reversals to occur in some heated sections. Test T9209 is an example in this category (see Figure 17). It should be noted that onset of first flow reversal occurred at about 24600 s in this test.

CONCLUDING REMARKS

Over seventy RD-14M tests (T- and R-series) have demonstrated the effectiveness of natural circulation cooling in a CANDU-typical figure-of-eight heat transport loop for coolant inventories varying from full to substantially reduced values. Following a loss of forced circulation, the heat source (at decay power levels) can be effectively cooled by single- or two-phase thermosyphoning. Local temperature excursions may be experienced in the transition period. If the coolant inventory is further reduced, RD-14M natural circulation experiments show that a transition from two-phase thermosyphoning to a flow pattern with reversed flow in some of the heated sections can occur. Analysis of these RD-14M tests has led to an understanding of the fundamental physical processes responsible for flow reversal and subsequent breakdown of FES cooling. Out of the seventy RD-14M (T- and R-series) tests, significant FES temperature excursions (>600°C) occurred at relatively high inventories (>85%) in only three T-series tests. It was noted that six other tests conducted under nominal conditions that were the same as those in these three tests did not experience high FES temperatures until the inventory had been reduced to below 70%. Analysis shows that in all tests, significant FES temperature excursions did not occur when 20% of the heated sections per pass (corresponding to flow reversal in one heated section per pass) reversed their direction of flow. In all tests, significant FES temperature excursions occurred when 40% of the heated sections per pass (corresponding to flow reversals in two heated sections per pass) reversed their direction of flow. Furthermore, experimental results and analysis of FES temperature excursions suggest that the maximum FES temperatures attained following reversal of flow in 40% of the heated sections per pass tend to approach asymptotic values that are significantly below 1000°C. Currently, additional RD-14M tests are being conducted to investigate the limits of these FES temperature excursions.

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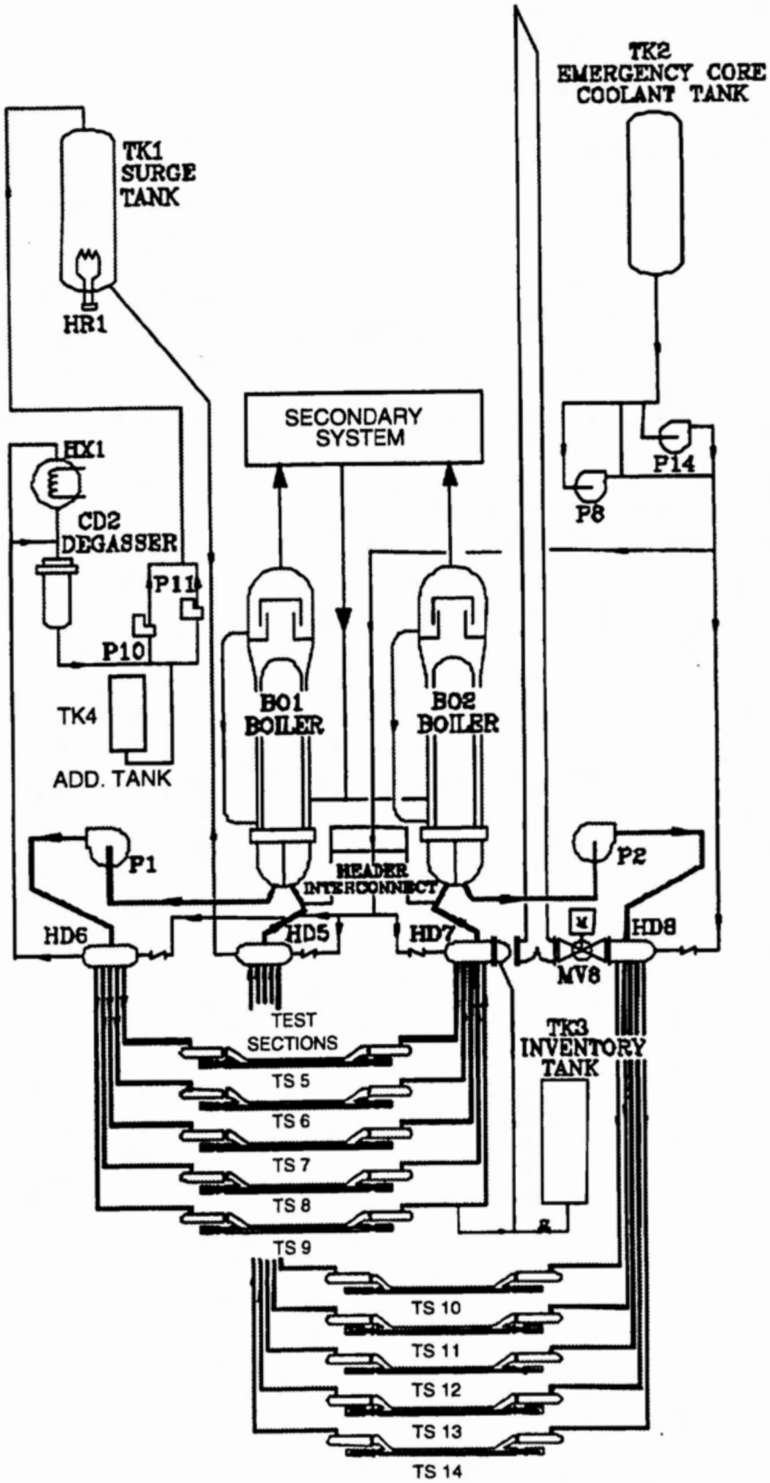


A SCHEMATIC OF THE RD-14M FACILITY

Figure 1

Figure 2 RD-14M - Test R8901
Pump Flow P1

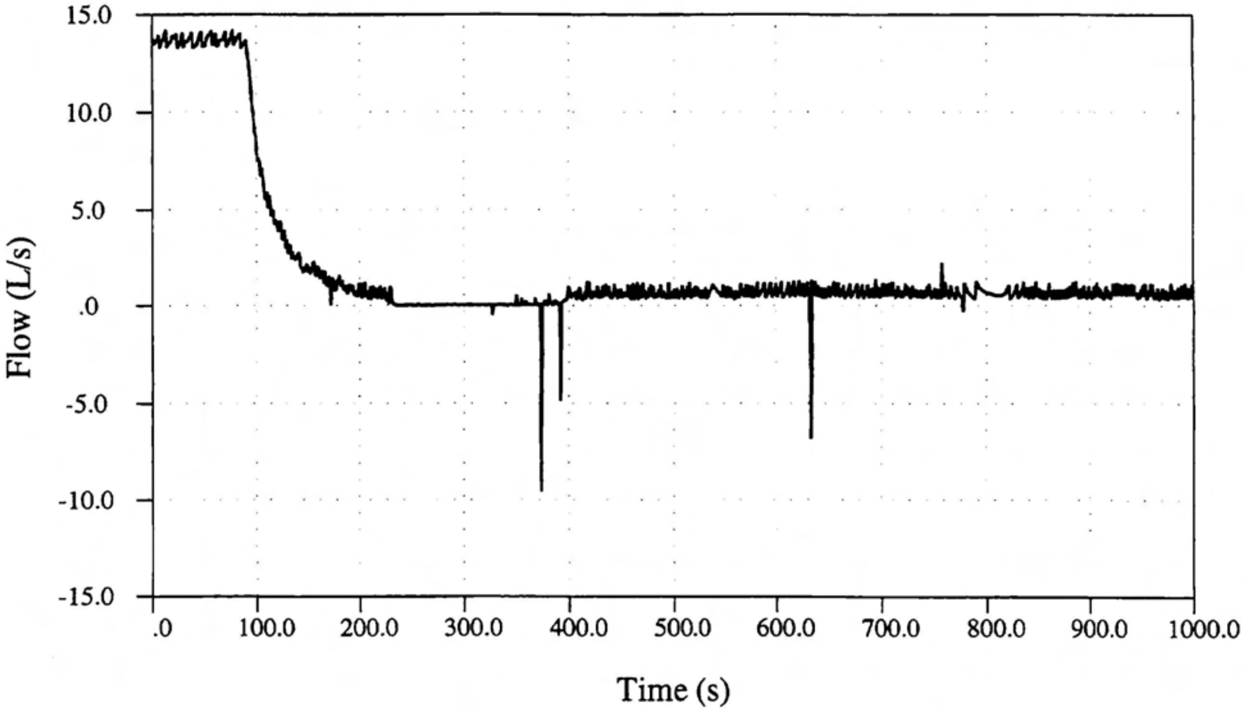


Figure 3 RD-14M - Test R8901
Pump Flow P2

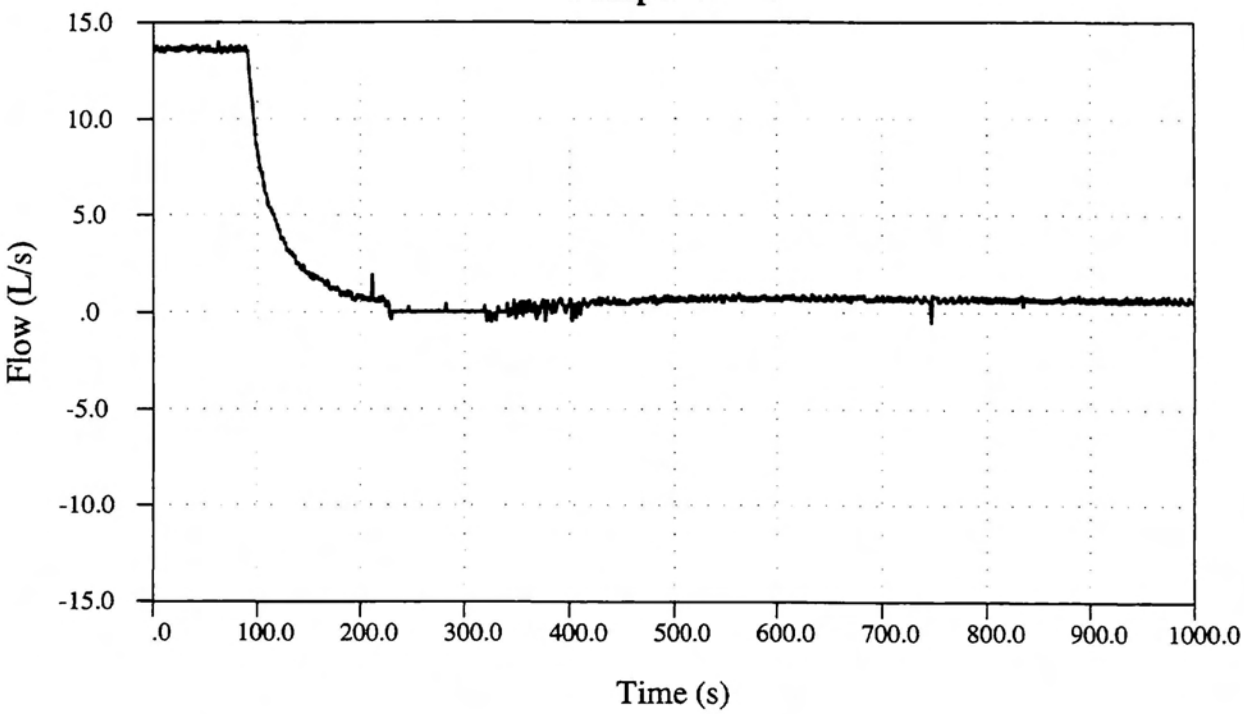


Figure 4 RD-14M - Test R8901
Inlet Header Temperature HDR6

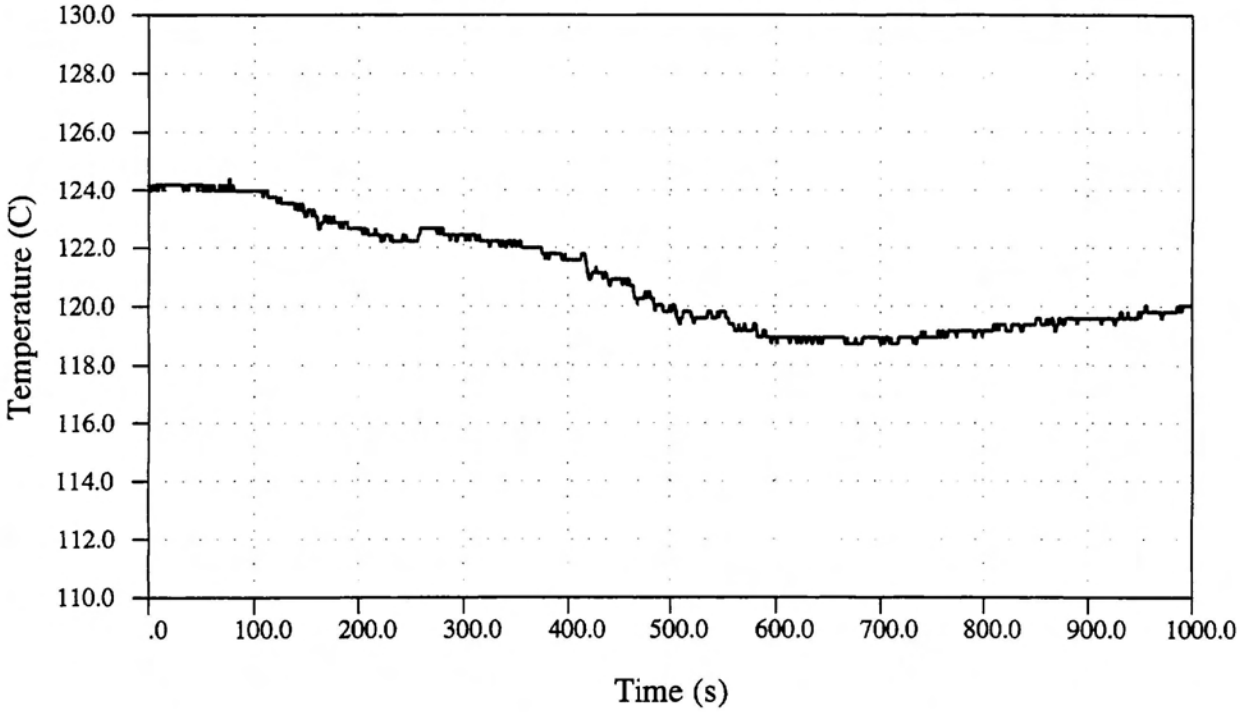


Figure 5 RD-14M - Test R8901
Outlet Header Temperature HDR7

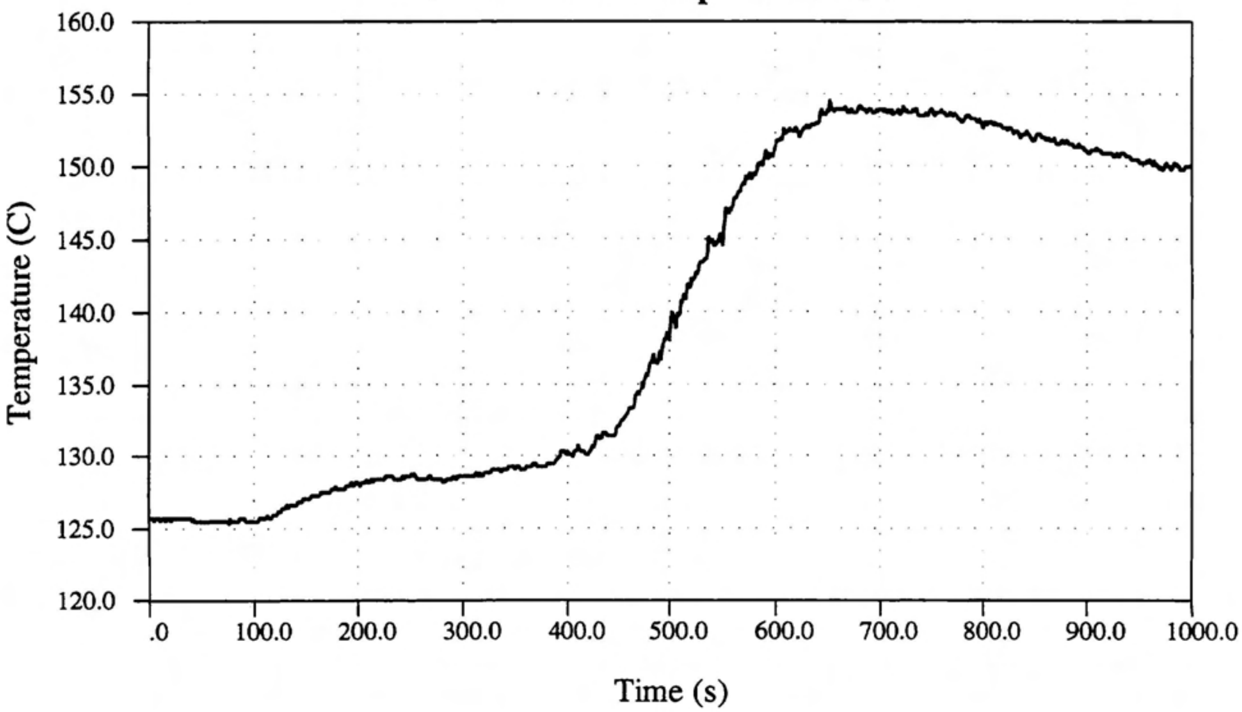


Figure 6 RD-14M Test R8901
Sheath Temperature - HS11 Inlet

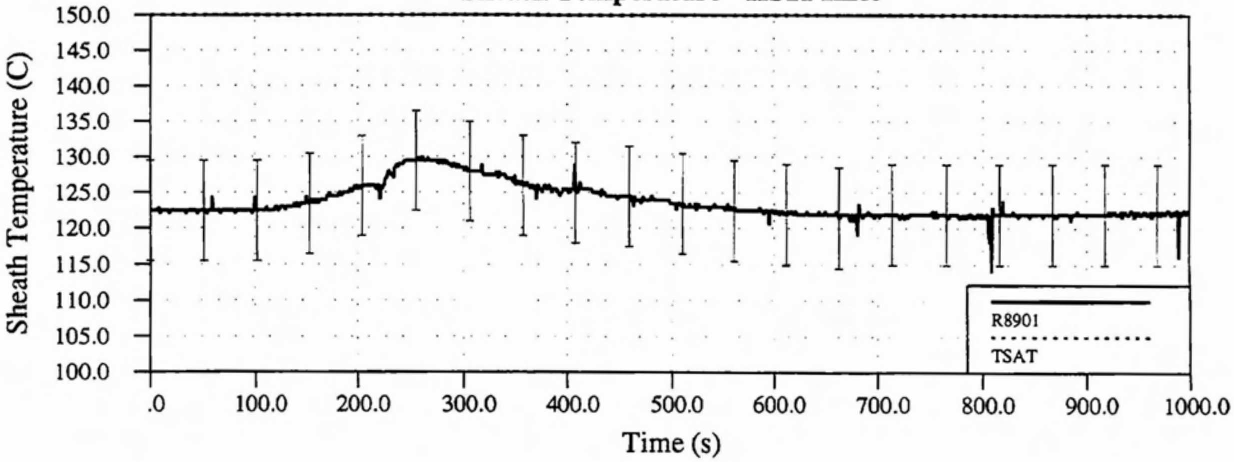


Figure 7 RD-14M Test R8901
Sheath Temperature - HS11 Centre

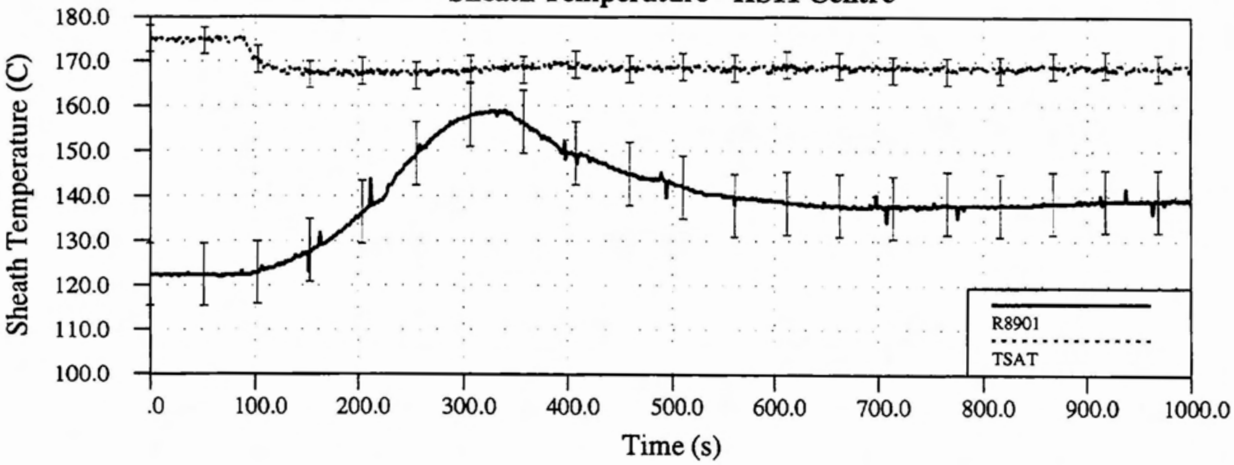
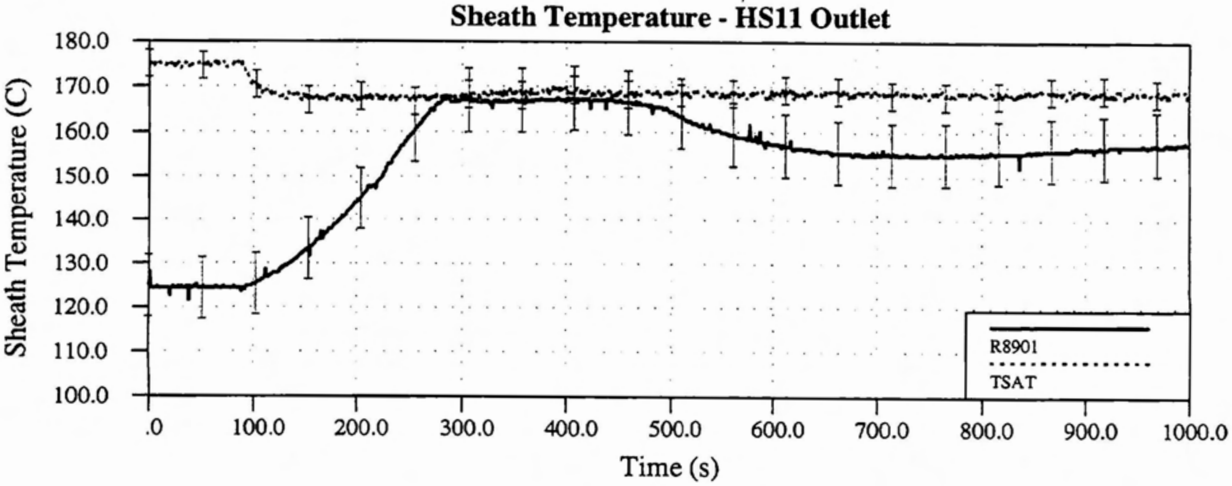


Figure 8 RD-14M Test R8901
Sheath Temperature - HS11 Outlet



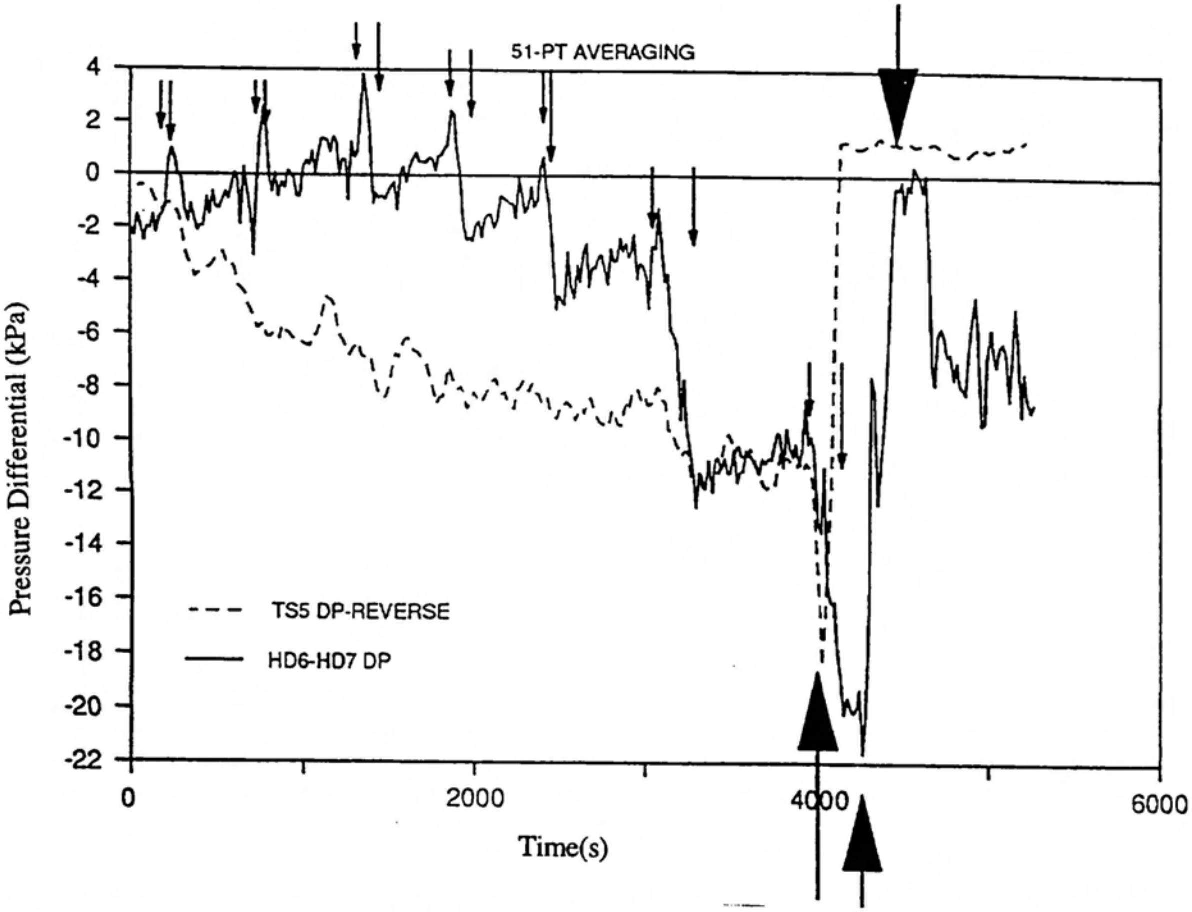


Figure 9 Comparison of Experimentally Measured Header-to-Header Pressure Differential and the Header-to-Header Pressure Differential Required to Flow Reversal in Heated Section 5 in Test T8805.

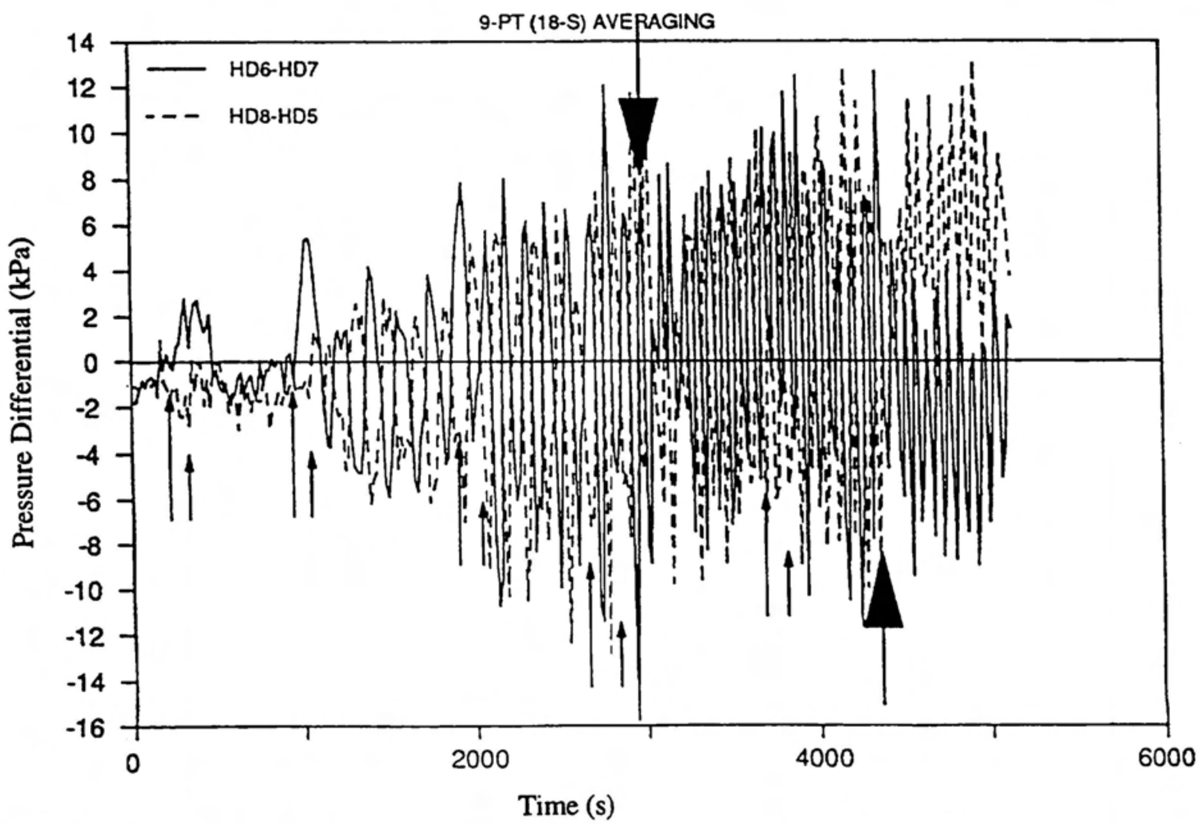


Figure 10 Header-to-Header Pressure Differential as a Function of Time in Test T8809

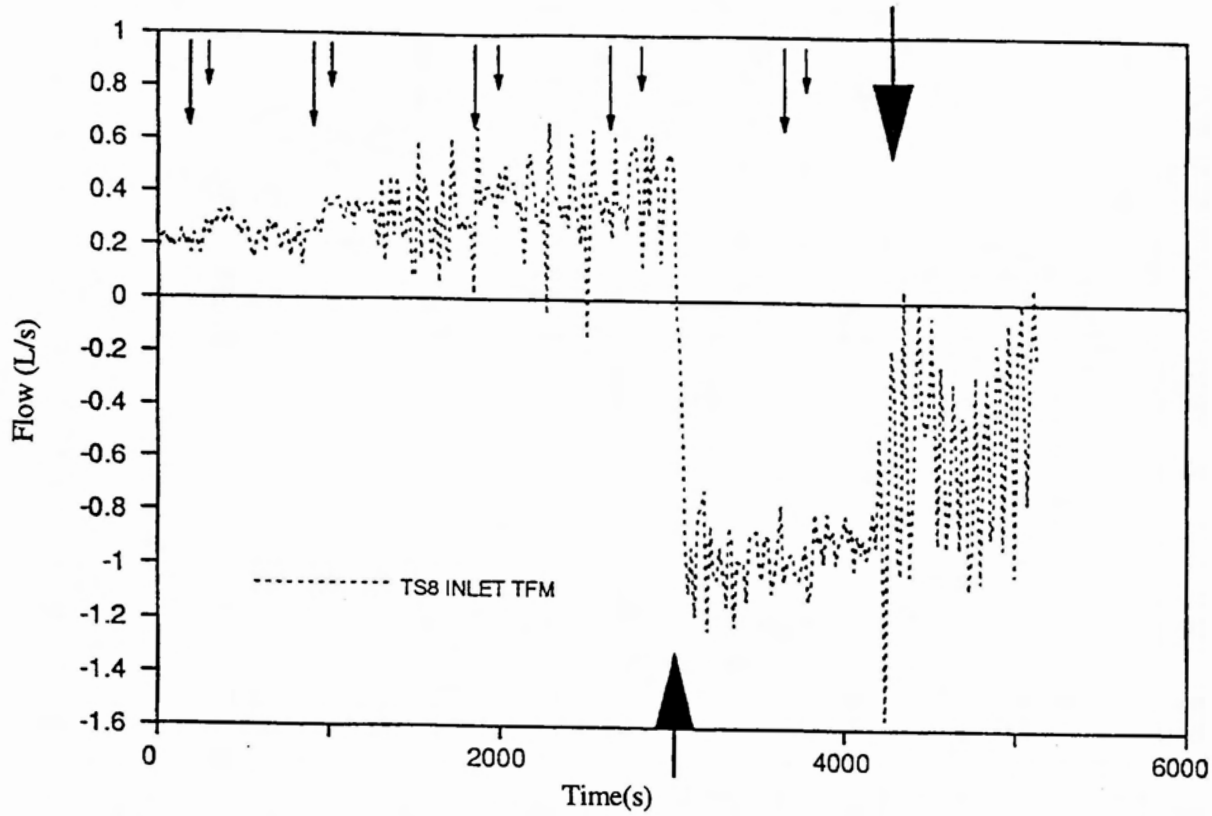


Figure 11 Inlet Feeder Turbine Flow Meter Reading Transient for Heated Section 8 in Test T8809.

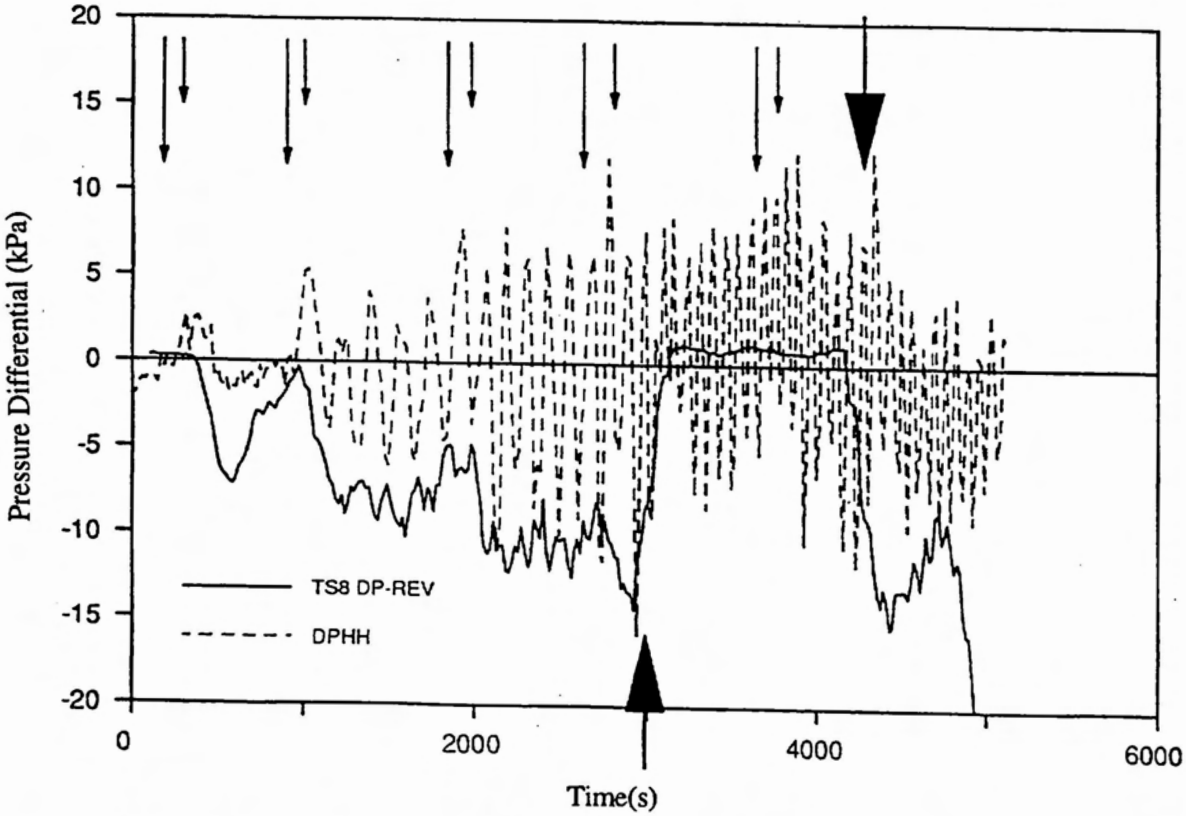


Figure 12 Comparison of Experimentally Measured Header-to-Header Pressure Differential (kPa) and the Header-to-Header Pressure Differential Required for Flow Reversal in Heated Section 8 in Test T8809.

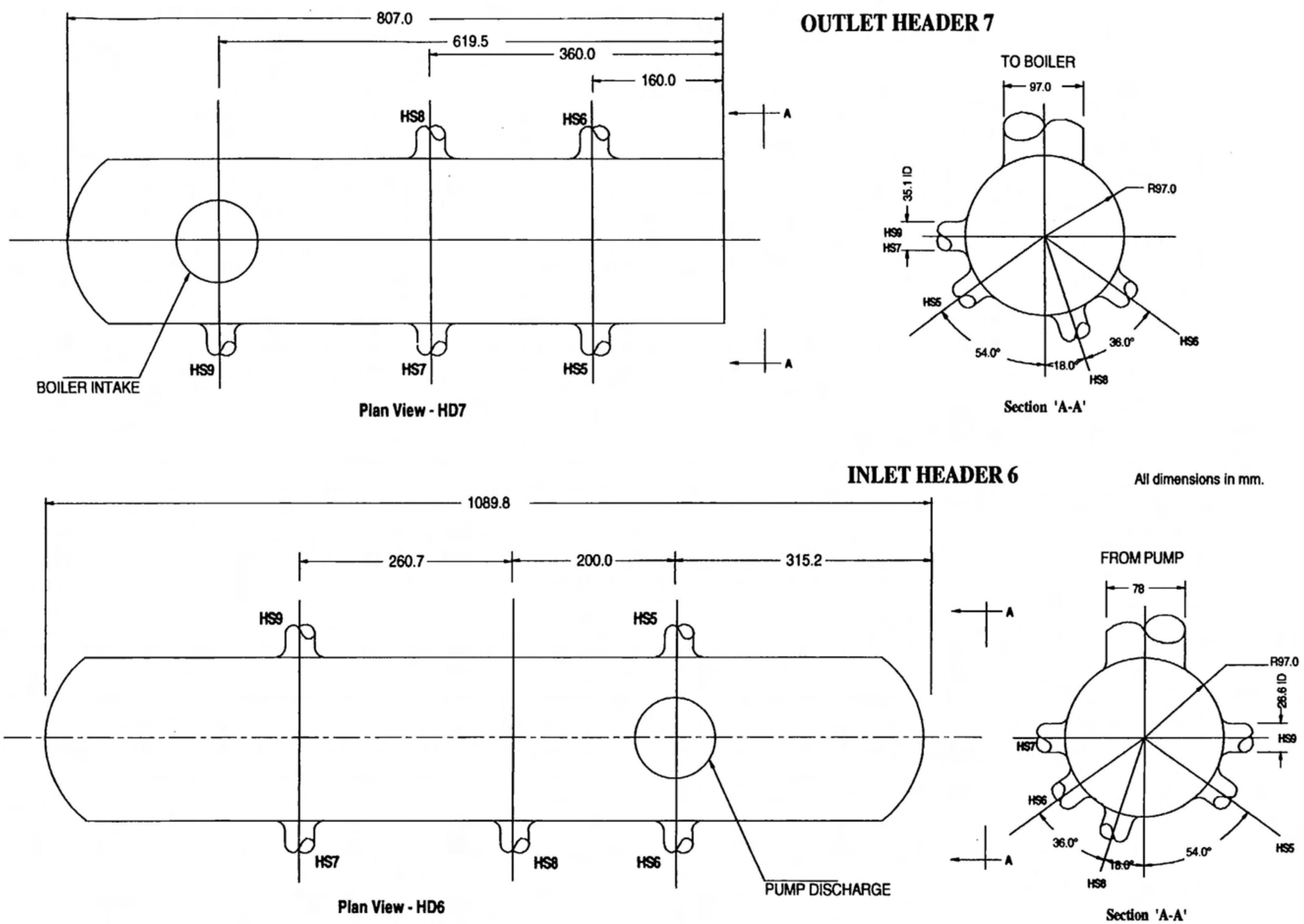


Figure 13. Schematic Diagram of Inlet Header 6 and Outlet Header 7.

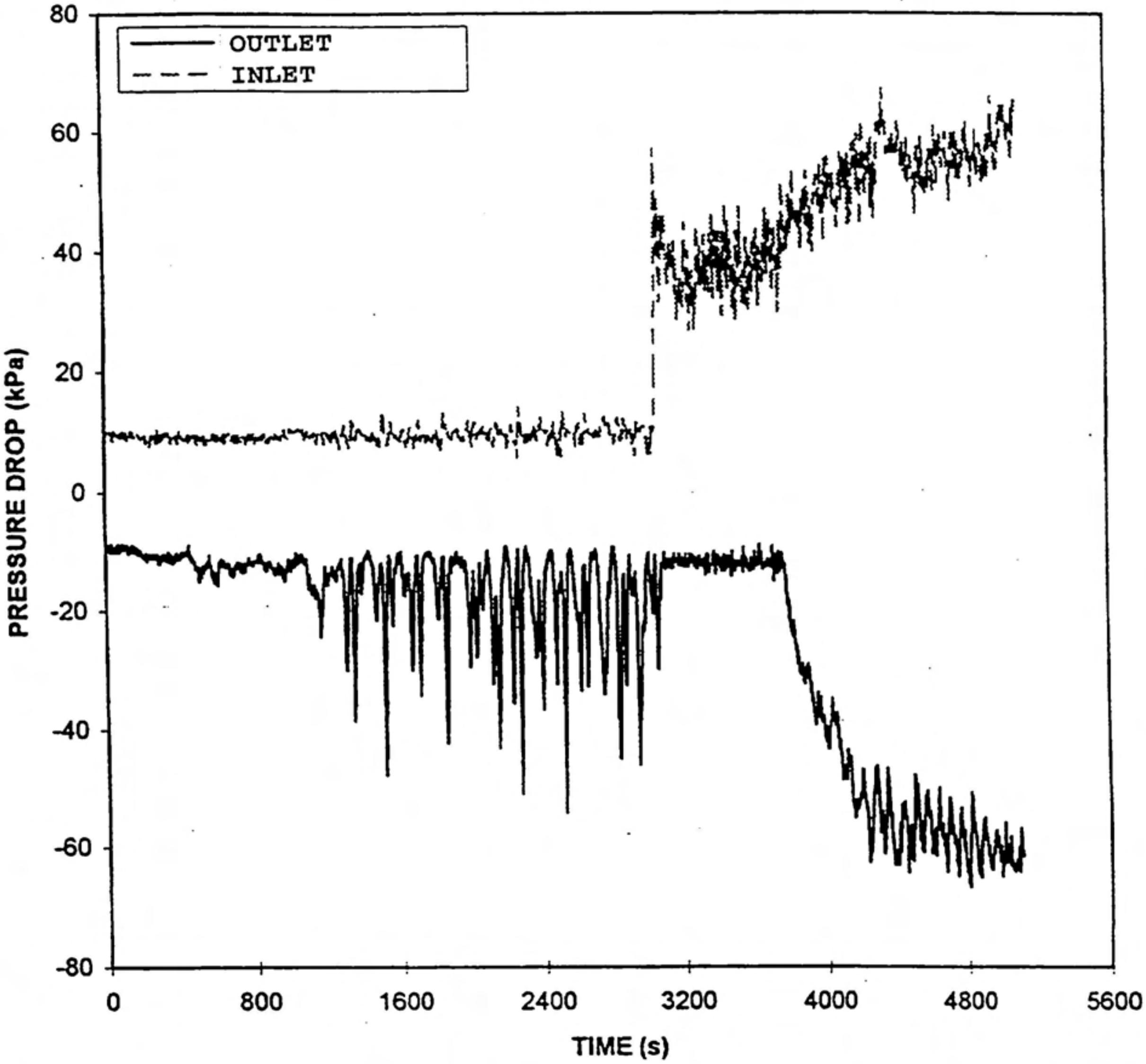


Figure 14 Inlet and Outlet Feeder Differential Pressure Measurements for Heated Section 8 in Test T8809.

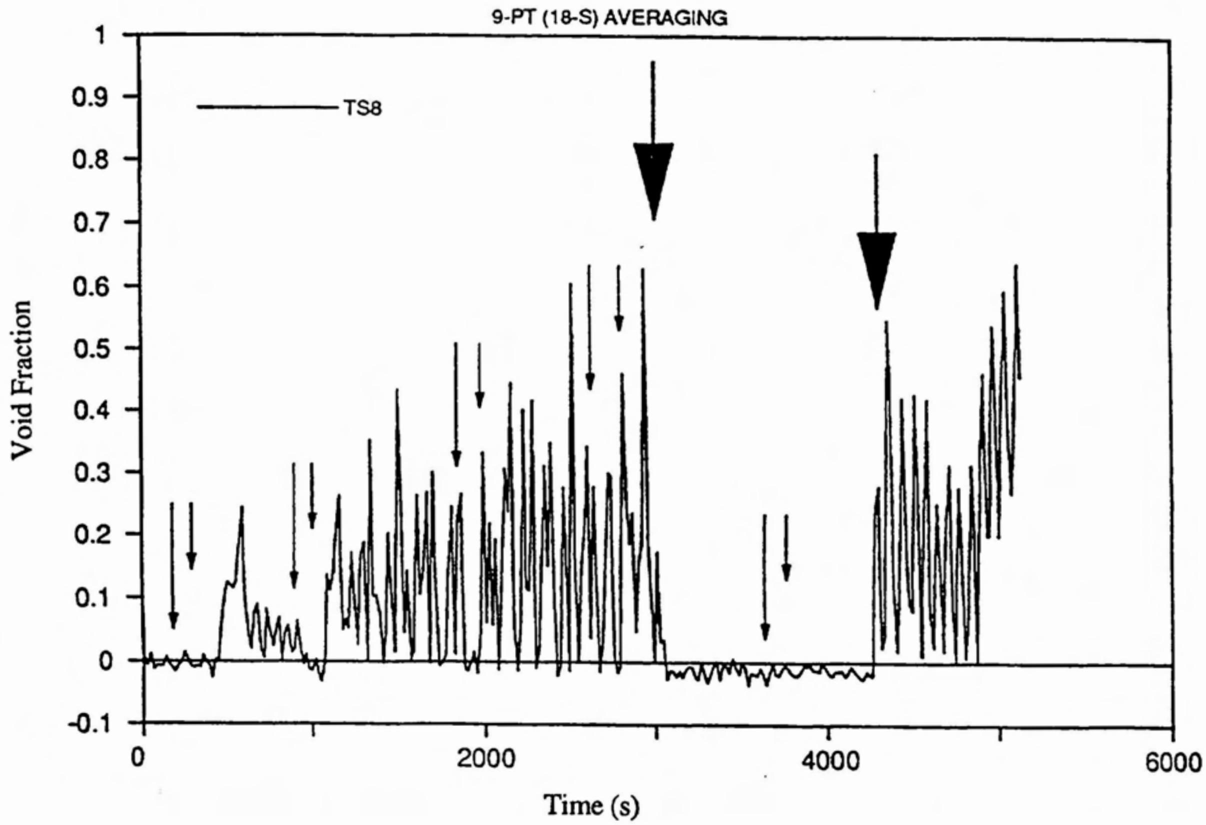


Figure 15 Void Fraction of Fluid Leaving Test Section 8 as a Function of Time in Test T8809.

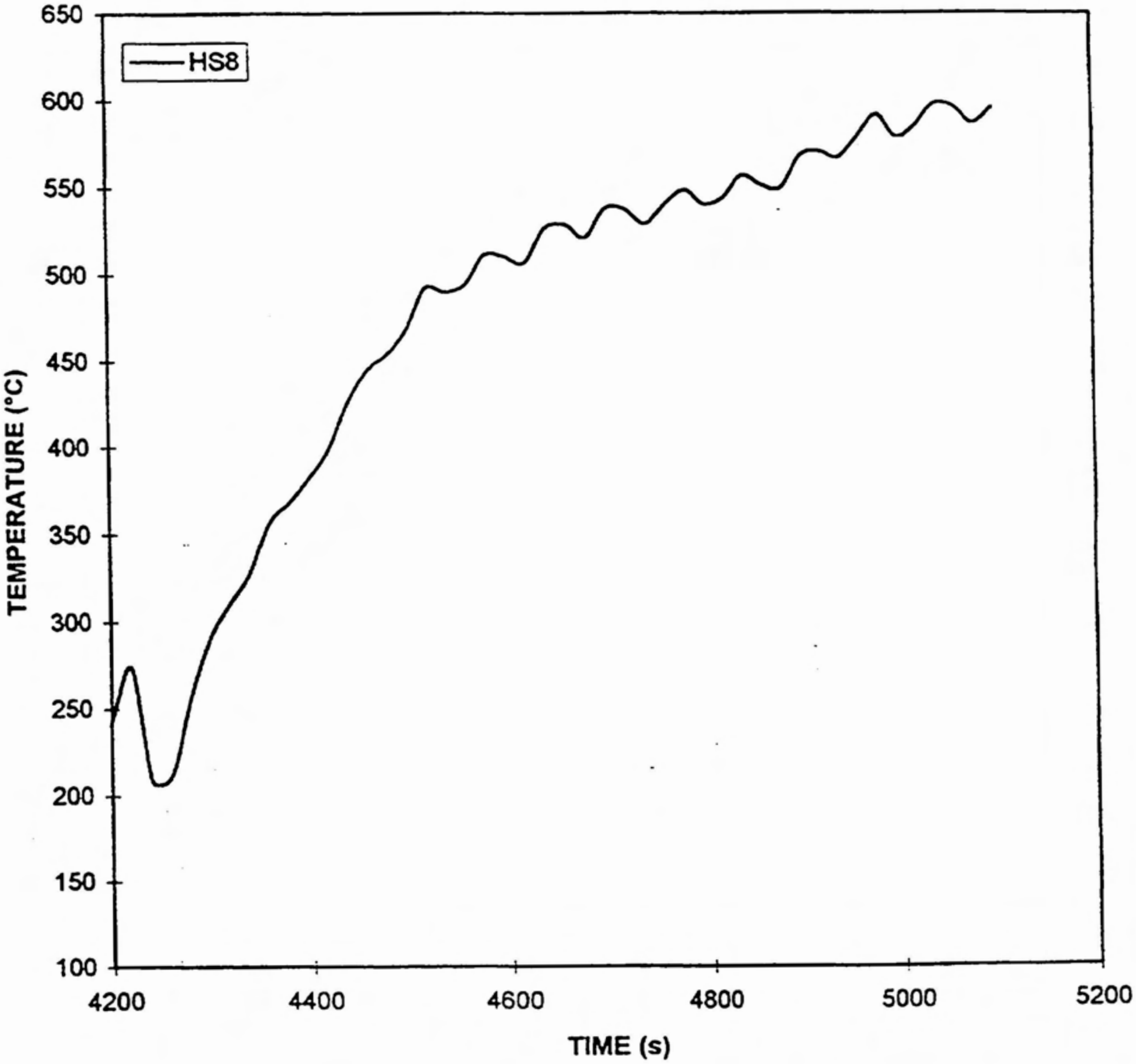


Figure 16 Peak FES Temperature Measured in Heated Section 8 in Test T8809.

Fig. 17 Header-to-Header ΔP inT9209