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NRC Research and Technical Assistance Report

INTERIM REPORT

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EG&G Idaho, Inc.

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October 19, 1979

Mr. R. E. Tiller, Director
Reactor Operations and Programs Division
Idaho Operations Office - DOE
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SEMISCALE UPPER HEAD DRAIN TESTS UHD-1 AND UHD-2 - A SUMMARY REPORT
(EGG-SEMI-5018) - DJO-116-79

Dear Mr. Tiller:

Attached is a summary report of the results of a preliminary analysis of data from upper head drain Tests UHD-1 and UHD-2. Tests UHD-1 and UHD-2 were the first tests in the Semiscale Mod-3 system to incorporate upper head injection (UHI) during the simulation of a large break (200%) loss-of-coolant accident. The tests were conducted with an initial steady state core power of about 2 MW, but the power was tripped to zero at 1.5 s prior to rupture. The primary objective of these tests was to assess the adequacy of the Semiscale Mod-3 system design and instrumentation to meet the requirements of future UHI tests. The results of the analysis indicate that, overall, the Mod-3 system is capable of providing information that will be useful in evaluating the effectiveness of upper head injection. However, hardware modifications in some areas of the Mod-3 system may be necessary to adequately simulate the response of a pressurized water reactor system with UHI. In particular, the effects of excessive structural heat transfer in the upper head and core regions should be reduced. Honeycomb insulators are currently being designed for the upper head and core regions, which should be a significant improvement over the steam-gap insulators currently employed.

Very truly yours,

Danny J Olson

D. J. Olson, Manager
Semiscale Program

JMC:nt

Attachment:
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October 1979

SEMISCALE MOD-3 TESTS UHD-1 AND UHD-2

UPPER HEAD DRAIN TESTS

POOR ORIGINAL

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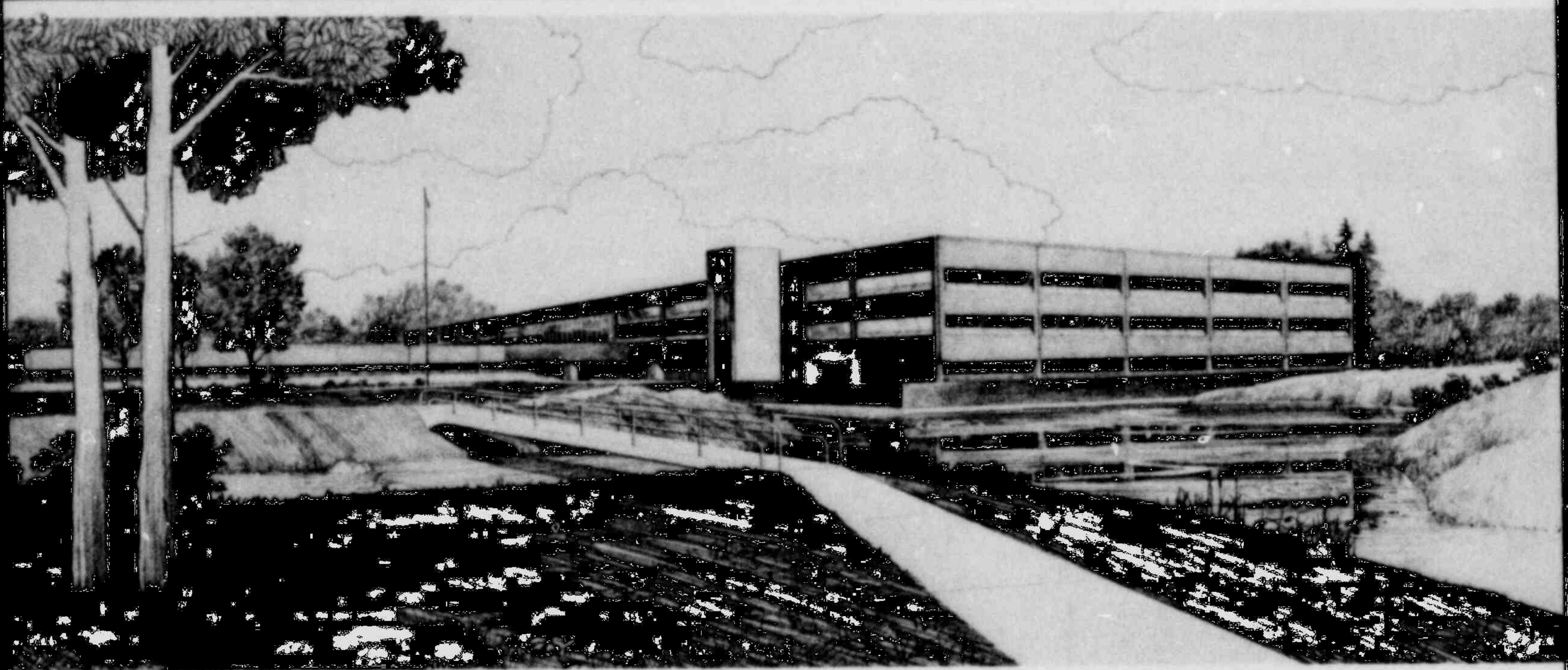
U.S. Department of Energy
Idaho Operations Office • Idaho National Engineering Laboratory



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INTERIM REPORT

PRELIMINARY

SEMISCALE MOD-3 TESTS UHD-1 AND UHD-2
UPPER HEAD DRAIN TESTS

by

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FIGURES (Contd)

FIGURES (Contd)

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SUMMARY

This report presents the results of a preliminary analysis of the data for upper head drain Tests UHD-1 and UHD-2 which were conducted to assess the adequacy of the Semiscale Mod-3 system design and instrumentation to meet the objectives of future UHI tests. Tests UHD-1 and UHD-2 were the first blowdown-refill experiments conducted in the Mod-3 system incorporating upper head injection (UHI). The initial and boundary conditions for the tests were selected to be similar (where possible) to the conditions existing in a commercial pressurized water reactor (PWR) with UHI during an hypothesized large break loss-of-coolant accident (LOCA). The core, however, was unpowered during the transient phase of both tests. In addition, the UHI fluid for Test UHD-2 was heated to allow an evaluation of the effects of UHI fluid subcooling on the resulting upper head and system response.

The upper head thermal-hydraulic response for the drain tests can be separated into three periods consisting of an injection period when the upper head accumulator forced subcooled water into the upper head through an injection nozzle, a reheat period when this subcooled fluid reached the saturation temperature, and a drain period when flashing of a portion of the upper head fluid forced the remaining liquid out of the upper head region. UHI flow began in both tests at about 2 s after rupture, when the system pressure dropped below 7.75 MPa, and continued until about 28 s after rupture for Test UHD-1 and 29 s for Test UHD-2. During the injection period, liquid was forced out of the upper head volume through the guide tube, the two support columns, and the upper head bypass line which connects the upper head volume to the downcomer inlet annulus. The flow split among the various paths out of the upper head was such that approximately 40% of the flow passed through the guide tube, while about 20% of the flow passed through each of the support columns. The liquid which passed through the guide tube and support columns entered the upper plenum where it was available for penetration into the core region. The remaining 20% of the flow passed through the upper head bypass line, and thus was not available as a source of coolant for the core.

Following the upper head injection period, a heatup period occurred in which the subcooled upper head fluid became saturated. Prior to conducting the drain tests it was anticipated that condensation of steam passing upward through the guide tube would be the primary mechanism for reducing the subcooling of the liquid in the upper head. However, an evaluation of the upper head flow response and metal and fluid temperatures indicates that structural heat transfer is the main cause of reheat of the upper head fluid in the Mod-3 system. Heatup of the upper head liquid by structural heat transfer rather than by condensation of steam flowing up the guide tube is not considered entirely typical of the behavior which is expected in a large PWR with UHI. Since the timing of the upper head heatup and drain is considered to be a critical factor in determining the effectiveness of UHI in a PWR system, it will be necessary to properly simulate these events in the Semiscale Mod-3 system. Therefore, a redesign of the upper head insulators has been initiated. The new insulator designs are in the final drawing stages, and the insulators should be available for installation in Semiscale prior to the start of the UHI test series.

The upper head drain was initiated when fluid below the top of the upper head became saturated and began to vaporize. Once vaporization began, the resulting increase in upper head pressure, relative to the system pressure, caused fluid to flow out the guide tube and support columns until draining was completed. In Test UHD-1 draining began at about 38 s after rupture, and an additional period of about 18 s was required for the upper head to drain completely. For Test UHD-2, the UHI fluid was near the system saturation temperature initially and saturation in the upper part of the upper head occurred even before UHI flow was terminated. As a result, draining of the upper head began immediately after UHI stopped (at about 29 s after rupture), and was completed by about 50 s.

The overall response of the Mod-3 system to the upper head injection was generally quite similar for Tests UHD-1 and UHD-2, with the exception that differences in upper head heatup and drain behavior caused minor differences in the hydraulic response of the system. Once UHI began, liquid was forced through the guide tube and support columns into the upper plenum. Much of this fluid passed downward through the core resulting in an increased potential for core metal-to-fluid heat transfer relative to a non-UHI test. However, not all of the fluid from the upper plenum penetrated into the core region. Some of the fluid which was delivered to the upper plenum was bypassed to the intact loop and broken loop hot legs during the injection and drain periods. For Test UHD-1, approximately 28% of the upper head liquid which entered the upper plenum was bypassed to the hot legs, while for Test UHD-2 considerably more (about 56%) was bypassed to the hot legs as a result of the small degree of subcooling present in the UHI fluid (relative to Test UHD-1).

The initiation of bottom flooding of the core for Tests UHD-1 and UHD-2 was considerably delayed relative to previous tests in the Mod-3 system conducted without UHI. Despite the fact that the core was unpowered for both tests, steam generation in the core region (primarily due to structural heat transfer to UHI liquid in the upper plenum and core) kept the system pressure above the containment system pressure until quite late in the transient. As a result, a strong upward steam flow was maintained in the downcomer causing bypass of much of the intact loop cold leg emergency core coolant (ECC). Reflooding of the core in both tests was not initiated until shortly after the containment system pressure was reached (at about 103 s for Test UHD-1 and about 120 s for Test UHD-2). This delay in initiation of core reflood for these tests is considered atypical of large PWR. In large systems, the downcomer gap width is sufficiently large that countercurrent flow (i.e., simultaneous liquid flow downward and steam flow upward) can occur, as evidenced by results of LOFT experiments. Further analysis is required to determine whether possible modifications of the current Mod-3 downcomer design will be necessary to adequately simulate PWR reflood initiation times. One possible solution to this problem is the installation of a two-pipe downcomer which is currently being fabricated.

An evaluation of the data for these two tests indicates that present upper head instrumentation, as well as overall system instrumentation, is basically satisfactory. However, some improvement in guide tube and support column flow measurement will be necessary before the initiation of the UHI test series. The turbine meters in the guide tube and support columns could not be ranged sufficiently low to monitor the relatively small flows that were experienced during Tests UHD-1 and UHD-2. Further design effort will be needed if the turbine meters are to be used in future UHI tests.

PRELIMINARY

I. INTRODUCTION

Tests UHD-1 and UHD-2 were the first experiments performed in the Semiscale Mod-3 facility incorporating upper head injection during a simulated large break loss-of-coolant accident (LOCA). The concept of upper head injection (UHI) involves injecting ambient temperature emergency core coolant (ECC) water into the upper head of the vessel very early in the blowdown sequence. As the system depressurizes, this fluid is expected to be drawn down through the heated core providing early core cooling. The Semiscale Mod-3 testing program, and in particular Test Series 8[a], is designed to provide a basic experimental understanding of the UHI process under LOCA conditions. The objectives of Tests UHD-1 and UHD-2 were (a) to assess the adequacy of the Semiscale Mod-3 system to meet the objectives of Test Series 8, (b) to establish the general influence of upper head injection on system response during an unpowered core transient, and (c) to evaluate the effectiveness of upper head instrumentation in recording important upper head thermal-hydraulic behavior during a 200% break LOCA.

In general, the initial and boundary conditions for Tests UHD-1 and UHD-2 were based on conditions expected in a commercial pressurized water reactor (PWR) with UHI during an hypothesized large break loss-of-coolant accident. Both tests were conducted from an initial pressure of about 15.6 MPa, a core inlet temperature of 577 K, and a core temperature rise of about 37 K. The total initial core power was approximately 2 MW; however, the core power was tripped 1.5 s before rupture and remained at zero for the duration of the tests. In both tests, ambient temperature ECC fluid was injected into

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[a] Test Series 8 is designated the UHI ECCS Evaluation test series. The primary objectives of the UHI test series are to investigate the influence of important UHI ECC parameters on the core thermal response and system hydraulic behavior during an integral LOCA test, and to provide data to develop and assess computer codes capable of calculating thermal-hydraulic behavior for postulated LOCAs involving a PWR with UHI. A complete description of the experiments to be conducted in Test Series 8 is presented in Reference 1.

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the intact loop cold leg through use of an accumulator, a low pressure injection system (LPIS), and a high pressure injection system (HPIS). A separate accumulator system was used to inject ECC fluid into the vessel upper head through a perforated nozzle. The UHI nozzle extended the entire length of the upper head and was designed to provide a uniform upper head fluid temperature during the injection period. Figure 1 shows the Mod-3 upper head configuration and illustrates the location of the injection nozzle. The upper head accumulator was set to begin injecting when the system pressure decreased below 7.75 MPa. For Test UHD-1 the upper head accumulator fluid was maintained at ambient temperature (300 K), while for Test UHD-2 the upper head accumulator fluid was heated to 422 K to allow determination of the effects of ECC fluid subcooling on the resulting upper head and system behavior. For both tests, a bypass line was connected between the downcomer inlet annulus and the vessel upper head to simulate the inlet annulus-to-upper head flow which occurs in a commercial PWR with UHI during normal operation. The bypass line is used to maintain the upper head fluid at the cold leg fluid temperature by circulating approximately 4% of the total cold leg flow through the upper head region.

The following sections contain a summary of the results from the upper head drain Tests UHD-1 and UHD-2. The actual test condition and test procedure are described initially. A discussion of the experimental results for the two tests is then presented.

II. TEST PROCEDURE AND TEST CONDITIONS

1. TEST PROCEDURE

Prior to the initiation of testing, the Mod-3 system was filled with demineralized water and vented to ensure a liquid-full system. Water in the steam generator feedwater tanks was heated to the desired temperature and the required levels were established in the steam generator secondary sides. The intact loop and upper head accumulator water levels were established and the accumulators were pressurized with nitrogen gas to the desired pressure. The instruments were then calibrated and zeroed as required and the system was leak checked and hydro checked. After the necessary protective trip controls and peripheral hardware controls (pumps, valves, etc.) had been set, the system was brought up to initial conditions and allowed to equilibrate. When the system had equilibrated and the initial conditions were within the specified tolerances, the core power was tripped and the test was initiated by bursting rupture discs in the broken loop to break the system pressure boundary. The broken and intact loop pump speed controls were initiated coincident with the rupturing of the system pressure boundary. The test were terminated at 300 s.

2. TEST INSTRUMENTATION, SPECIFIED AND ACTUAL CONDITIONS

The general instrumentation locations for the Semiscale Mod-3 system are shown in Figures 2, while Figures 3 and 4 show instrumentation locations in the upper head and core regions, respectively. Details of the instrumentation specifications are presented in Reference 2. The specified and actual test conditions for Tests UHD-1 and UHD-2 are compared in Table I. Important test parameters and boundary conditions were judged satisfactory to meet the test objectives.

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TABLE I

INITIAL CONDITIONS FOR TESTS UHD-1 AND UHD-2

	Specified	Test UHD-1	Test UHD-2
System Pressure	15.513 MPa	15.67 MPa	15.78 MPa
Hot Leg Fluid Temperature	594 K	594 K	595 K
Cold Leg Fluid Temperature	557 K	558 K	558 K
Core Temperature Differential	37 K	36 K	37 K
Core Power	2 MW	2.04 MW	2.04 MW
Core Inlet Flow Rate	9.77 kg/s	9.8 kg/s	9.7 kg/s
Upper Head Fluid Temperature	557 K	555 K	555 K
Pressure Suppression System Pressure	138 kPa	138 kPa	138 kPa
ECC Injection Accumulator			
Actuation Pressure	2757 kPa	2500 kPa	2580 kPa
Injection Rate	1.21 kg/s	0.63 kg/s	0.65 kg/s
Fluid Temperature	300 K	300 K	300 K
LPIS			
Actuation Pressure	1030 kPa	1073 kPa	1040 kPa
Injection Rate	0.16 kg/s	0.23 kg/s	0.24 kg/s
HPIS			
Actuation Pressure	12410 kPa	12400 kPa	12400 kPa
Injection Rate	0.062 kg/s	0.015 kg/s	0.016 kg/s
UHI			
Actuation Pressure	8272 kPa	8300 kPa	8150 kPa
Injection Rate	0.81 kg/s	0.84 kg/s	0.72 kg/s
Fluid Temperature			
UHD-1	300 K	300 K	----
UHD-2	422 K	----	422 K

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III. TEST RESULTS

To address each of the test objectives discussed in the introduction, the test results are presented in four sections. The first section analyzes the transient in the upper head. The time frame of concern in this section is from 0 to 60 s since once the fluid in the upper head has drained the behavior of the upper head does not affect system behavior. The second section discusses the overall system thermal-hydraulic behavior during the first 100 s of the blowdown sequence. The third section covers the remainder of the transient, and presents a discussion of the influence of the containment pressure and steam generation on the reflood behavior of the Mod-3 system. The final section examines the behavior of the upper head instrumentation for both tests.

Since Test UHD-2 was conducted with essentially the same initial and boundary conditions as Test UHD-1 (with the exception of the UHI accumulator fluid temperature), the test results section is concerned primarily with an evaluation of Test UHD-1 data. Comparisons between Test UHD-1 and UHD-2 are presented only when differences in the upper head response or overall system behavior occurred as a result of the different UHI fluid temperatures.

1. UPPER HEAD THERMAL-HYDRAULIC RESPONSE DURING INJECTION, REHEAT, AND DRAIN PERIODS

The upper head thermal-hydraulic response can be separated into three periods, consisting of an injection period when the upper head accumulator forced subcooled water into the upper head through an injection nozzle, a reheat period when this subcooled fluid reached the saturation temperature, and a drain period when flashing of a portion of the upper head fluid forced liquid through the guide tube and support columns into the upper plenum. Each of the periods is discussed separately and the important characteristics for each period is analyzed. In addition, a discussion of the phenomena controlling upper head behavior and possible impacts on the ability of the Mod-3 system to simulate a PWR with UHI is given.

1.1 Injection Period

Upper head injection began in Test UHD-1 at approximately 2 s after rupture when the system pressure dropped below 7.75 MPa, and was terminated at about 28 s after rupture when a specified amount of liquid had been injected into the upper head. The UHI volumetric flow rate for Test UHD-1 is shown in Figure 5, and is overlayed with the system depressurization response. As indicated in the figure, the UHI flow rate was dependent on the system pressure in that variations in the UHI flow rate correspond directly to changes in the system depressurization rate.

During the injection period, liquid was forced out of the upper head volume through the guide tube, the two support columns, and the upper head bypass line which connects the upper head volume to the downcomer inlet annulus. Figures 6 and 7 show the mass flow rate in the guide tube and one of the support columns, respectively, for Test UHD-1, and indicate the strong positive flow out of the upper head during the injection period (i.e., until about 28 s.) The flow split among the various paths out of the upper head was such that approximately 40% of the flow passed through the guide tube, while about 20% of the flow passed through each of the support columns. The remaining 20% of the flow passed through the upper head bypass line, and thus was not available as a source of coolant for the core.

The UHI liquid was injected through a perforated nozzle that was designed to distribute the liquid uniformly over the length of the upper head. The perforated nozzle was used to reduce temperature stratification in the upper head fluid to a minimum, since in a PWR the upper head geometry and location of the injection nozzles are such that although the fluid temperature decreases with time, a relatively uniform fluid temperature is expected during the injection period. The results of the Mod-3 tests, however, indicate that some fluid temperature stratification did occur during the injection period even though the perforated nozzle was used. Figure 8 compares fluid temperatures at different elevations in the upper head for Test UHD-1 (refer to Figure 3 for relative locations of the thermocouples). As shown in the figure, the lower two-thirds of the upper head fluid volume (up to about the 312-cm elevation) exhibited an essentially uniform fluid temperature that decreased throughout the injection period. In the top third of the upper head, however, considerable fluid temperature stratification was evident, with the higher fluid temperatures occurring near the top of the upper head. In fact, fluid at the 401-cm elevation and above was saturated between about 17 and 25 s. Similar temperature stratification was observed for Test UHD-2 as indicated in Figure 9 which shows the upper head fluid temperatures for that test.

Although the fluid temperature stratification does not affect the upper head hydraulic response during the injection period, it can have a significant influence on the time at which saturation occurs, and thus the time at which upper head drain begins. Complete mixing of the upper head fluid during the injection period (resulting in uniform upper head fluid temperatures) could lead to a longer reheat period and a corresponding delay in the initiation of the upper head drain. Tests are currently planned for Test Series 8 to evaluate the effects of different injection nozzle geometries on the upper head fluid temperature distribution and the corresponding drain characteristics.

1.2 Reheat Period

Upon completion of the injection period, a reheat period was expected in which the subcooled liquid in the upper head was heated to saturation. Condensation of steam that passed upward through the guide tube was anticipated to be the primary mechanism to reduce the subcooling of the liquid in the upper head. However, an evaluation of the upper head flow response and metal and fluid temperatures indicates that structural heat transfer was the main cause of reheat of the upper head fluid.

The reheat period for Test UHD-1 extended from 27 to about 38 s. During this period, the flow rate and flow direction in the guide tube and support columns were highly sensitive to small changes in the differential pressure between the upper head and upper plenum.

Figures 10 and 11 compare the guide tube and support column mass flow rates respectively with the differential pressure between the upper head and upper plenum for Test UHD-1. Shortly after the termination of UHI (at about 28 s), flow in both the guide tube and support columns reversed (resulting in upward flow) corresponding to a reduction of the upper head pressure below that of the upper plenum pressure. However, the upward flow in the guide tube and support columns continued only until about 29 s. At about 29 s, fluid in the very top of the upper head became saturated[a], as indicated in Figure 12, which compares the fluid temperature at the 401-cm elevation with the saturation temperature[b]. The resulting vaporization of this fluid caused a positive differential pressure between the upper head and upper plenum, and flow in the guide tube and support columns became positive out of the upper head. By about 31 s, sufficient water in the top of the upper head had been vaporized that the liquid level dropped into an area where somewhat better insulation was available. As a result, heat transfer to the fluid was considerably reduced leading to a termination of the vaporization and a corresponding reduction in the flow out the guide tube and support columns. Between 31 and 38 s, the upper head pressure again fell below the upper plenum pressure, apparently due to an increase in flow

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[a] As discussed in the section covering the UHI period, considerable fluid stratification existed in the top third of the upper head, such that fluid in the very top of the upper head was at or near saturation. Also, because of numerous instrumentation penetrations and an expansion fitting for the upper head insulator, structural heat transfer at the very top of the upper head is expected to be greater than at lower elevations. Thus a very short period of time was required to saturate the fluid in this region once the UHI flow was terminated.

[b] Figure 12 indicates that fluid at the 401-cm elevation became saturated at about 30 s rather than 29 s. However, because of temperature stratification, it is likely that fluid at higher elevations became saturated somewhat earlier.

out the upper head bypass line (as shown in Figure 13) caused by condensation in the intact loop cold leg and downcomer inlet annulus region[a]. During this period, flow in the guide tube became predominantly negative (i.e., into the upper head) as a result of the negative upper head to upper plenum pressure differential. Flow in the support columns remained positive (but at a lesser flow rate than observed prior to 31 s) because of the static head of the liquid above the support columns.

The predominantly negative flow in the guide tube between 32 and 38 s was comprised mainly of saturated steam from the upper plenum region of the vessel. As mentioned previously, it was expected that condensation of this steam in the upper head would be the primary mechanism for heating the upper head liquid. However, the total amount of steam entering the upper head region via the guide tube during this period of time was only 15 to 20% of the amount required to saturate the liquid just above the top of the guide tube (between the 335-cm and 375-cm elevations). In addition, as indicated in Figure 8, considerable heating of the fluid over the entire length of the upper head occurred prior to 32 s when the guide tube flow became negative. Thus, it is evident that structural heat transfer played a major role in reheating the upper head fluid.

Structural heat transfer was recognized as a potential problem during the design of the Mod-3 upper head, since the surface area-to-volume ratio in the Mod-3 upper head is approximately 9 times greater than in a PWR system. As a result, steam-gap insulators were placed on the upper head walls to reduce the metal-to-fluid heat transfer rate. The principle behind the steam gap insulators is that the hot metal wall of the vessel will vaporize any liquid in the gap thus decreasing the conductivity across the gap by at least an order of magnitude. However, an evaluation of test data indicates that the

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[a] The intact loop accumulator began injecting ambient temperature ECC liquid into the cold leg at about 23 s for Test UHD-1.

steam gap insulators do not provide sufficient resistance to heat flow from the vessel walls when subcooled liquid is present in the upper head. This is graphically illustrated in Figure 14 which compares the upper head metal temperature at the 343-cm elevation for Test UHD-1 with the fluid temperature and fluid saturation temperature at the same elevation. As shown in the figure, the metal temperature dropped rapidly during the period when subcooled liquid was present in the upper head[a] indicating that significant heat transfer to the fluid was occurring. However, once the upper head fluid became saturated, the metal temperature remained relatively constant indicating that very little heat transfer was taking place.

Based on the results of Test UHD-1, it is apparent that structural heating in the upper head (combined with the fluid temperature stratification in the top portion of the upper head) is overshadowing heating due to condensation. Since condensation heating is expected to be the primary mechanism for reheat of the upper head fluid in a PWR system, proper simulation of a PWR upper head response using the Mod-3 system will require improved insulators in the upper head to reduce the effects of structural heat transfer. Honeycomb type insulators, which should be a significant improvement over the steam-gap insulators, are currently being designed for the Mod-3 upper head and should greatly reduce the effects of structural heat transfer.

1.3 Drain Period

The drain period in Test UHD-1 began at about 38 s after rupture and terminated at about 55 s. Figure 15 shows the upper head collapsed liquid level obtained from a differential pressure measurement and indicates the decrease in liquid inventory as the

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[a] The subcooled liquid in the upper head apparently condensed the steam in the insulator gap thus greatly increasing the conductivity across the gap.

drain period commenced. The upper head drain was initiated when fluid below the top of the upper head became saturated and began to vaporize. Once vaporization began, the resulting increase in upper head pressure, relative to the system pressure, caused fluid to flow out the guide tube and support columns (refer to Figures 10 and 11) until the drain was completed. The liquid-vapor interface passed the top of the guide tube at about 41 s as indicated in Figure 16 which shows the fluid density at the 339-cm elevation for Test UHD-1. The drain period was essentially completed by about 55 s when the liquid-vapor interface passed the top of the support columns as indicated in Figure 17 which shows the fluid density at the 174-cm elevation.

The hydraulic response of the upper head just prior to the initiation of the drain appears to have been influenced by a brief period of condensation in the upper head, although the time at which the drain began did not seem to be significantly affected. Between 31 and 37 s, the liquid level was near the 375-cm elevation (Figure 15) which is considerably below the top of the upper head (421-cm). The liquid-vapor interface fell to this level during the period between 28 and 31 s when fluid near the top of the upper head became momentarily saturated (as previously discussed in the section on upper head reheat). At about 37 s, however, the upper head liquid level began to increase. The increase in liquid level corresponded to a rapid decrease in the upper head pressure relative to the system pressure, as indicated in Figure 18 which compares the upper head and system pressures for Test UHD-1. At the same time (i.e., about 37 s), both the guide tube and support column flow measurements indicated flow into the upper head (Figures 10 and 11), thus providing the necessary fluid for the rise in liquid level. The decrease in upper head pressure and resulting upflow in the guide tube and support columns apparently was caused by condensation of steam at the top of the upper head, although at present, the source of subcooled liquid required to cause the condensation has not been identified. (A possible source of subcooled liquid is the upper head ECC injection line). The increase in upper head liquid level due to the condensation caused cooler fluid from the lower portion of the upper head to move upward, as indicated in Figure 19 which shows the fluid temperatures at various elevations in the upper head. The drop in fluid temperatures at most elevations[a] at about 38 s corresponds to the upward movement of cooler fluid past the thermocouple locations. Overall, however, the brief period of condensation and the resulting increase in liquid level does not appear to have significantly affected the time of the initiation of the upper head drain. Figure 20 compares the fluid temperature at the 373-cm elevation with the saturation temperature for Test UHD-1 (recall that prior to 37 s the upper head liquid level was near the 375-cm elevation). Based on the rate of temperature increase just prior to 37 s, it is evident that the top layer of liquid in the upper head would have become saturated at about 39 to 40 s regardless of the condensation effects that were observed.

The degree of subcooling in the UHI fluid had a considerable effect on the upper head drain characteristics. As mentioned previously, the UHI fluid temperature for Test UHD-2 was about 422 K (as compared to 300 K for Test UHD-1). As a result, fluid near the top of the upper head became saturated well before the termination of the UHI flow, and thus there were no distinct periods of reheat and drain as occurred in Test UHD-1. Figure 21 compares the fluid temperature near the top of the upper head (401-cm elevation) with the saturation temperature for Test UHD-2 and indicates that the fluid became saturated at about 15 s after rupture while subcooled ECC was still being injected into the upper head. Following the termination of the UHI flow at about 29 s, the guide tube uncovered immediately as shown in Figure 22 which compares the UHI accumulator volumetric flow with the upper head fluid density at the 339-cm elevation. The upper head drain was completed by about 50 s, as shown in Figure 23 which indicates a rapid decrease in the fluid density near the top of the support columns (174-cm elevation) for Test UHD-2 at this time.

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[a] The increase in fluid temperature near the bottom of the upper head (180-cm elevation) at 38 s is a result of hotter fluid from the upper plenum region moving up the support columns into the upper head.

2. INFLUENCE OF UPPER HEAD BEHAVIOR ON SYSTEM RESPONSE

The response of the Mod-3 system to the upper head injection was generally quite similar for Tests UHD-1 and UHD-2, with the exception that differences in drain behavior caused minor differences in the hydraulic response of the system. Once UHI began, liquid was forced through the guide tube and support columns into the upper plenum as indicated by the relatively high upper plenum fluid density for Test UHD-1 shown in Figure 24. Figure 25, showss the fluid densities near the top, midsection, and bottom of the core for Test UHD-1 and indicates that much of the fluid that entered the upper plenum penetrated downward through the core. The relatively high fluid densities in the core during both the injection and drain periods provide excellent potential for cooling of the heater rods. It must be realized, however, that with a powered core, the characteristics of the UHI ECC fluid penetration into the core region may be considerably different.

ECC liquid that passed downward through the core and entered the lower plenum was de-entrained from the steam flow by the flow skirt such that little, if any, liquid passed up the downcomer during the injection and drain periods. Figure 26 shows the fluid density near the bottom of the downcomer and indicates essentially saturated steam flow up the downcomer during these periods. The lower plenum liquid inventory, however, was considerably greater than for tests without UHI. Figure 27 compares the density obtained from a diagonal density shot for Tests UHD-1 and S-07-3[a] and indicates a substantially higher liquid inventory in the lower plenum during the blowdown period (until about 53 s) due to the presence of the UHI fluid.

Not all of the fluid from the upper head penetrated into the core region. Some of the fluid which was delivered to the upper plenum was bypassed to the intact loop and broken loop hot legs during the

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[a] Test S-07-3 was conducted with initial and boundary conditions that were similar to those in Test UHD-1 except that UHI was not used and the core was powered during the transient. A discussion of Test S-07-3 results is presented in Reference 3.

injection and drain periods. The bypass to the hot legs is illustrated in Figures 28 and 29 which show increased fluid densities in the intact and broken loop hot legs near the vessel during these periods for Test UHD-1. However, the subcooled liquid in the upper plenum and upper core regions resulted in periods of condensation which in turn caused flow back towards the vessel in the hot legs (especially in the intact loop hot leg). Figure 30 compares the fluid temperature near the top of the core with the fluid saturation temperature for Test UHD-1. The subcooling present in this region of the vessel provided considerable potential for condensation. The effects of the condensation are illustrated in Figure 31 which shows periods of negative flow back toward the vessel in the intact loop hot leg for Test UHD-1. The total mass leaving the vessel via the intact and broken loop hot legs was small compared to the total mass entering the upper plenum through the guide tubes and support columns. Figure 32 compares the sum of the integrated hot leg mass flow rates (flow out of vessel) with the sum of the integrated guide tube and support column mass flow rates (flow into vessel) and indicates that by the time the drain period was completed about 28% of the upper head liquid that entered the upper plenum left through the hot legs. The remainder of the liquid passed downward through the core.

In Test UHD-2 the amount of fluid bypassed to the hot legs during the injection and drain periods was considerably greater than for Test UHD-1. Figure 33 compares the sum of the integrated hot leg mass flow rates with the sum of the guide tube and support column mass flow rates for Test UHD-2. As indicated in the figure, by the end of the drain period (50 s) about 56% of the upper head liquid that entered the upper plenum left through the hot legs. The higher bypass flow out the hot legs (relative to Test UHD-1) can be attributed to the substantial reduction in condensation in the upper plenum region resulting from the higher temperature of the UHI fluid in Test UHD-2. The reduced condensation in the upper plenum virtually eliminated the backflow into the vessel that was evident in Test UHD-1 as indicated in Figure 34 which compares the intact loop hot leg volumetric flow rates for Tests UHD-1 and UHD-2.

3. REFLOOD BEHAVIOR OF THE MOD-3 SYSTEM DURING A UHI TEST

Although the upper head drain was essentially completed by about 55 s after rupture for Test UHD-1 (and about 50 s for Test UHD-2), the lingering presence of UHI liquid in the upper plenum and upper portion of the core resulted in a considerable delay in the start of bottom reflooding of the core relative to a non-UHI test. The liquid in the core region continued to vaporize even after the drain had been completed, thus maintaining the system pressure considerably above the containment pressure as indicated in Figure 35 which compares the two pressures for Test UHD-1. The resulting high steam flow up the downcomer, shown in Figure 36, prevented penetration of the cold leg ECC into the downcomer until dryout of the entire core region had occurred. Once vaporization in the core terminated, the system pressure dropped to the containment pressure (Figure 35), and ECC began to flow down the downcomer. The fluid density near the top of the downcomer, shown in Figure 37, indicates liquid penetration began at about 103 s after rupture for Test UHD-1. Core reflood began at about 110 s as indicated in Figure 38 which shows the fluid density near the inlet to the core. (For Test UHD-2 reflood began at about 120 s after rupture). This compares to a reflood start time of about 65 s for typical non-UHI tests in the Mod-3 system(3).

The delayed reflood in Tests UHD-1 and UHD-2 indicate two potential problem areas in the Mod-3 system in terms of modeling the reflood behavior of a PWR system with UHI. These problem areas include excessive structural heat transfer in the core region[a] (other than from heater rods) and the one-dimensional nature of the Mod-1 downcomer. The excessive structural heat transfer in the core

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(a) Excessive structural heat transfer from the massive metal walls in the core region had been identified as a problem area in previous Series 7 tests. Reflective steam gap type insulators are employed in the core region. However, as in other regions of the Mod-3 system, the steam gap insulators do not fuction as expected.

region provides the potential for generating large amounts of steam, which when combined with the steam generated on the heater rod surfaces, can result in non-typical system hydraulic behavior. Honeycomb type insulators are currently being fabricated for the core region, and are expected to provide the thermal resistance necessary to reduce the effects of the excessive structural heat transfer.

The one-dimensional nature of the Mod-3 downcomer is such, that as long as the system pressure remains above the containment pressure (generally due to steam generation in the core region), steam flow up the downcomer is sufficient to prevent ECC penetration. This behavior is not typical of the response observed in larger systems, such as LOFT, in which countercurrent liquid and steam flow exists. A possible solution to this potential problem is the installation of a two pipe downcomer which is currently being fabricated. Further analysis, however, will be required to determine whether or not the two-pipe downcomer should be installed prior to running the UHI test series.

Other than the considerable delay in the start of reflood for Test UHD-1 (as well as for Test UHD-2), the reflood behavior of the system was typical of the behavior exhibited in the Mod-3 baseline test, Test S-07-6, and therefore will not be discussed here. A complete description of the Mod-3 system reflood behavior is presented in Reference 4.

4. MOD-3 UPPER HEAD INSTRUMENTATION CAPABILITY

One of the major objectives of Tests UHD-1 and UHD-2 was to evaluate the capability of the Mod-3 system instrumentation to accurately measured the thermal-hydraulic behavior in the upper head region. Of primary concern was the ability to measure the mass flow rates in the guide tube and support columns, since the area available for measurement devices (including turbine flow meters and drag body devices) is very limited, and the flow rates expected in these locations are near the limits of current state of the art flow measurement technology.

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Results of a preliminary analysis of the instrumentation response indicate that, in general, instrumentaion including pressure probes, thermocouples (both fluid and metal), densitometers, and the guide tube and support column drag devices provide accurate measurements of the upper head thermal-hydraulic behavior. An indication of the accuracy of the guide tube and support column drag bodies to measure mass flow is given in figure 39. The figure compares the total integrated mass flow into the upper head (obtained from a turbine flowmeter in the accumulator injection line) with the total integrated mass flow out of the upper head (obtained from the drag devices in the guide tube and support columns, and a turbine flowmeter in the upper head bypass line) during the period when the upper head was liquid full. As indicated in the figure the total mass injected into the upper head over the injection period corresponds very well to the total mass leaving the upper head.

Turbine flowmeters were also installed in the guide tube and support columns. However, these devices did not provide good flow data, primarily due to the fact that flow rates were considerably below the operating range of the turbine meters during periods of liquid flow, and considerably higher than operating range during periods of steam flow leading to damage of the rotor units. Further design work on the turbine flowmeters will be necessary prior to use in future UHI tests.

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IV. CONCLUSIONS

The results of the analysis of data from Tests UHD-1 and UHD-2 indicate that, overall, the Mod-3 system is capable of providing information that will be useful in evaluating the effectiveness of upper head injection. However, some modifications to the Mod-3 system are necessary to adequately simulate the response of a PWR system with UHI. Some characteristics of the Mod-3 system, such as excessive structural heat transfer in the upper head and core regions, long refill/reflood times, and temperature stratification in the upper head region are believed to be atypical of a PWR. The excessive structural heat transfer in the core region causes atypically high steam generation rates that affect the resulting system hydraulic response. New insulators have been designed for the core in order to reduce the metal heat transfer to the system fluid and will be installed prior to running the UHI test series.

The Mod-3 system also exhibits long refill/reflood times relative to a PWR. This is a two-fold problem. First the steam generated by the core has to flow up the downcomer or out the hot legs. This steam flow coupled with the single-pipe downcomer bypasses cold leg ECC for a longer period of time than expected in a PWR. However, with the new core insulators, the steam generation should be reduced greatly. Also, if necessary, a parallel pipe downcomer (sometimes called a two-pipe downcomer) may be installed to help relieve the bypass problem.

The temperature stratification in the top part of the upper head is believed to be atypical of the uniform temperature profile expected in a PWR. However, modification to the injection nozzle as well as the incorporation of better upper head insulators should reduce the temperature stratification noticed in these tests.

The upper head drain tests indicate the strengths and shortcomings of the Mod-3 UHI capability. The shortcomings are not insurmountable and with the suggested modifications the ability of Mod-3 to simulate PWR behavior will be greatly enhanced.

PRELIMINARY

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1. Semiscale Program, Semiscale EOS Appendix 8, SEMI-TR-002, EG&G Idaho, Inc. (February 1979).
2. Semiscale Program, Semiscale EOS Appendix 7, WR-S-78-002, EG&G Idaho, Inc. (March 1978).
3. J. M. Cozzuol, Quick Look Report for Semiscale Mod-3 Test S-07-3 Baseline Test Series, WR-S-78-017, EG&G Idaho, Inc. (August 1978).
4. J. M. Cozzuol, Quick Look Report for Semiscale Mod-3 Test S-07-6 Baseline Test Series, WR-S-78-020, EG&G Idaho, Inc. (October 1978).

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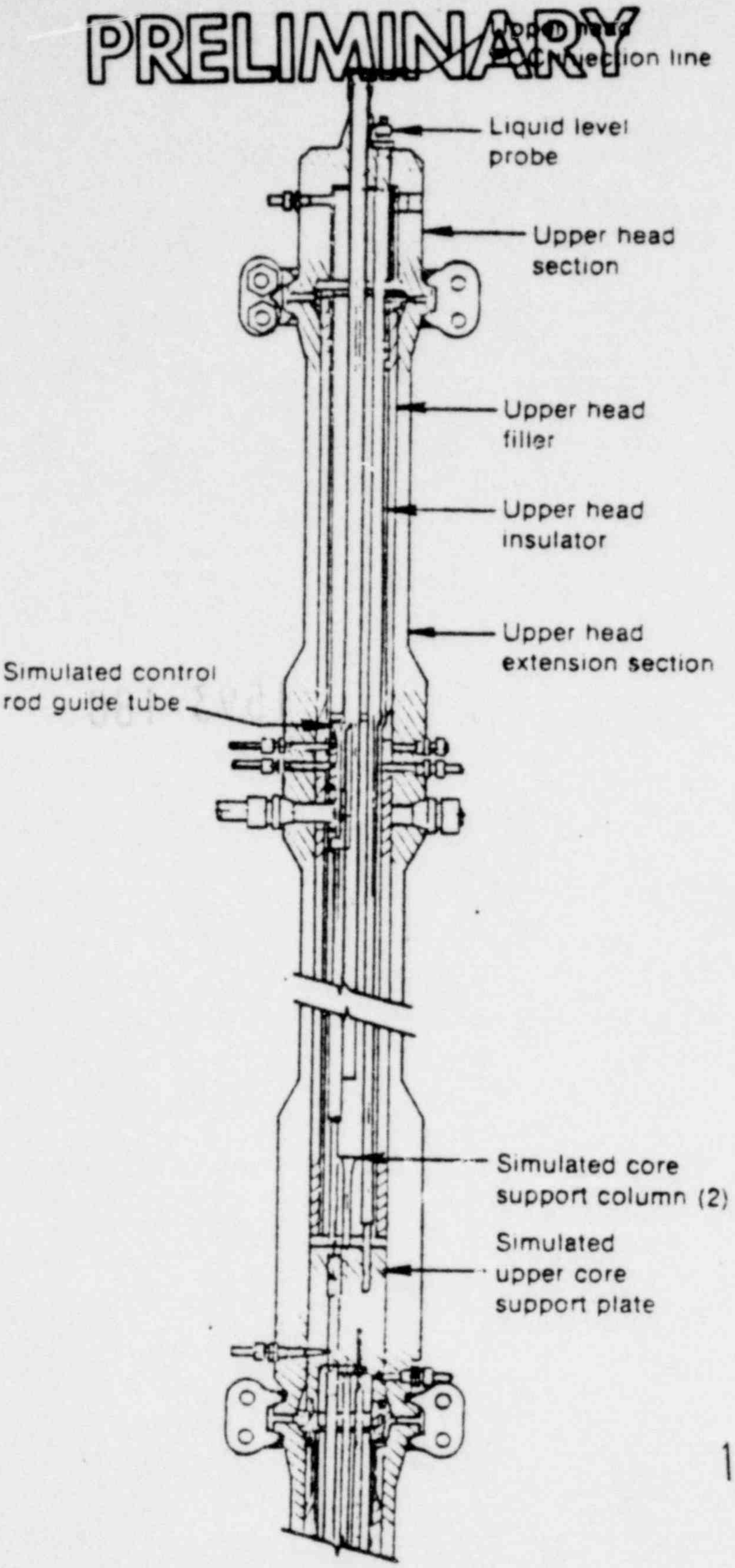

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Fig. 1 Semiscale Mod-3 pressure vessel upper head region.

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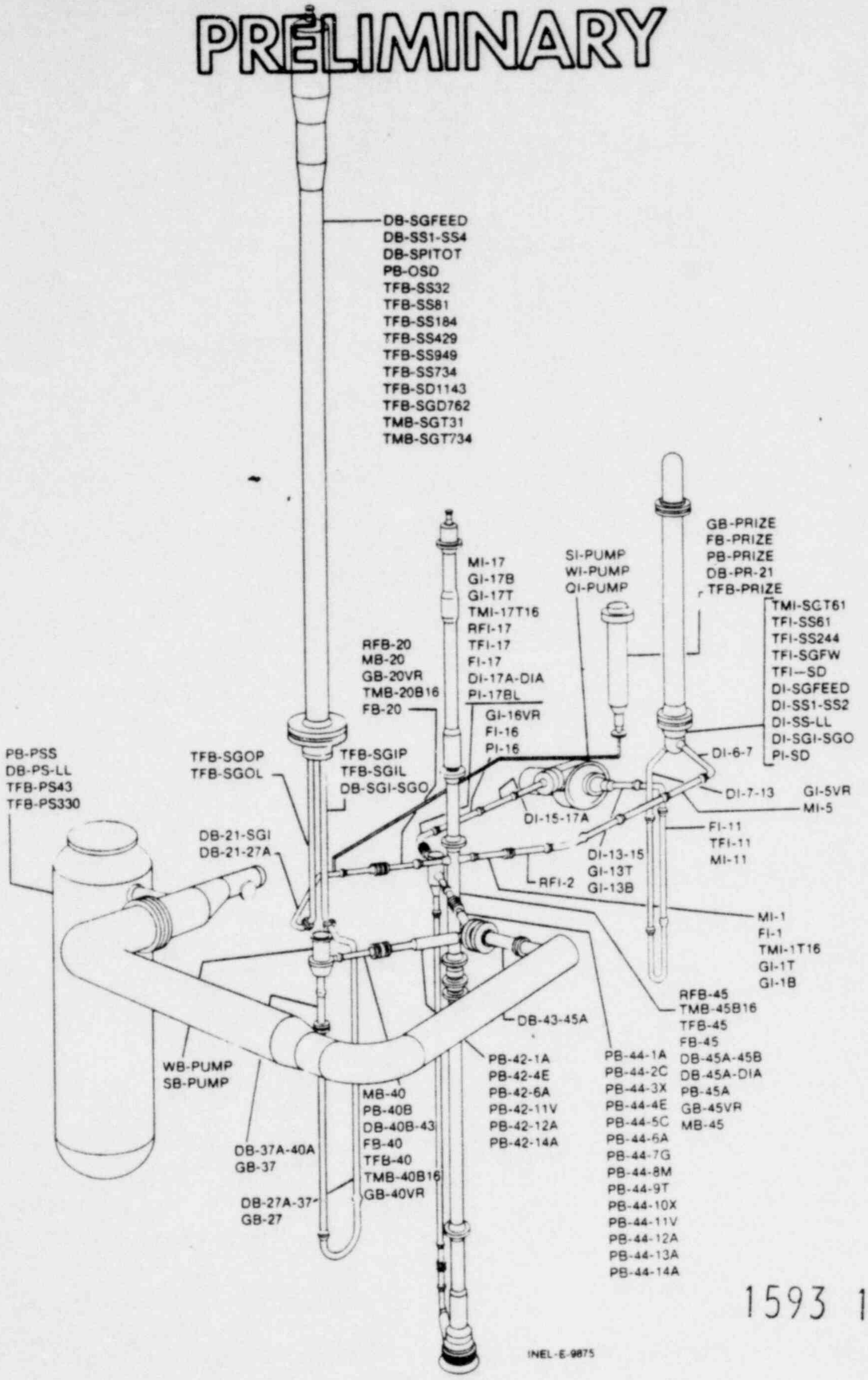

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Fig. 2 Semiscale Mod-3 system cold leg noncommunicative break configuration - isometric with available instrumentation locations.

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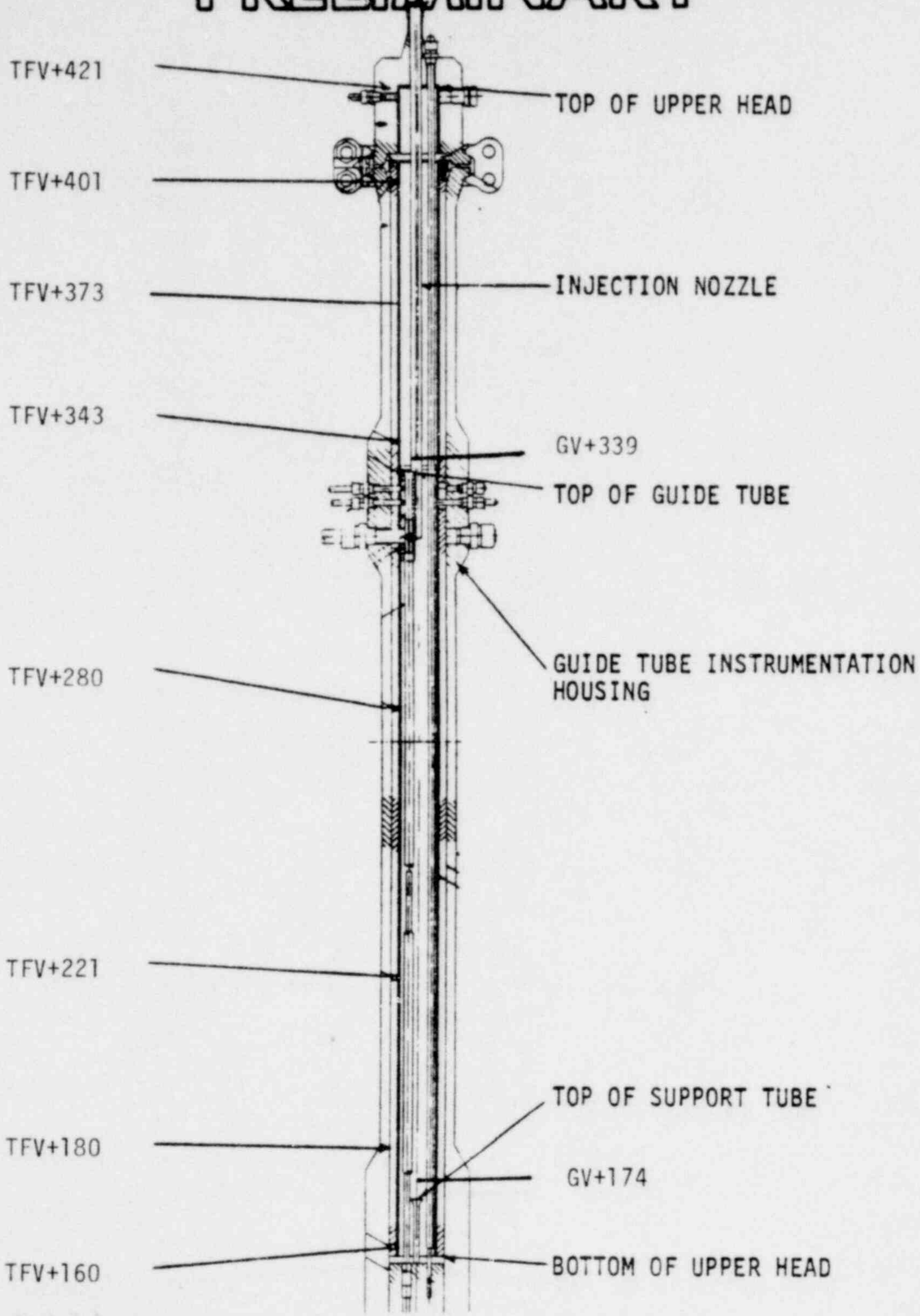

Fig. 3 Semiscale Mod-3 upper head instrumentation locations.

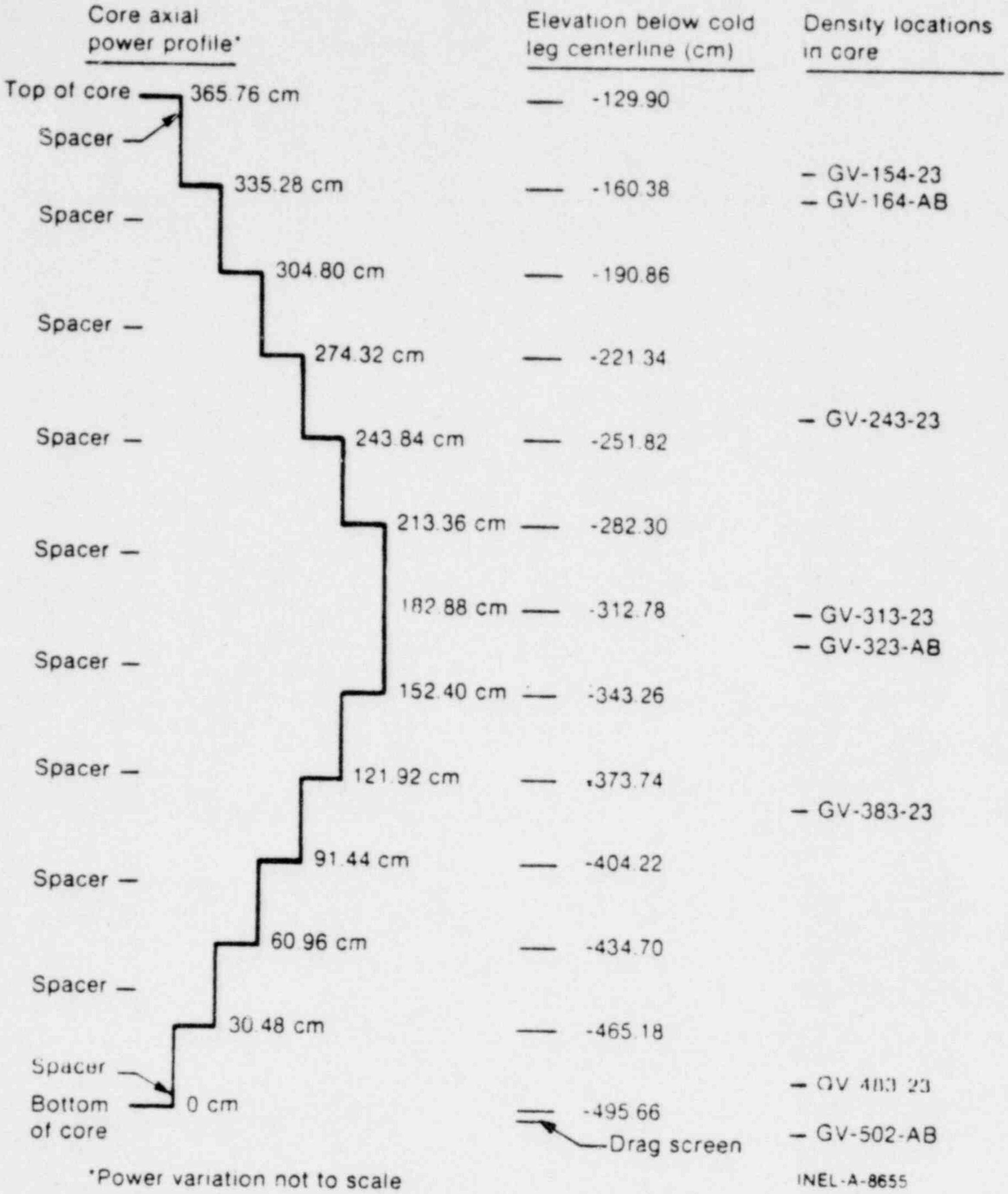

Fig. 4 Axial power profile in relation to vessel instrumentation.

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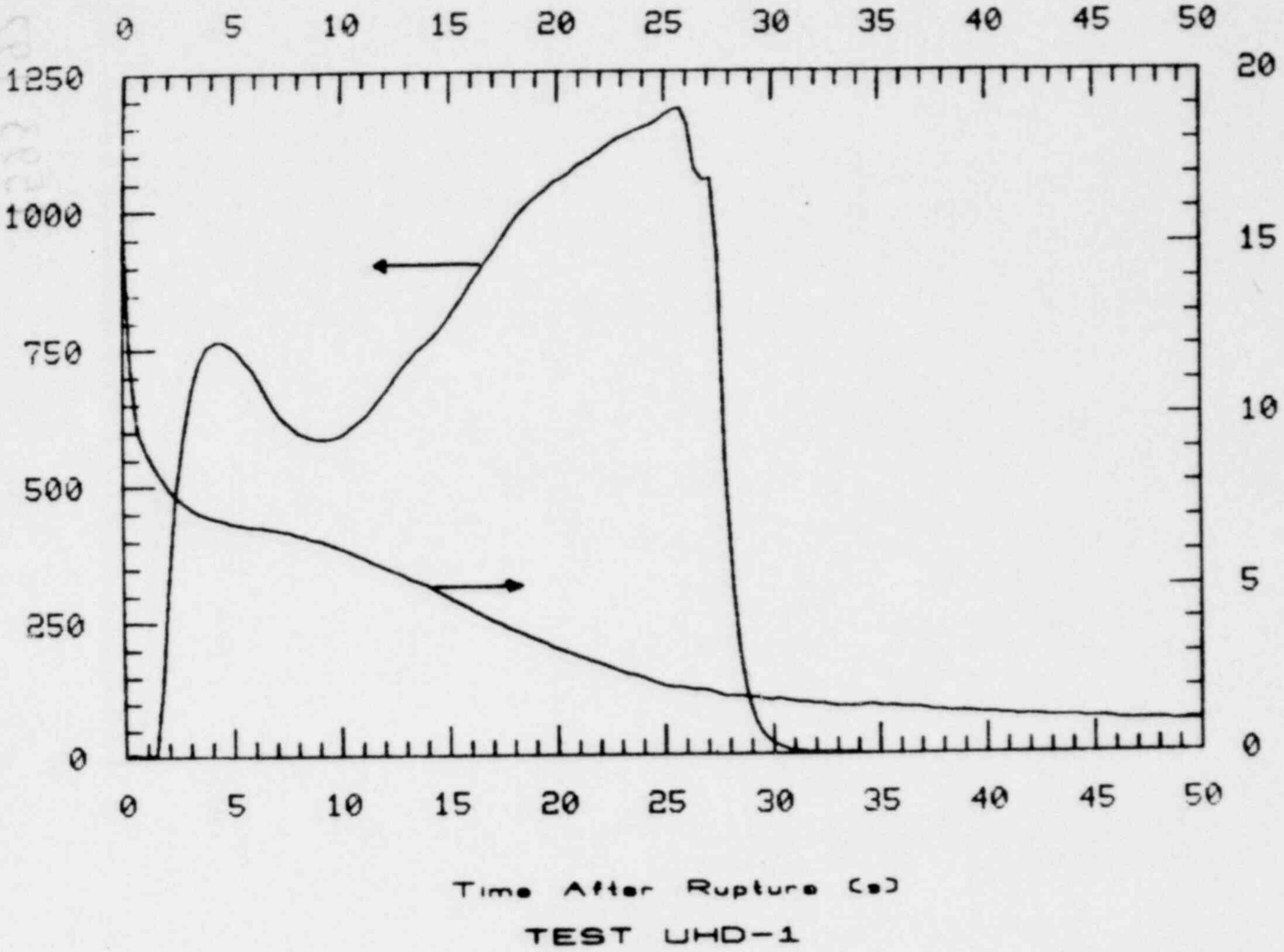

Fig. 5 Upper head injection volumetric flow rate versus system depressurization rate for Test UHD-1.

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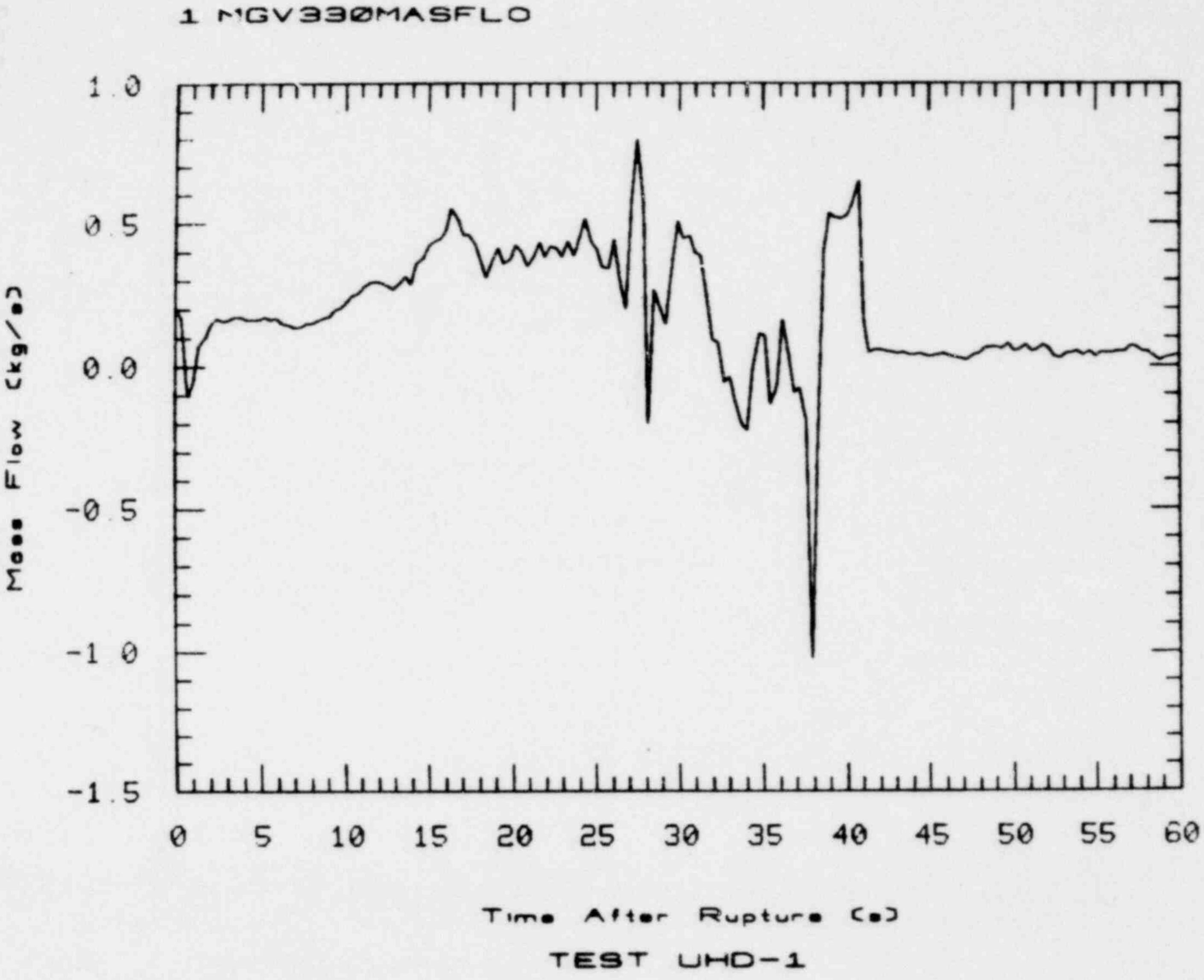

Fig. 6 Guide tube mass flow rate for Test UHD-1.

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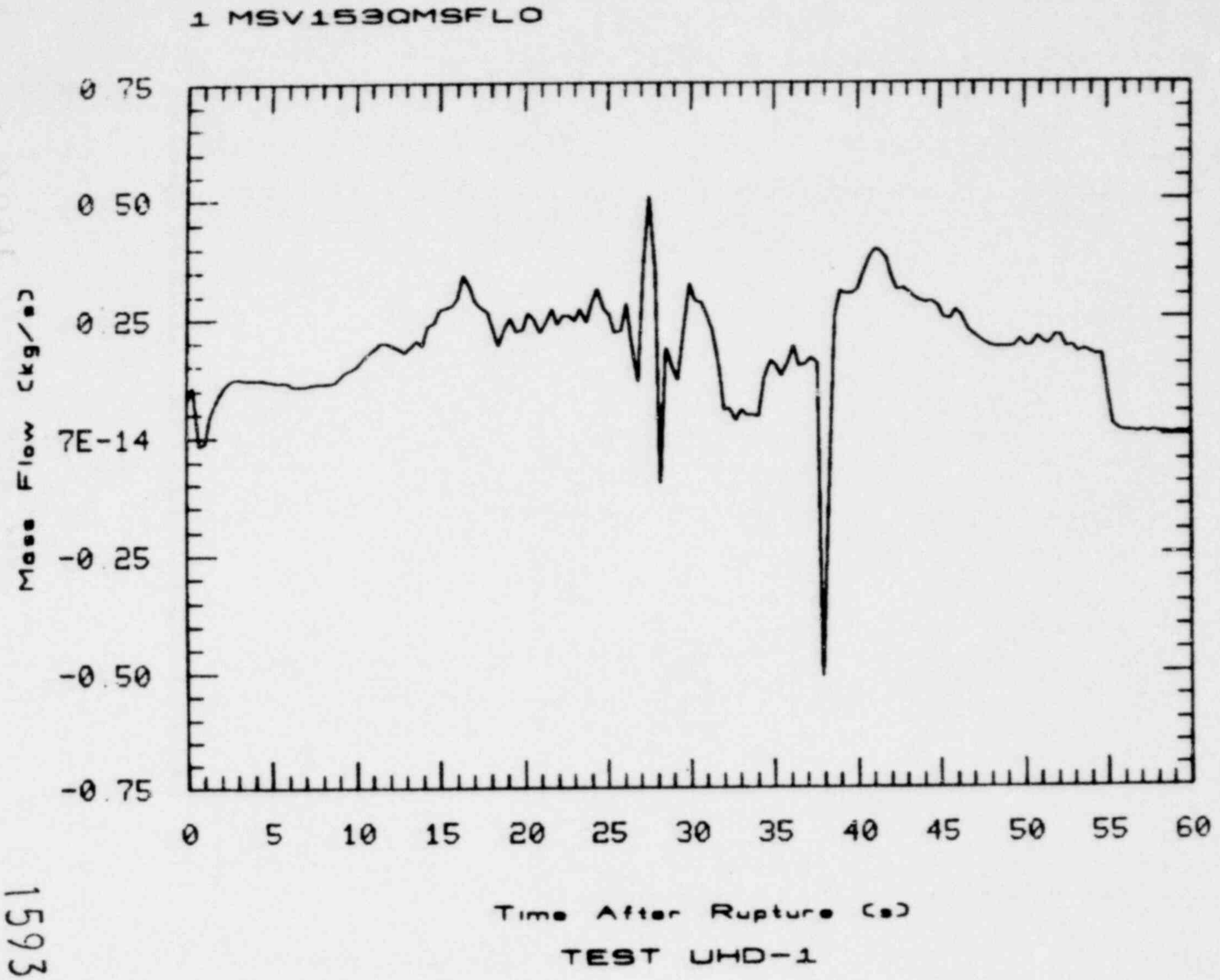

Fig. 7 Support column mass flow rate for Test UHD-1.

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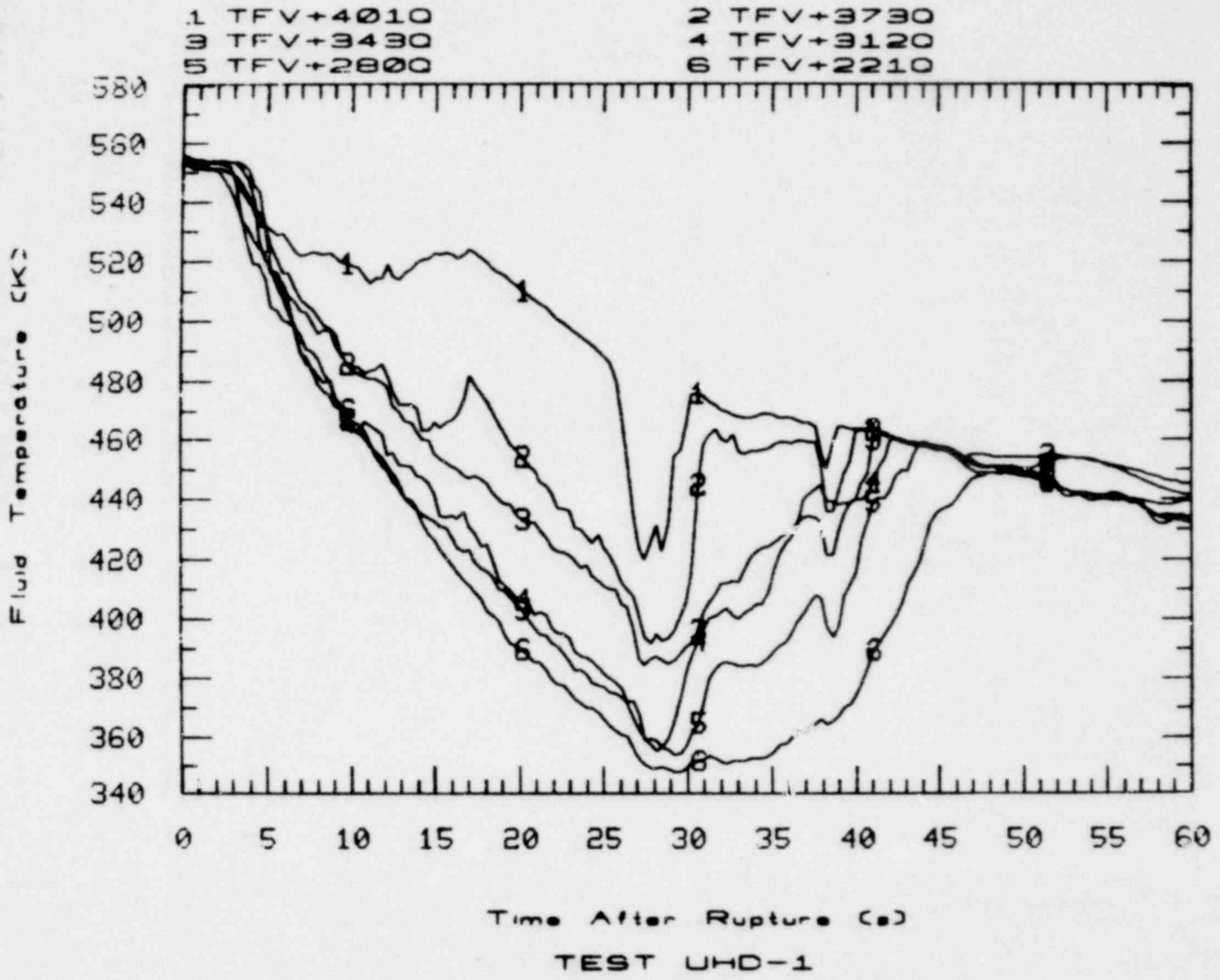

Fig. 8 Comparison of upper head fluid temperatures for Test UHD-1.

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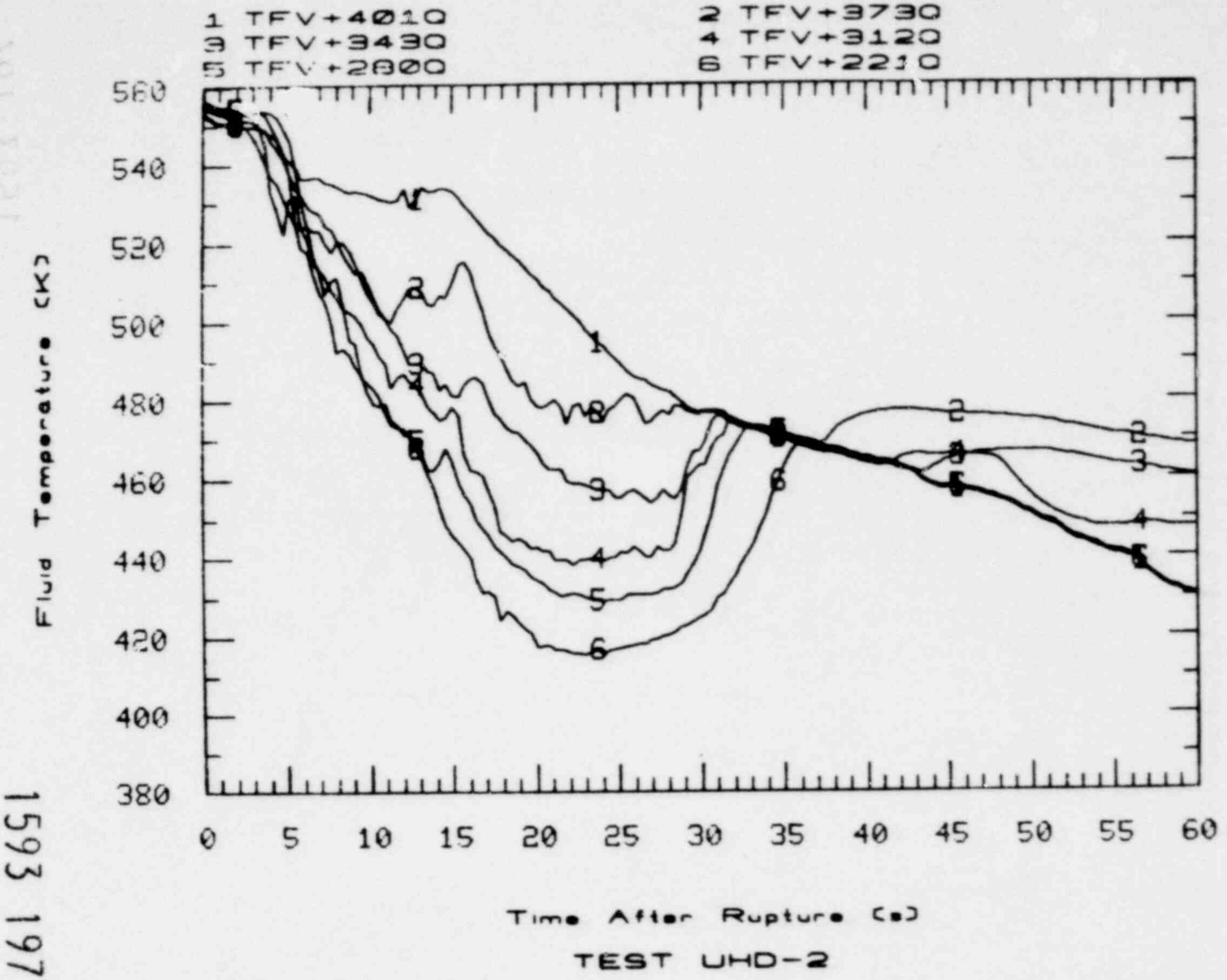

Fig. 9 Comparison of upper head fluid temperatures for Test UHD-2.

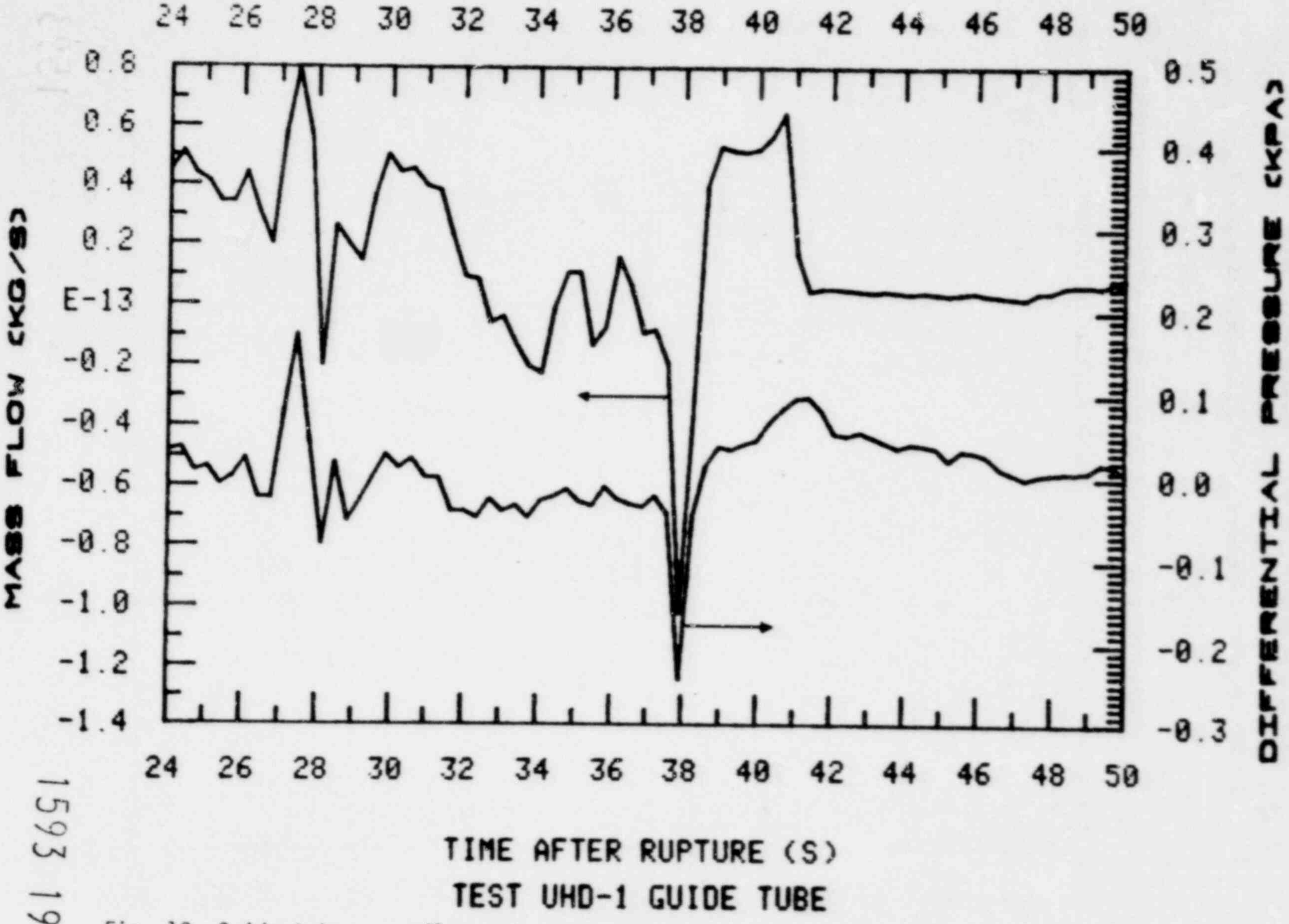

Fig. 10 Guide tube mass flow rate versus upper head-to-upper plenum differential pressure for Test UHD-1.

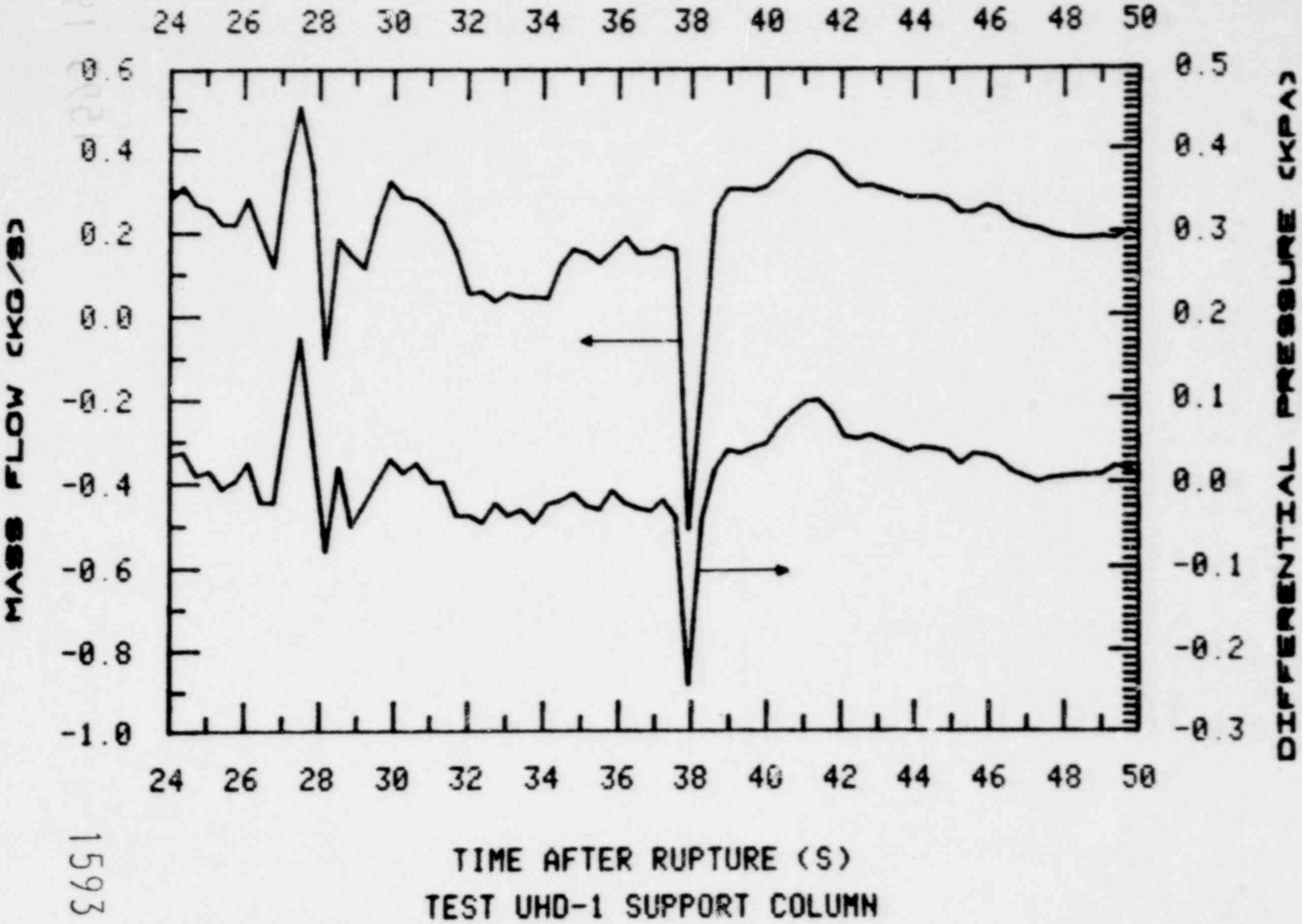

Fig. 11 Support column mass flow rate versus upper head-to-upper plenum differential pressure for Test UHD-1.

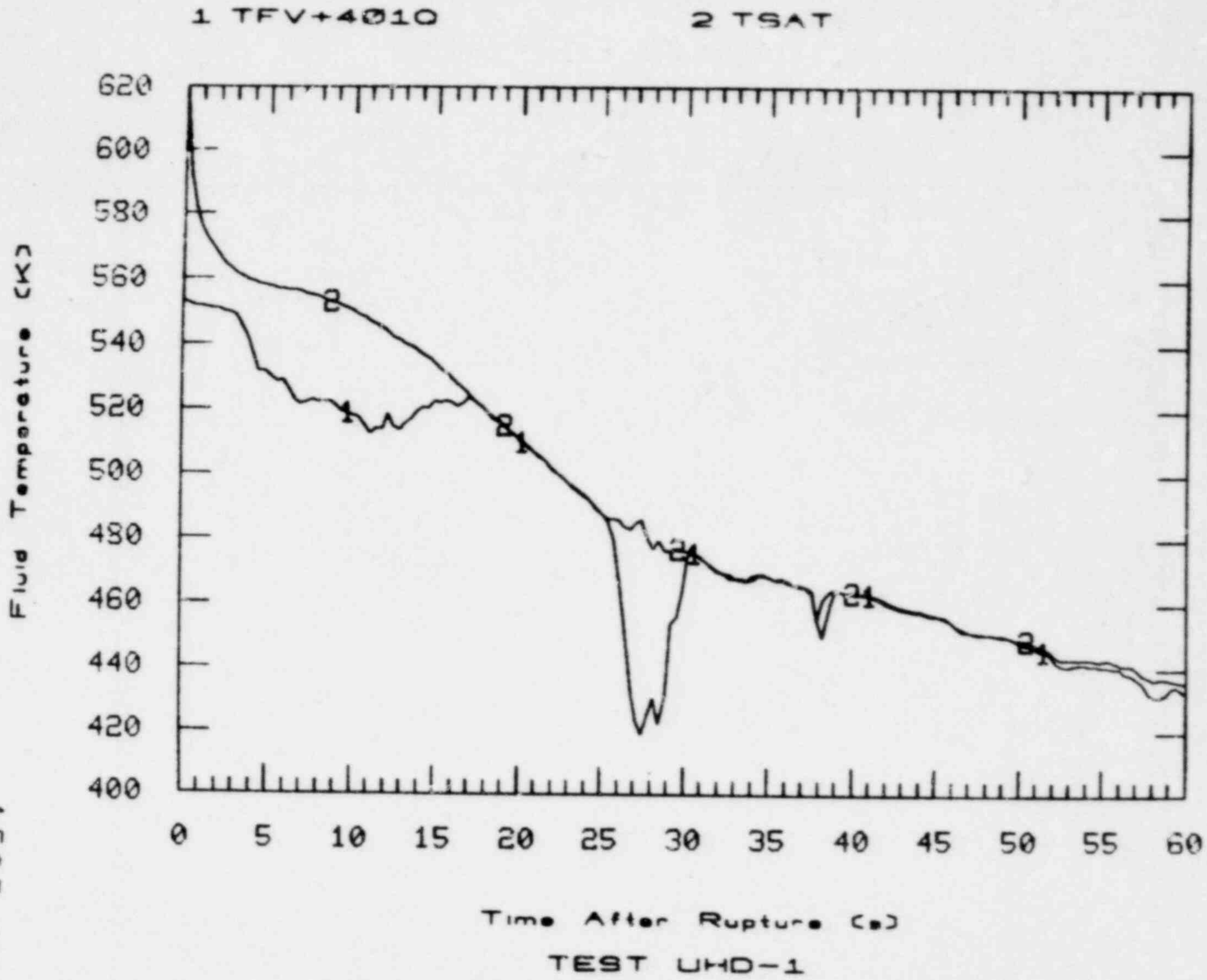

Fig. 12 Comparison of the upper head fluid temperature at the 401-cm elevation with the saturation temperature for Test UHD-1.

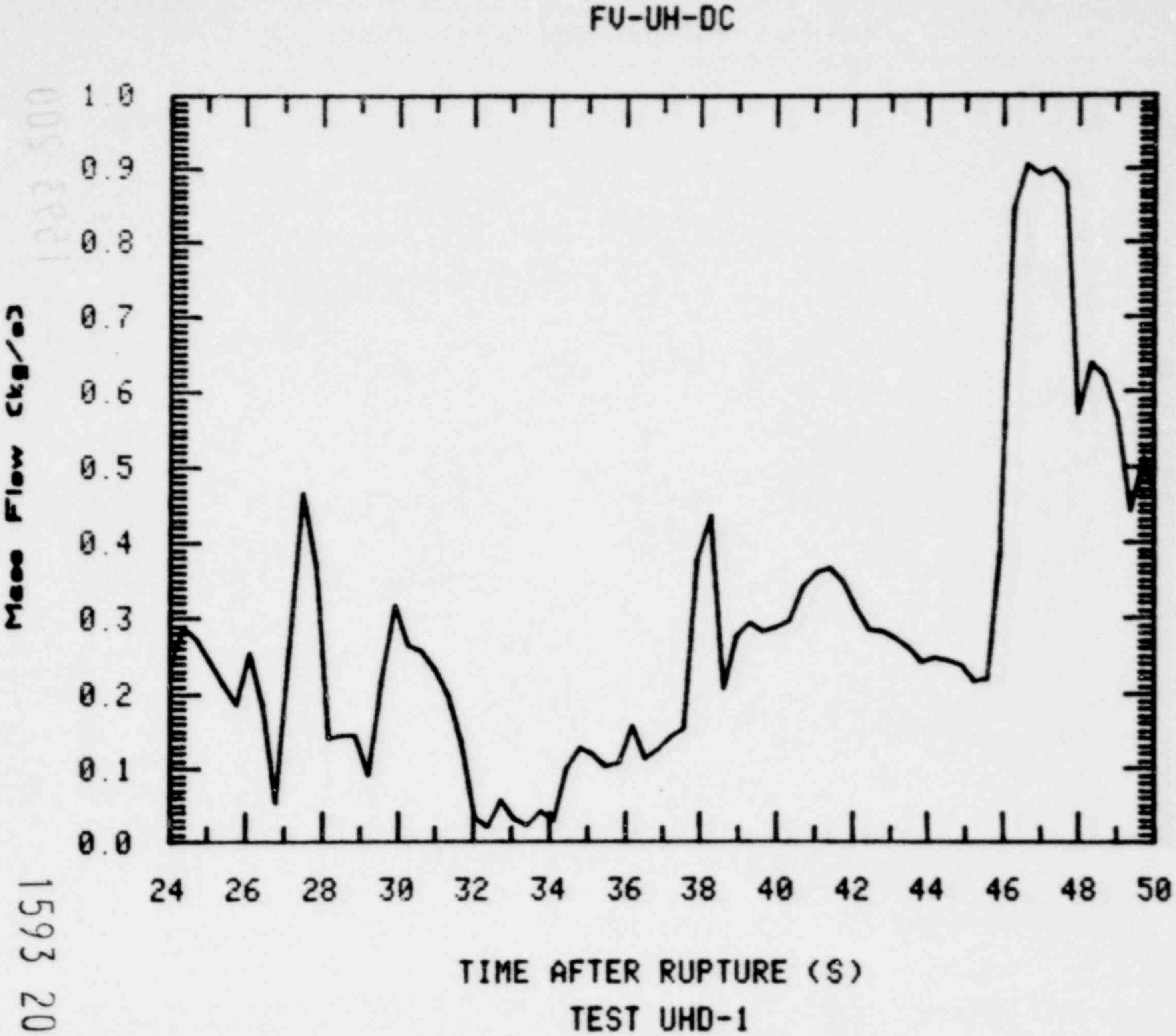

Fig. 13 Upper head bypass line mass flow rate for Test UHD-1.

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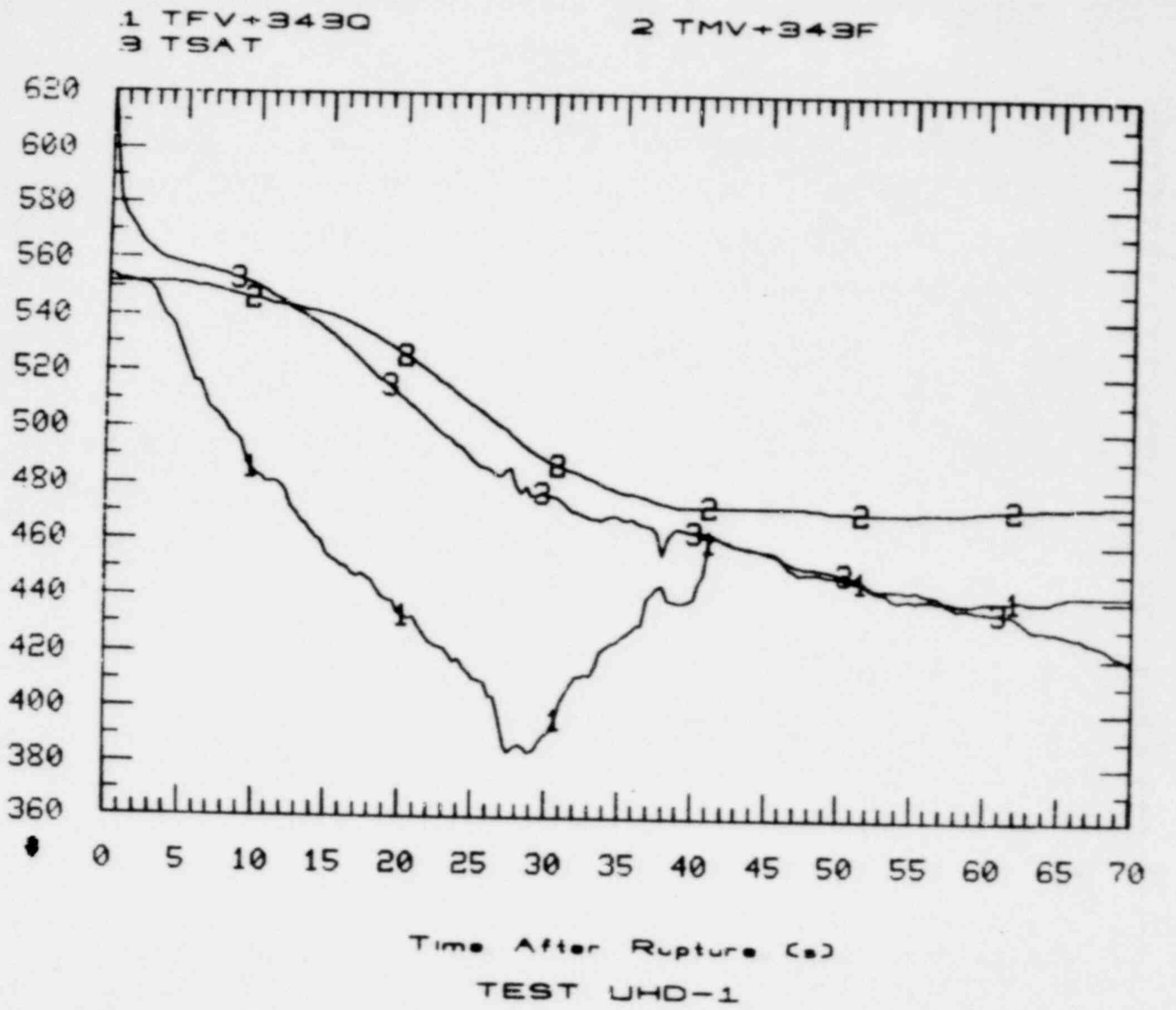

Fig. 14 Comparison of the upper head metal temperature and saturation temperature at the 343-cm elevation for Test UHD-1.

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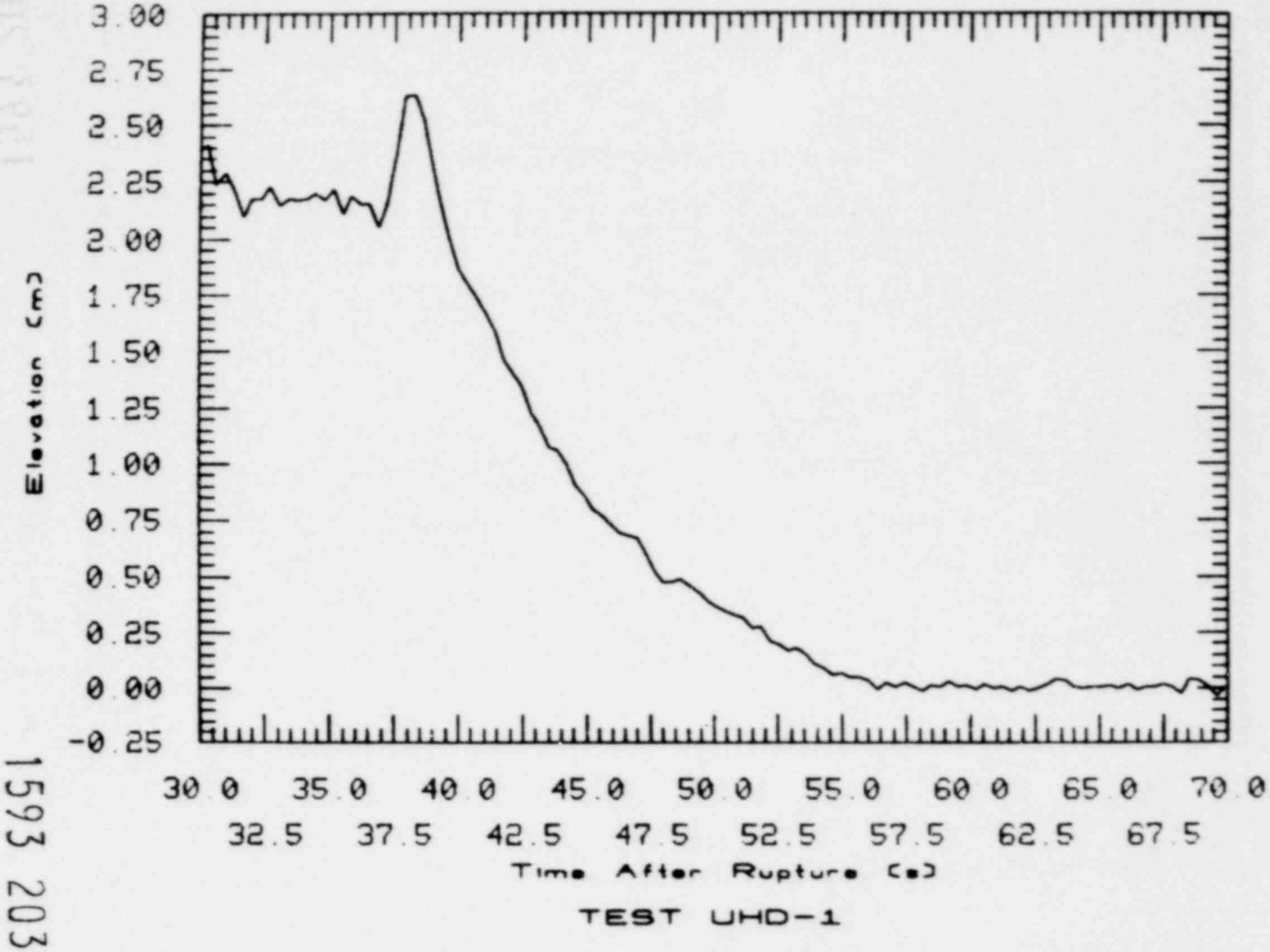

Fig. 15 Upper head collapsed liquid level for Test UHD-1.

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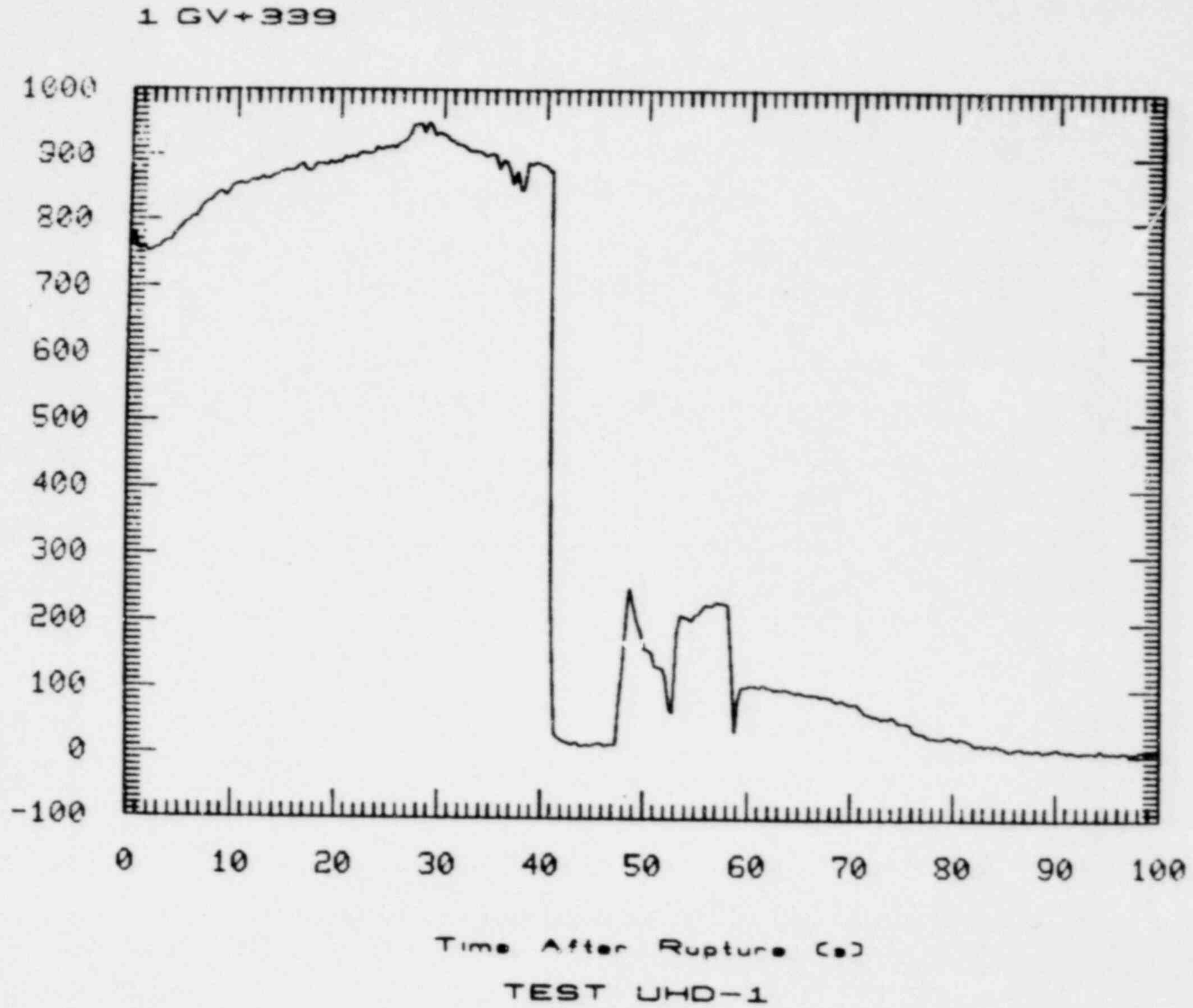

Fig. 16 Fluid density near the top of the guide tube (339-cm elevation) for Test UHD-1.

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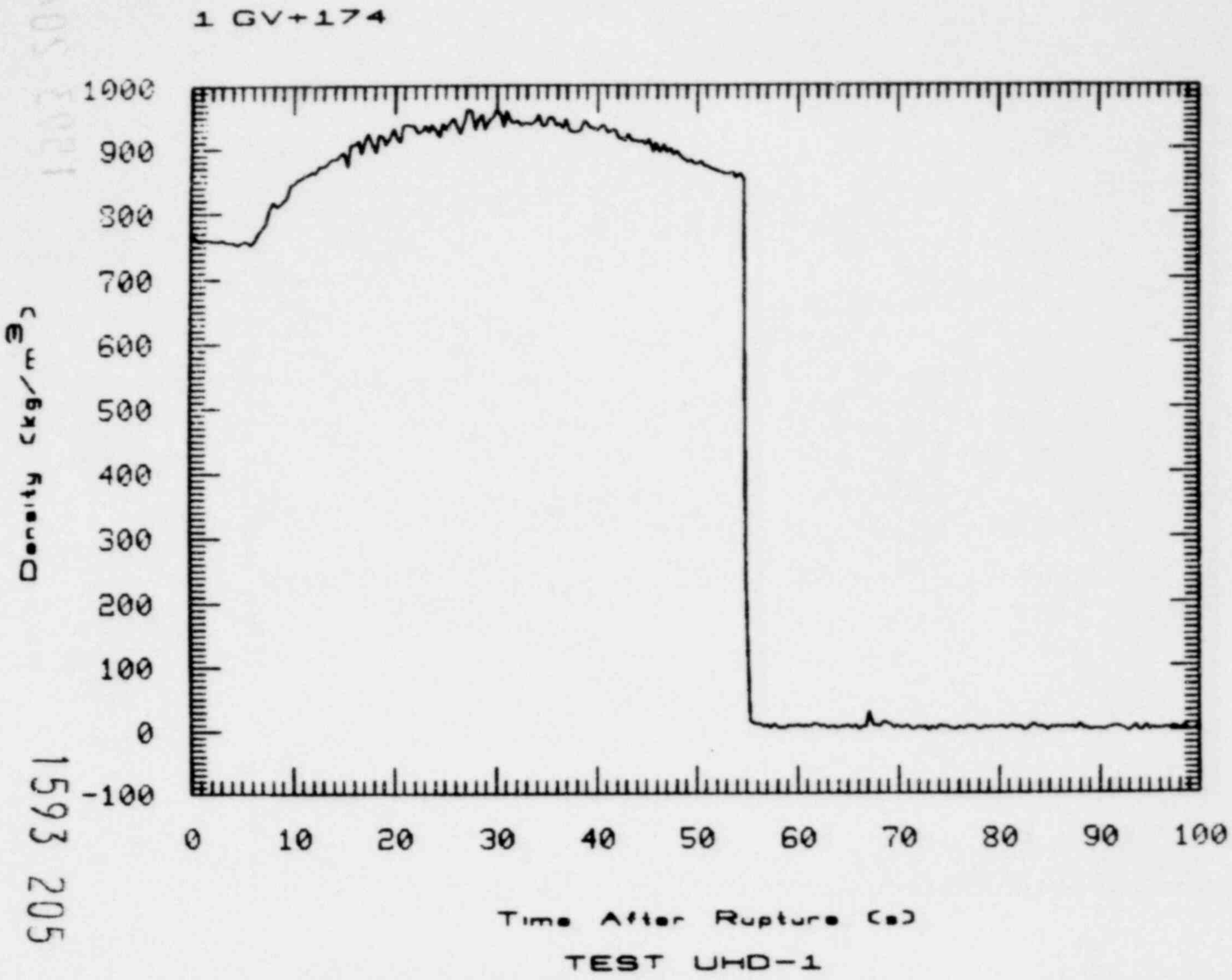

Fig. 17 Fluid density near the top of the support columns (174-cm elevation) for Test UHD-1.

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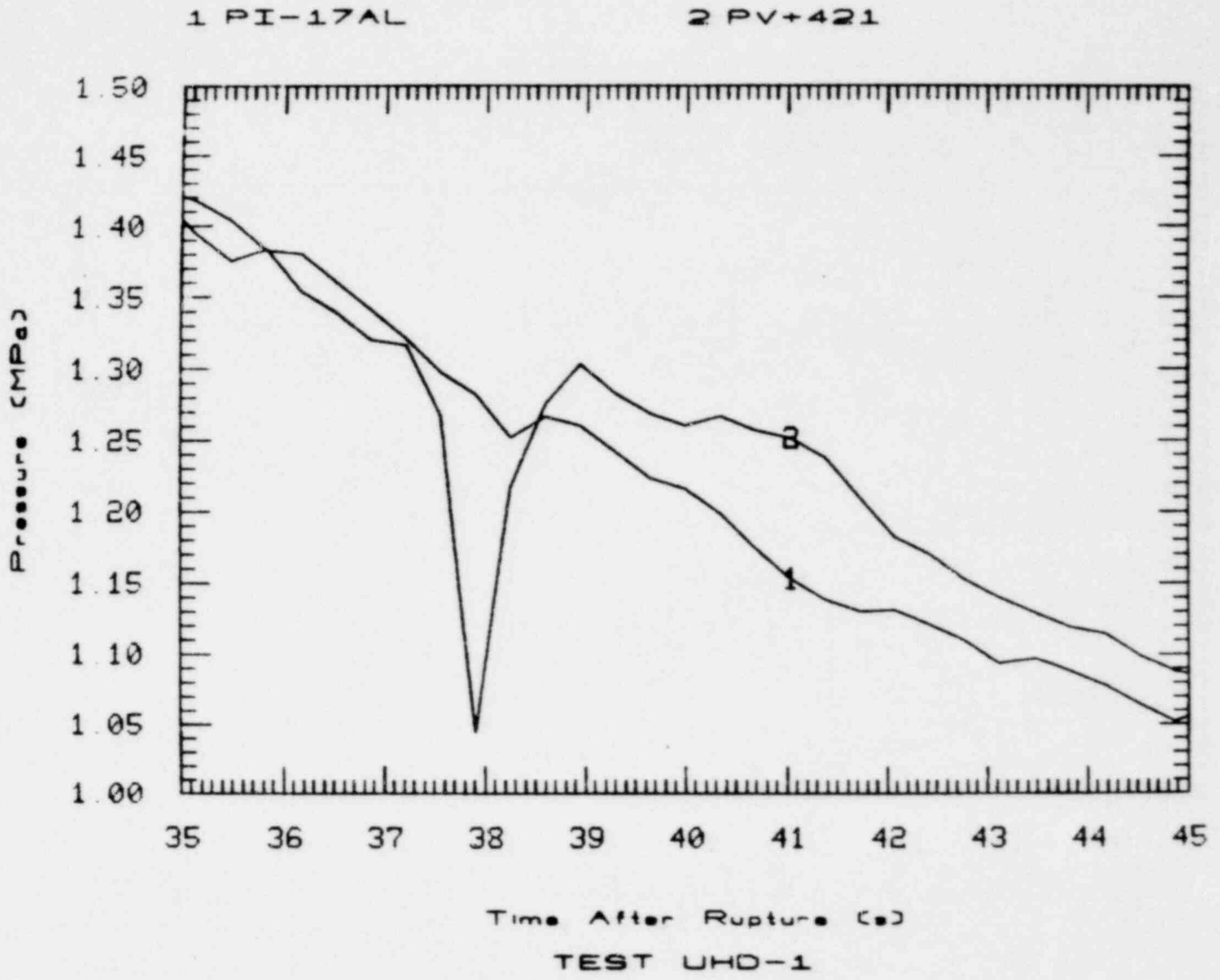

Fig. 18 Comparison of the upper head and system pressure for Test UHD-1.

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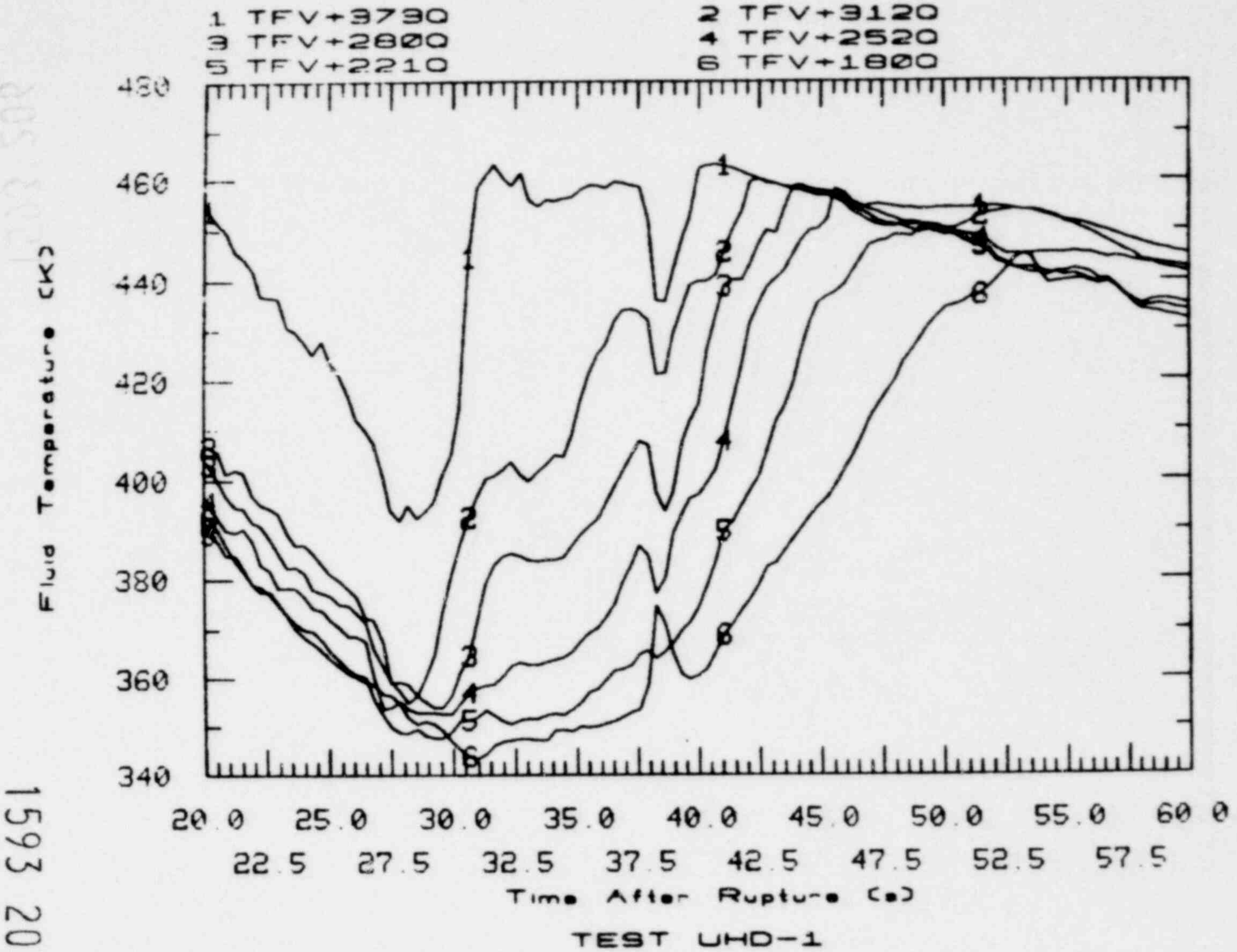

Fig. 19 Comparison of the upper head fluid temperatures for Test UHD-1.

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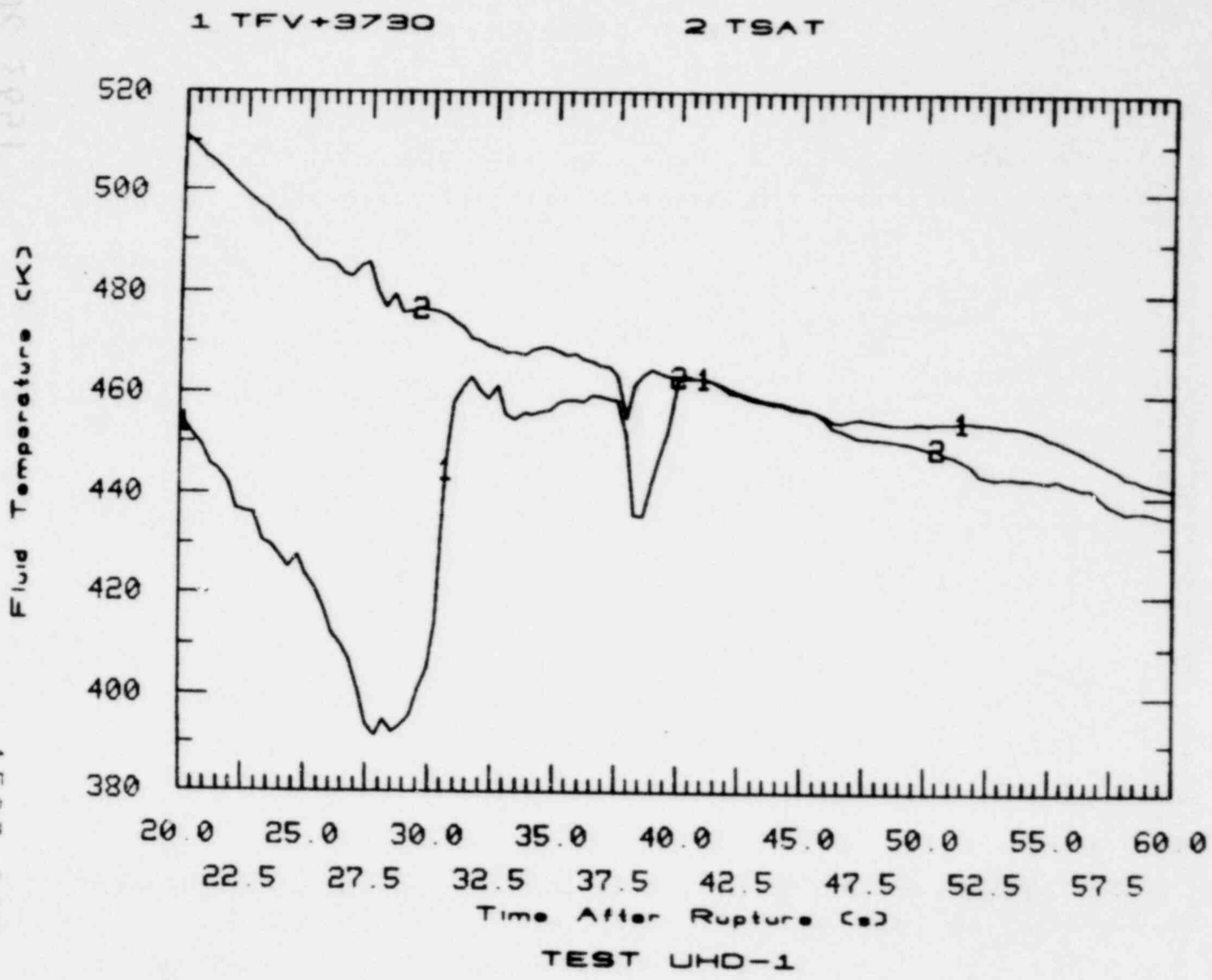

Fig. 20 Comparison of the upper head fluid temperature at the 373-cm elevation with the saturation temperature for Test UHD-1.

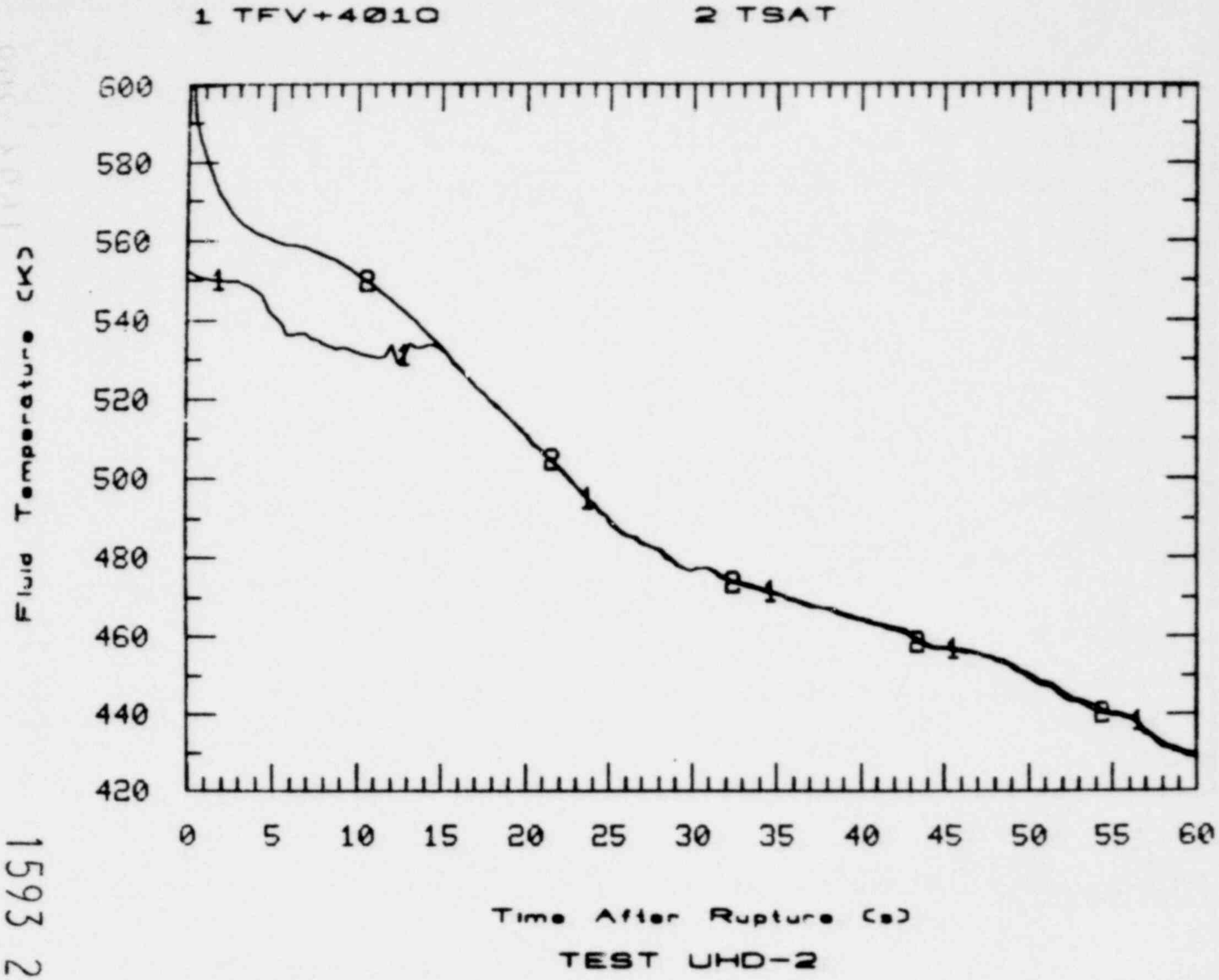

Fig. 21 Comparison of the upper head fluid temperature at the 401-cm elevation with the saturation temperature for Test UHD-2.

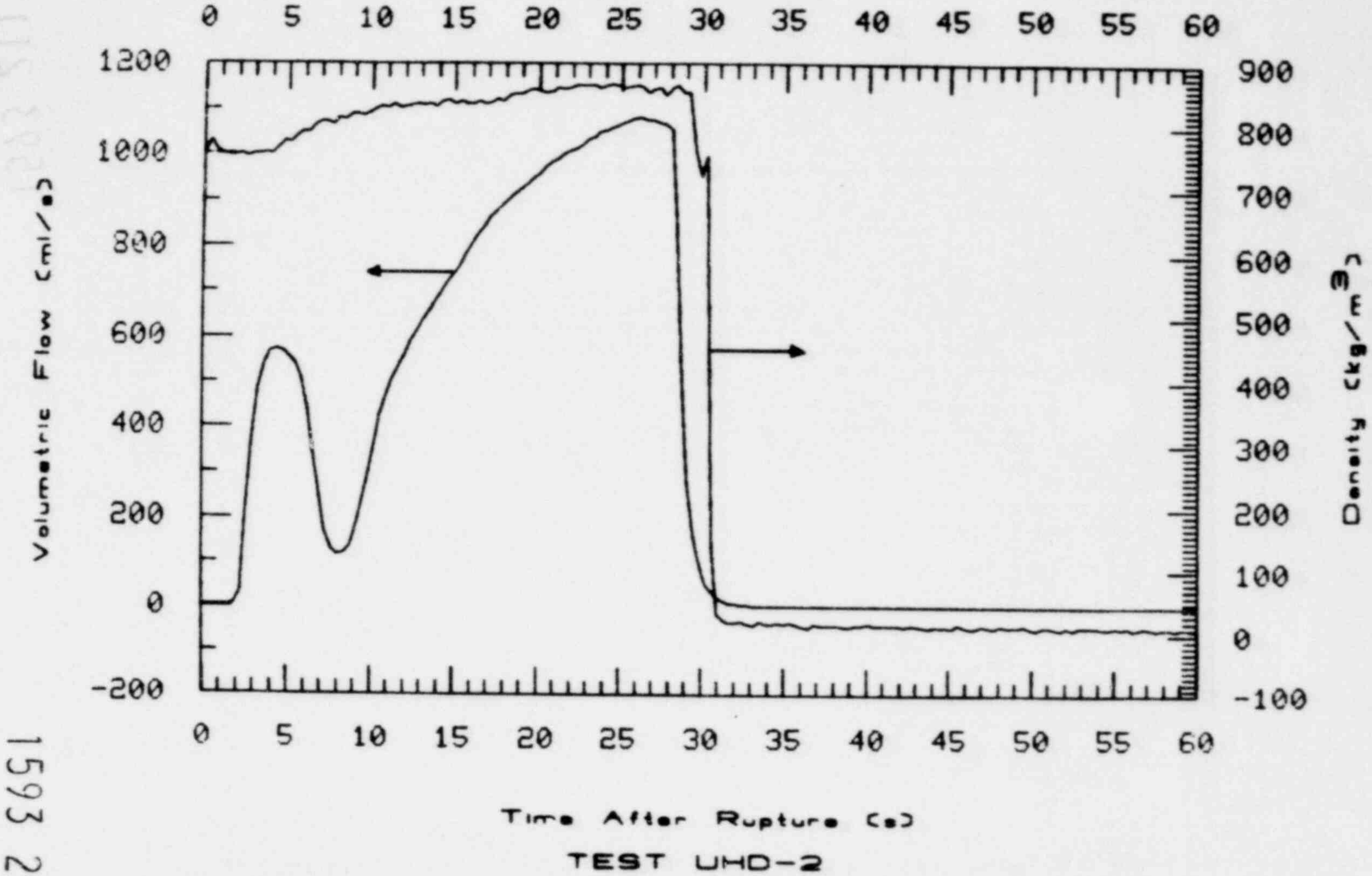

Fig. 22 Upper head injection volumetric flow rate versus fluid density near the top of the guide tube (339-cm elevation) for Test UHD-2.

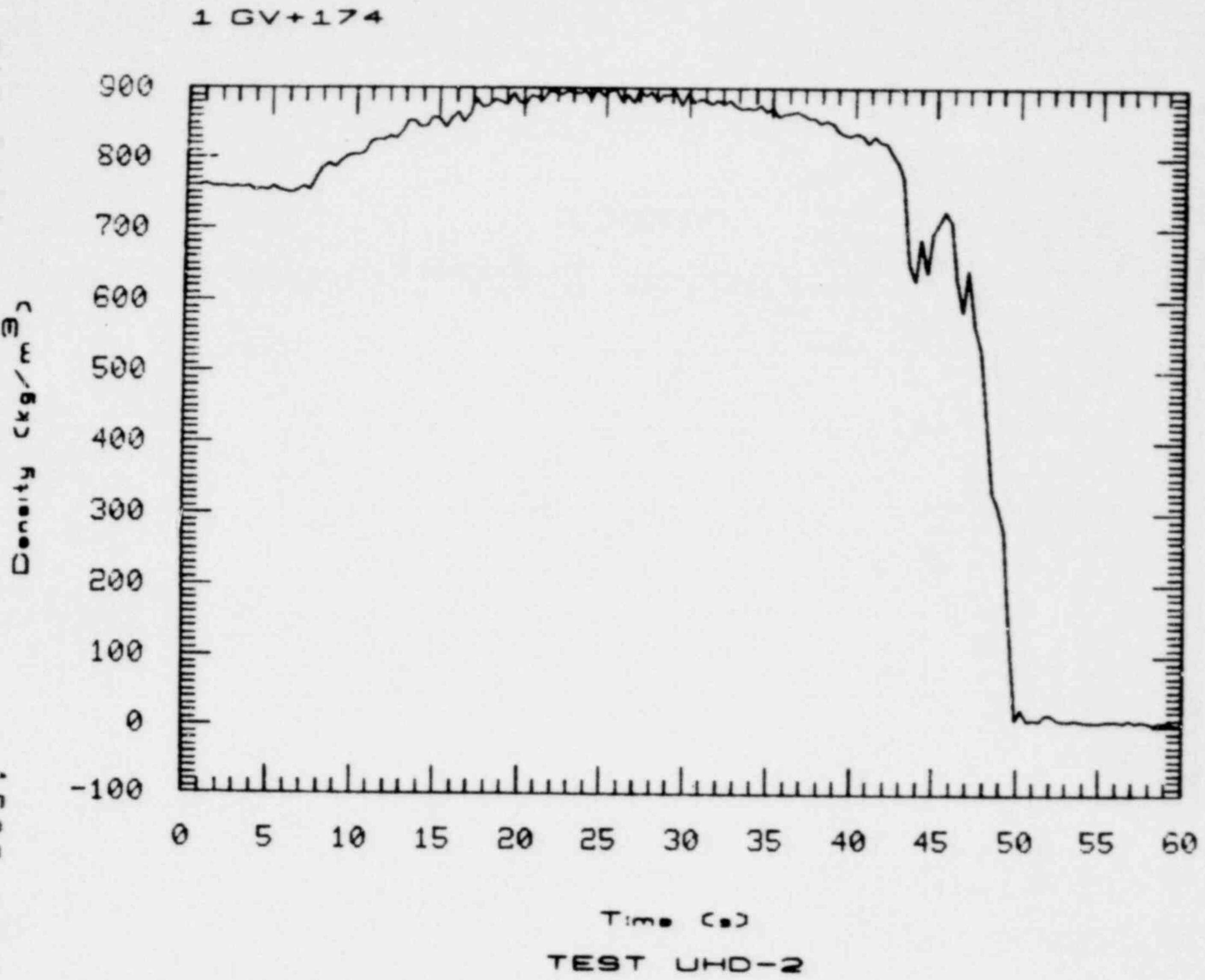

Fig. 23 Fluid denisty near the top of the support columns (174-cm elevation) for Test UHD-2.

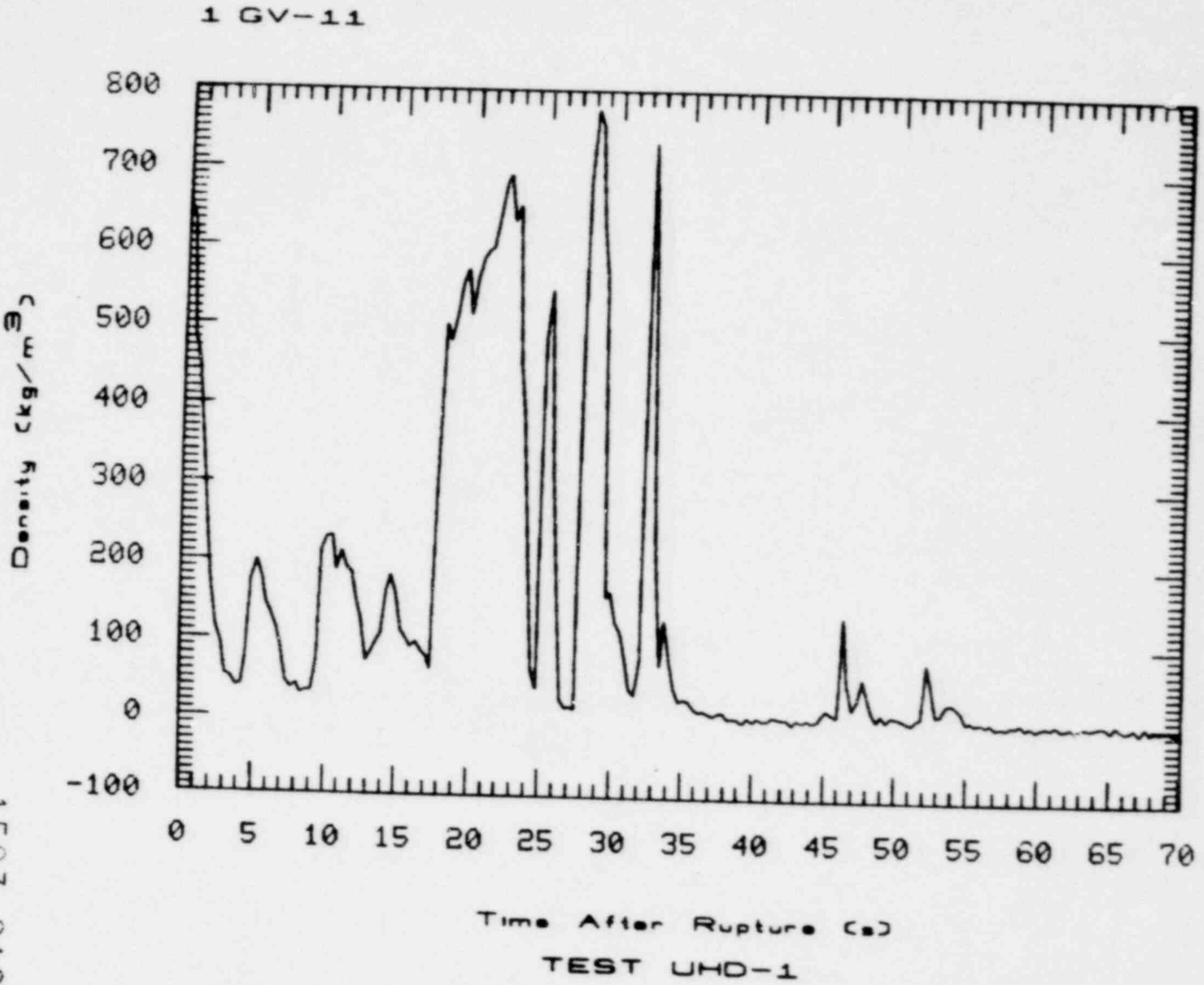

Fig. 24 Upper plenum fluid density for Test UHD-1.

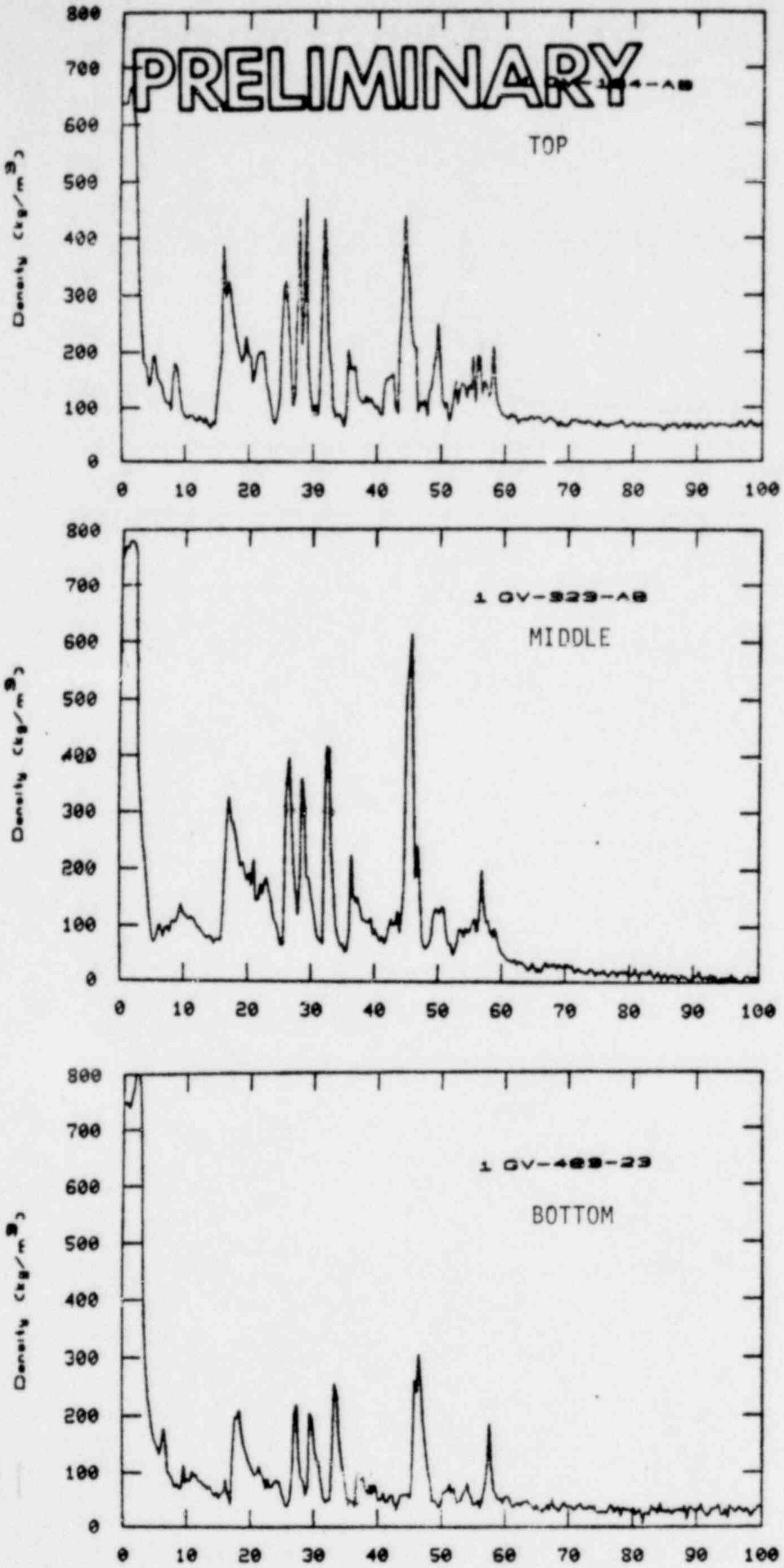

Fig. 25 Fluid densities near the top, middle, and bottom of the core for Test UHD-1.

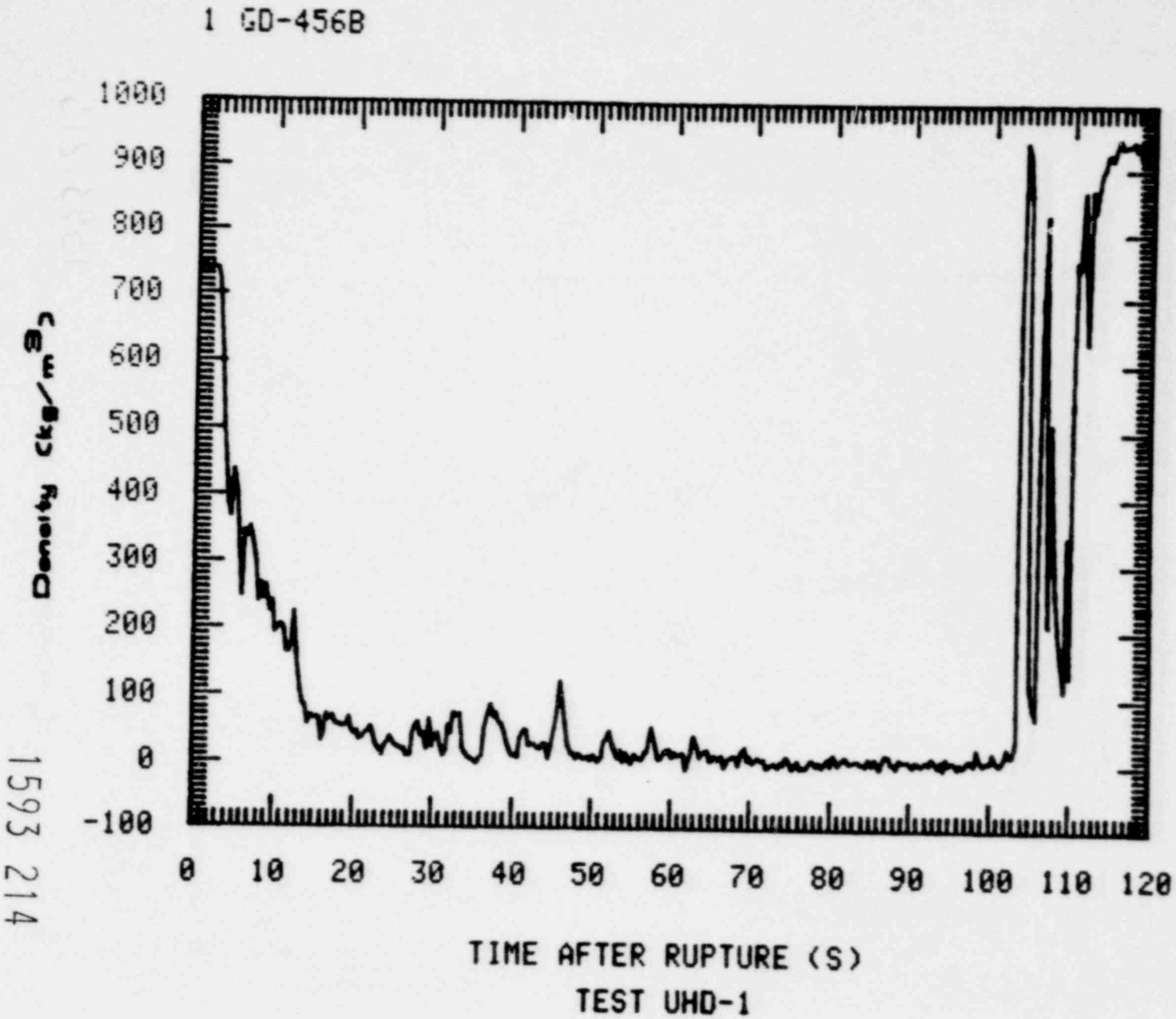

Fig. 26 Fluid density near the bottom of the downcomer for Test UHD-1.

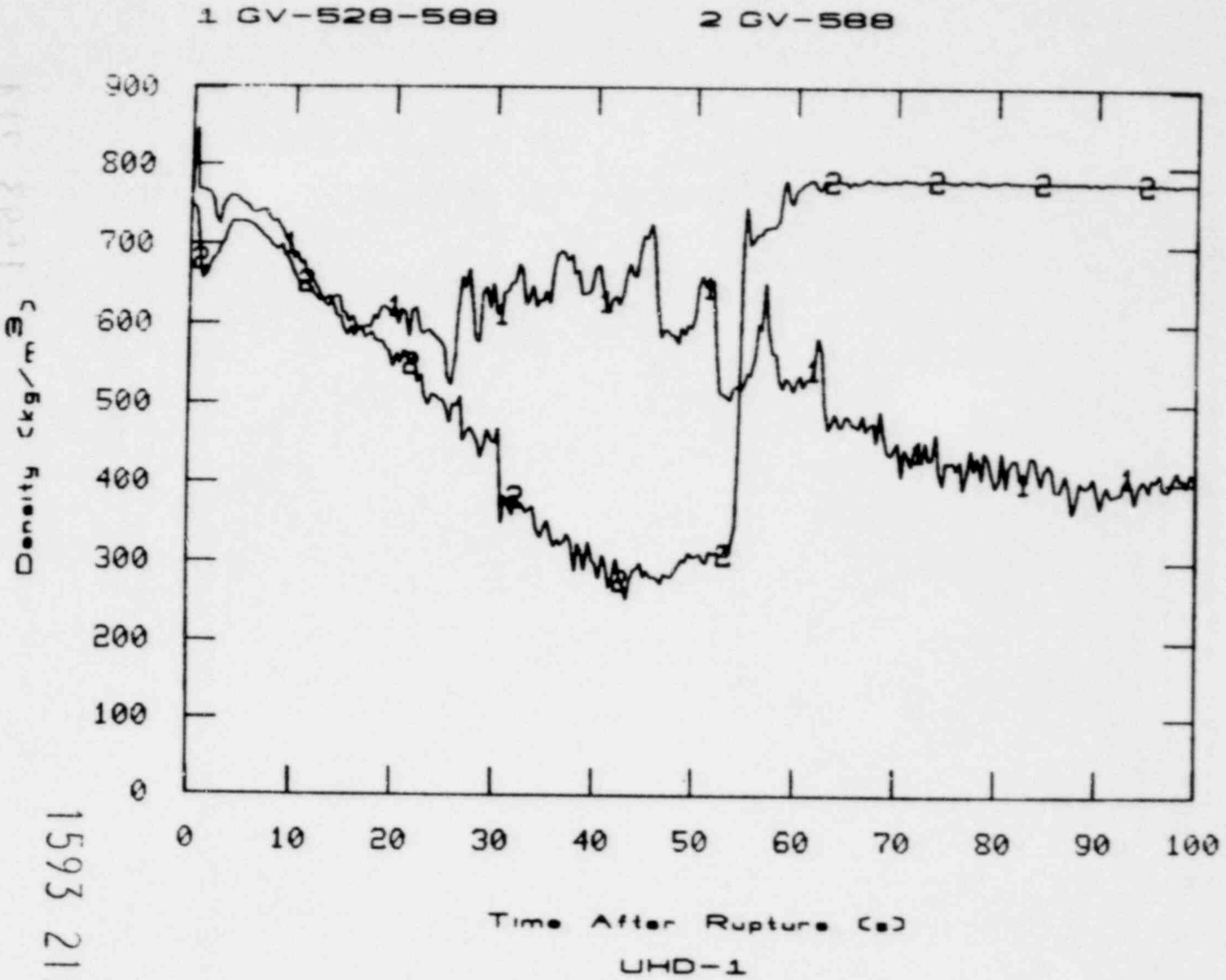

Fig. 27 Comparison of the lower plenum fluid density for Tests UHD-1 and S-07-3.

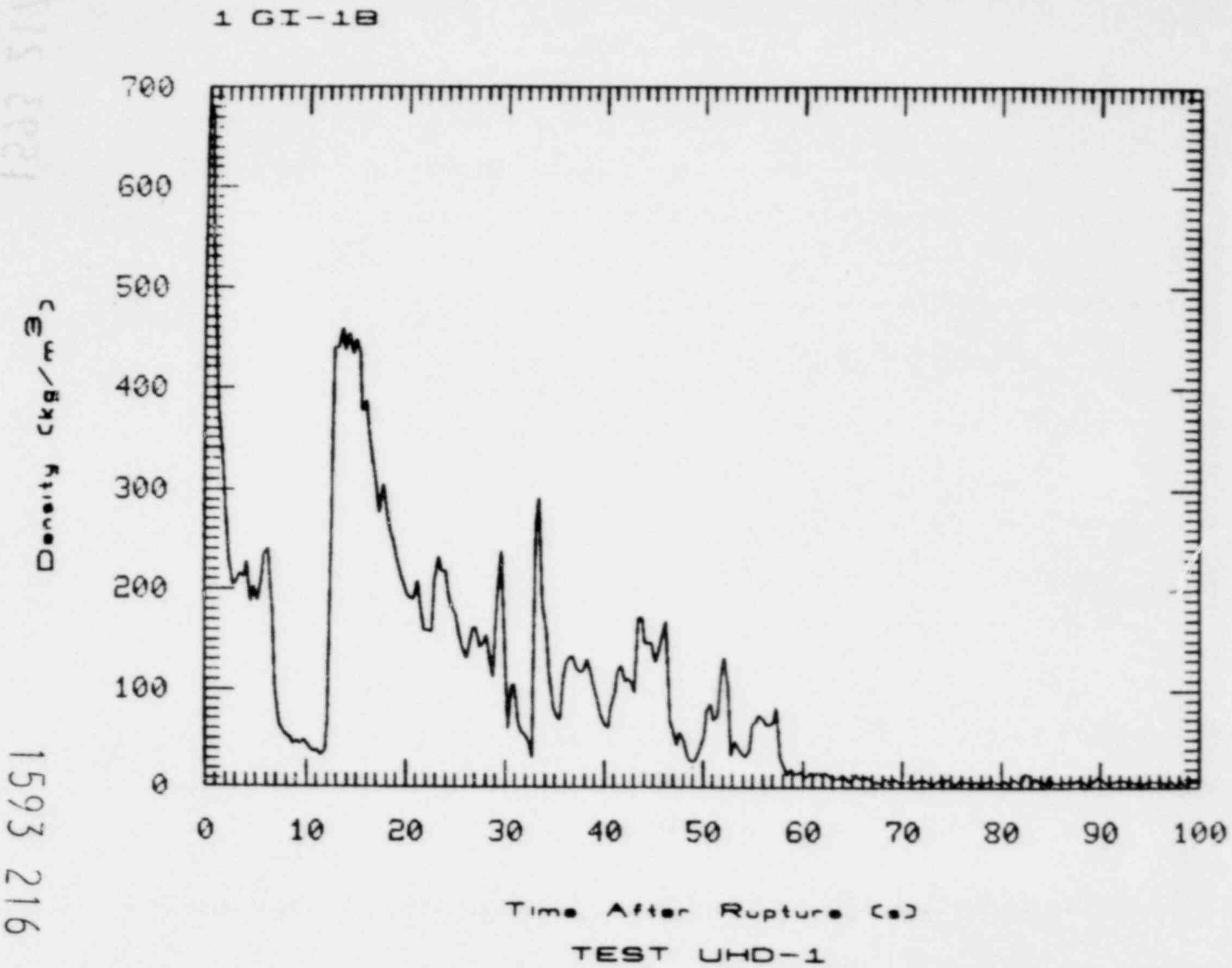

Fig. 28 Intact loop hot leg fluid density for Test UHD-1.

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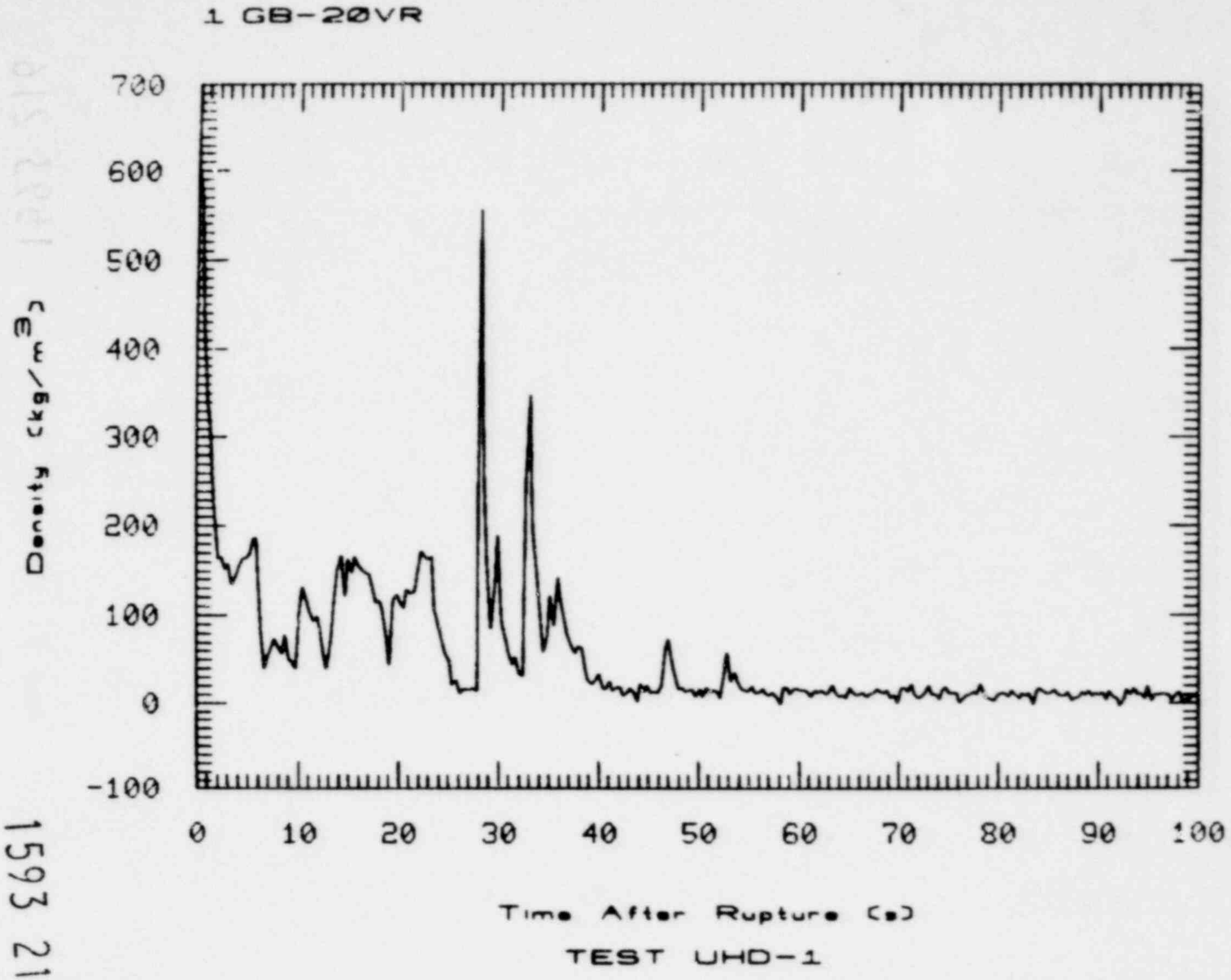

Fig. 29 Broken loop hot leg fluid density for Test UHD-1.

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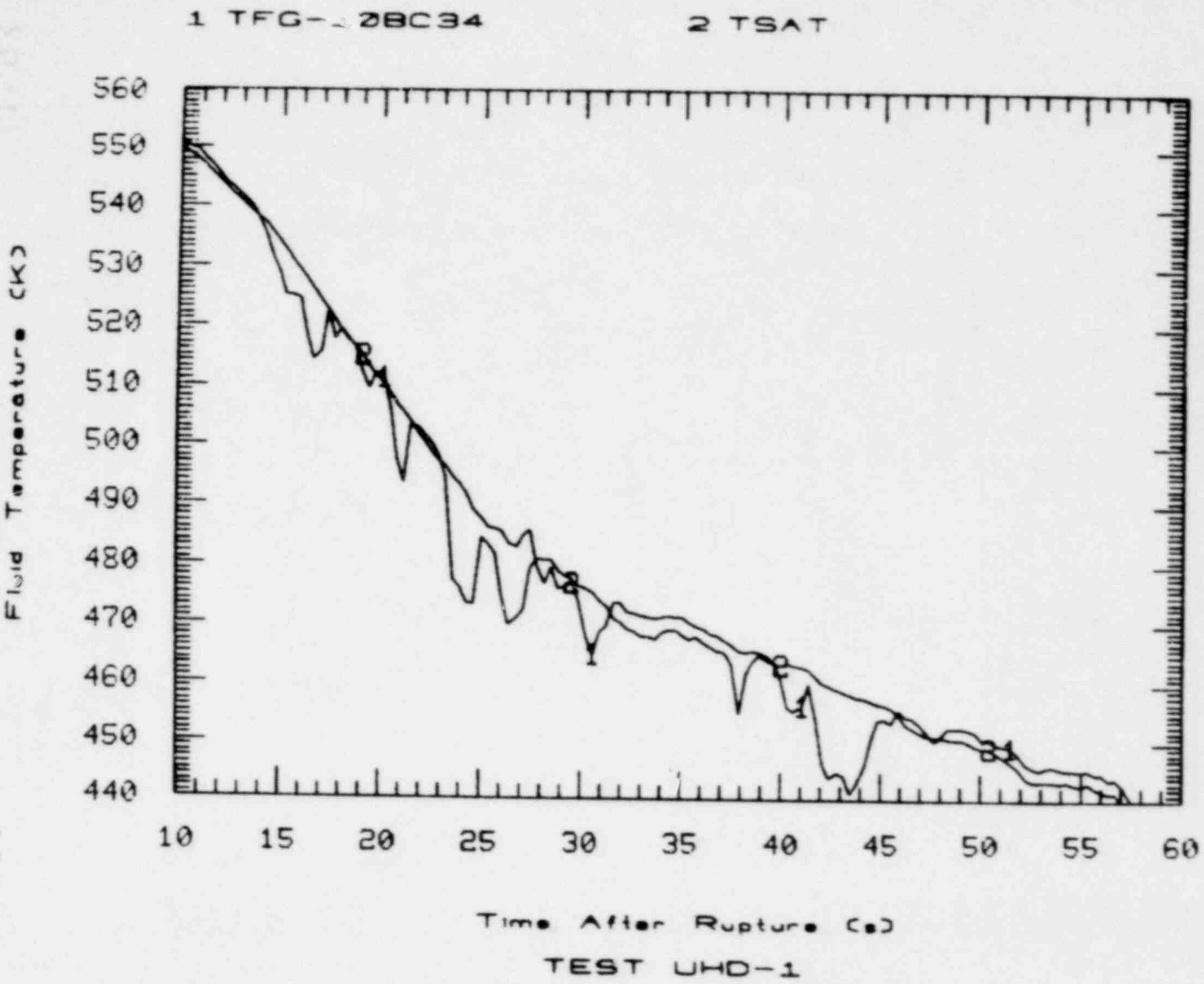

Fig. 30 Comparison of the fluid temperature near the top of the core with the saturation temperature for Test UHD-1.

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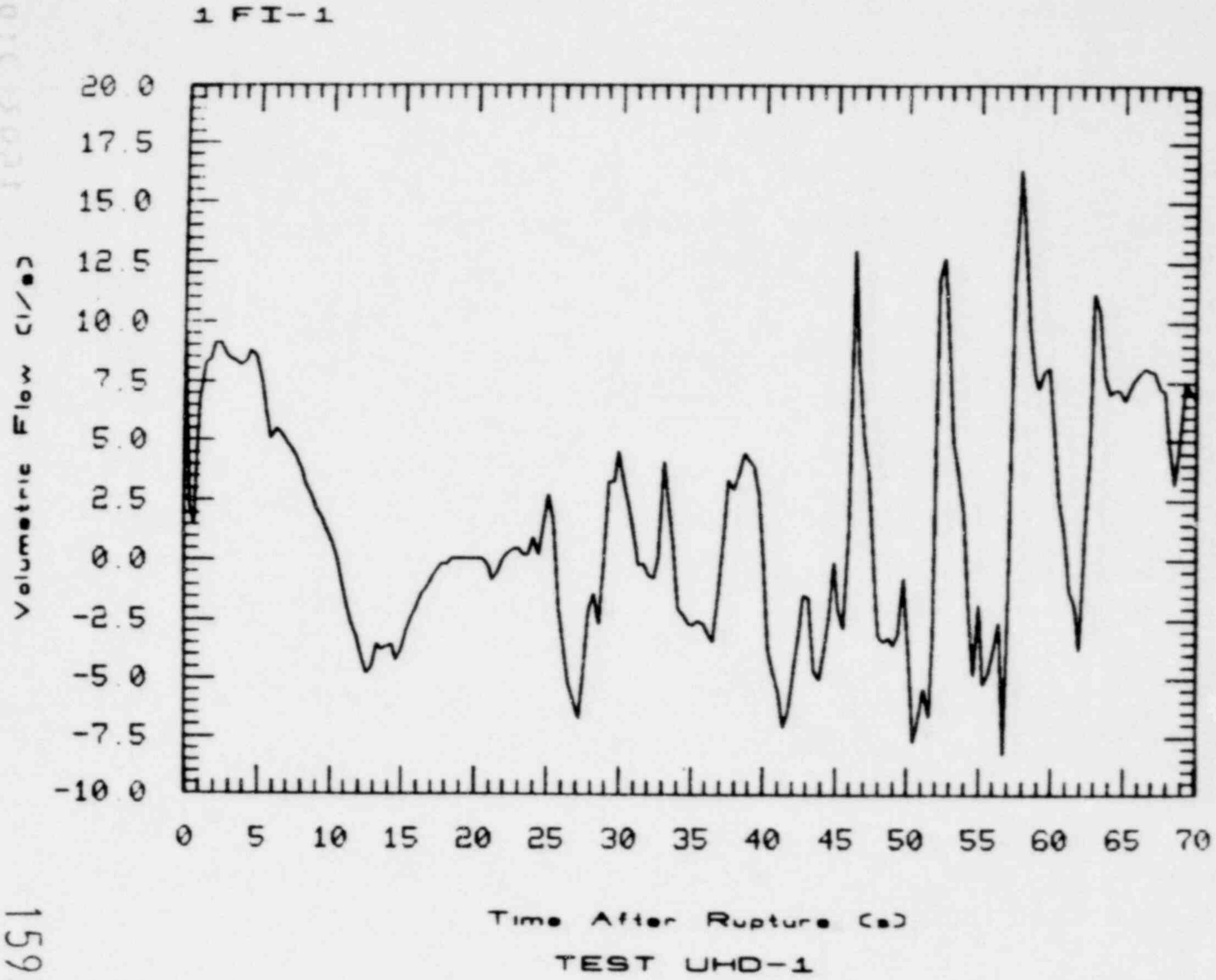

Fig. 31 Intact loop hot leg volumetric flow rate for Test UHD-1.

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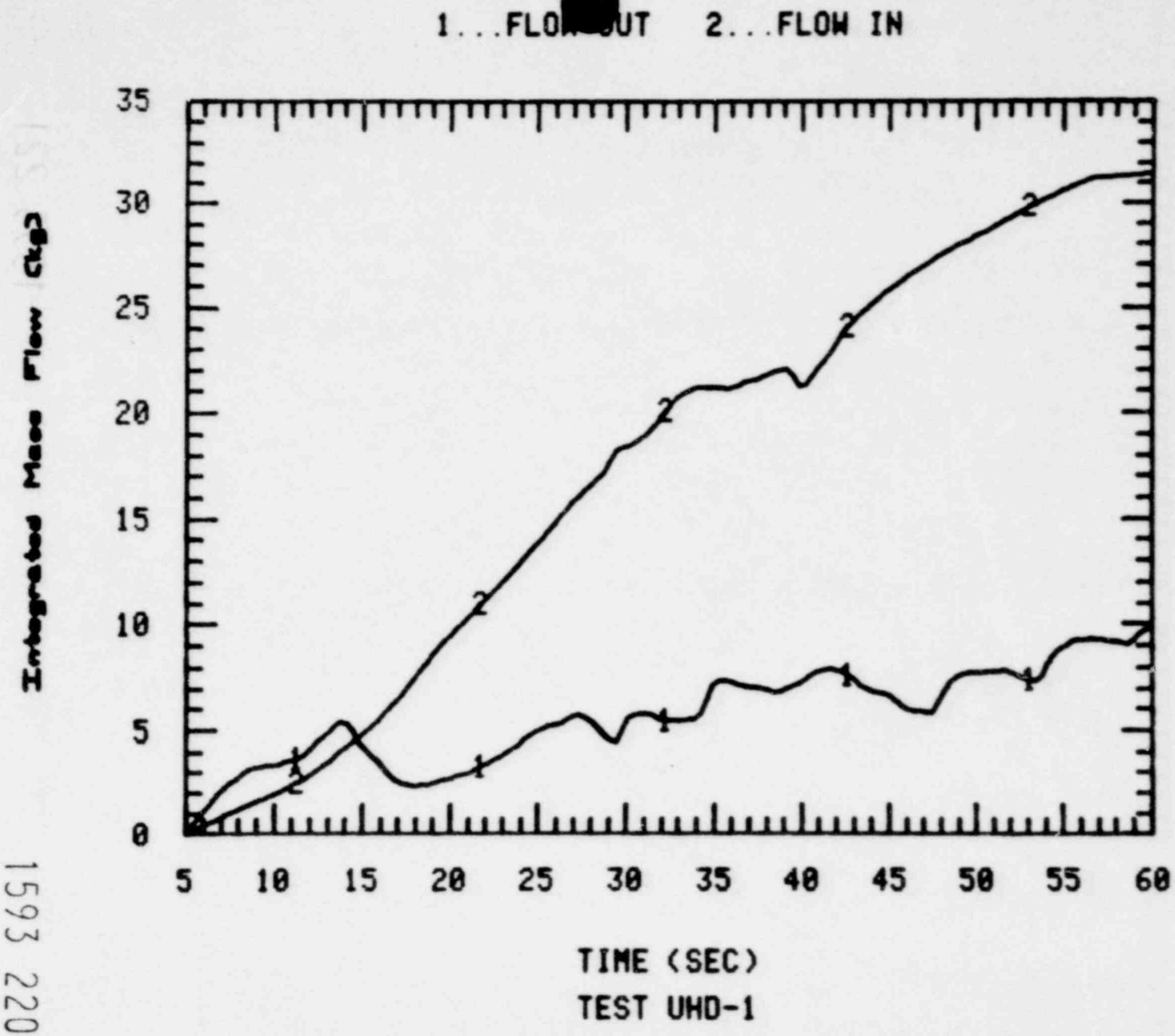

Fig. 32 Comparison of the integrated mass flow leaving the upper plenum via the intact and broken loop hot legs (flow out) with the integrated mass flow entering the upper plenum via the guide tube and support columns (flow in) for Test UHD-1.

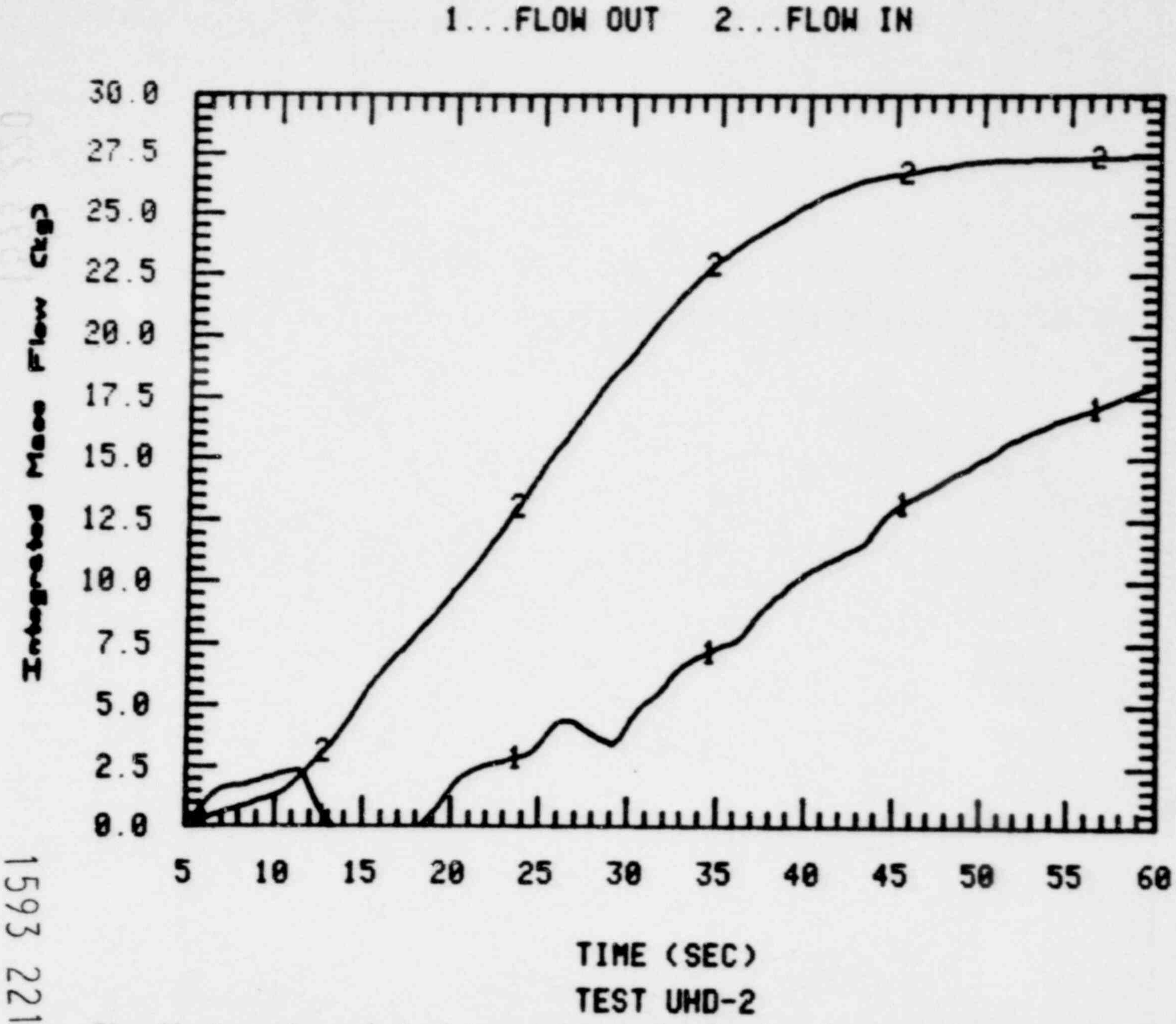

Fig. 33 Comparison of the integrated mass flow leaving the upper plenum via the intact and broken loop hot legs (flow out) with the integrated mass flow entering the upper plenum via the guide tube and support columns (flow in) for Test UHD-2.

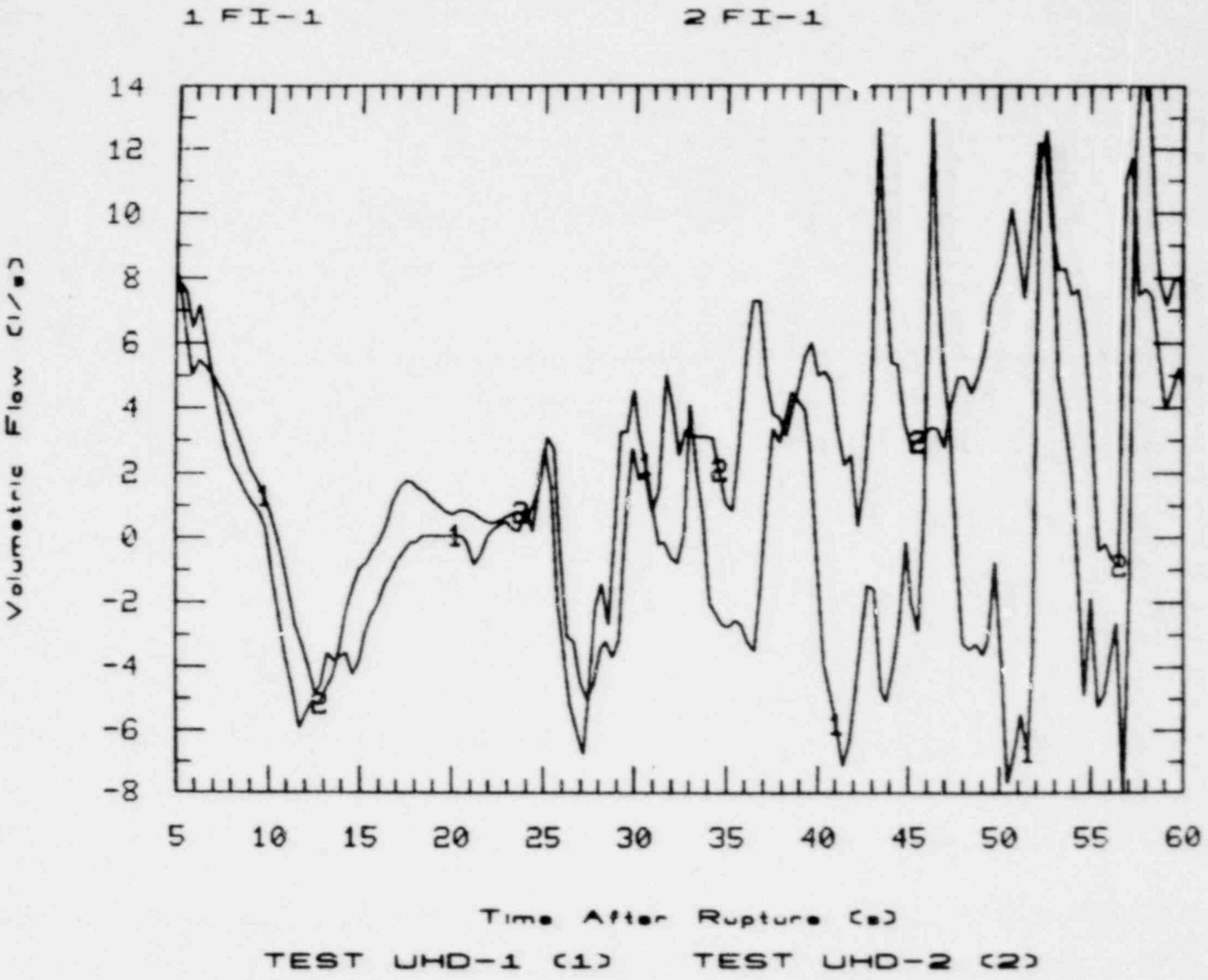

Fig. 34 Comparison of the intact loop hot leg volumetric flow rates for Tests UHD-1 and UHD-2.

1593 223

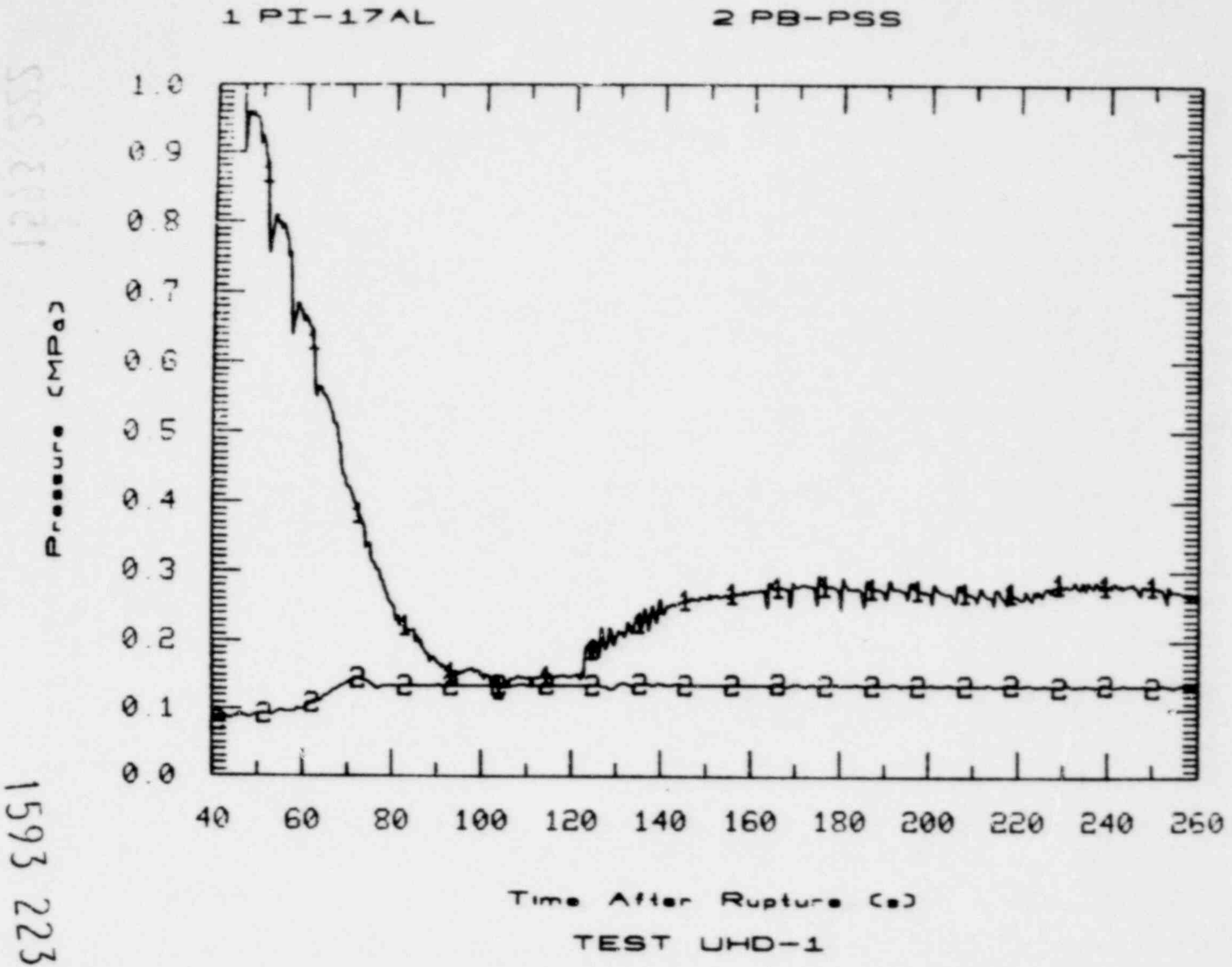

Fig. 35 Comparison of the system pressure and the pressure suppression system pressure for Test UHD-1.

PRELIMINARY

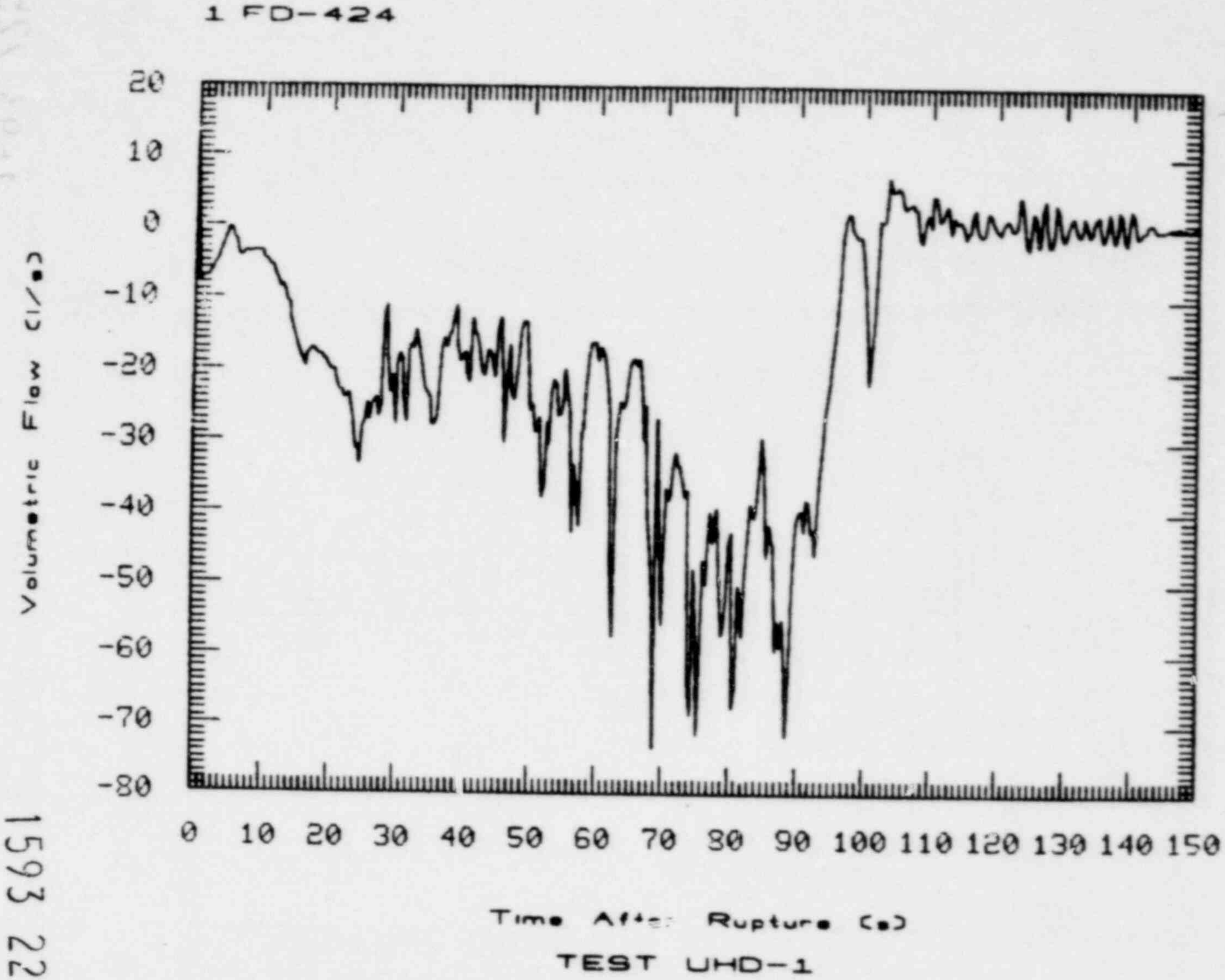

Fig. 36 Downcomer volumetric flow rate for Test UHD-1.

PRELIMINARY

1593 224

PRELIMINARY

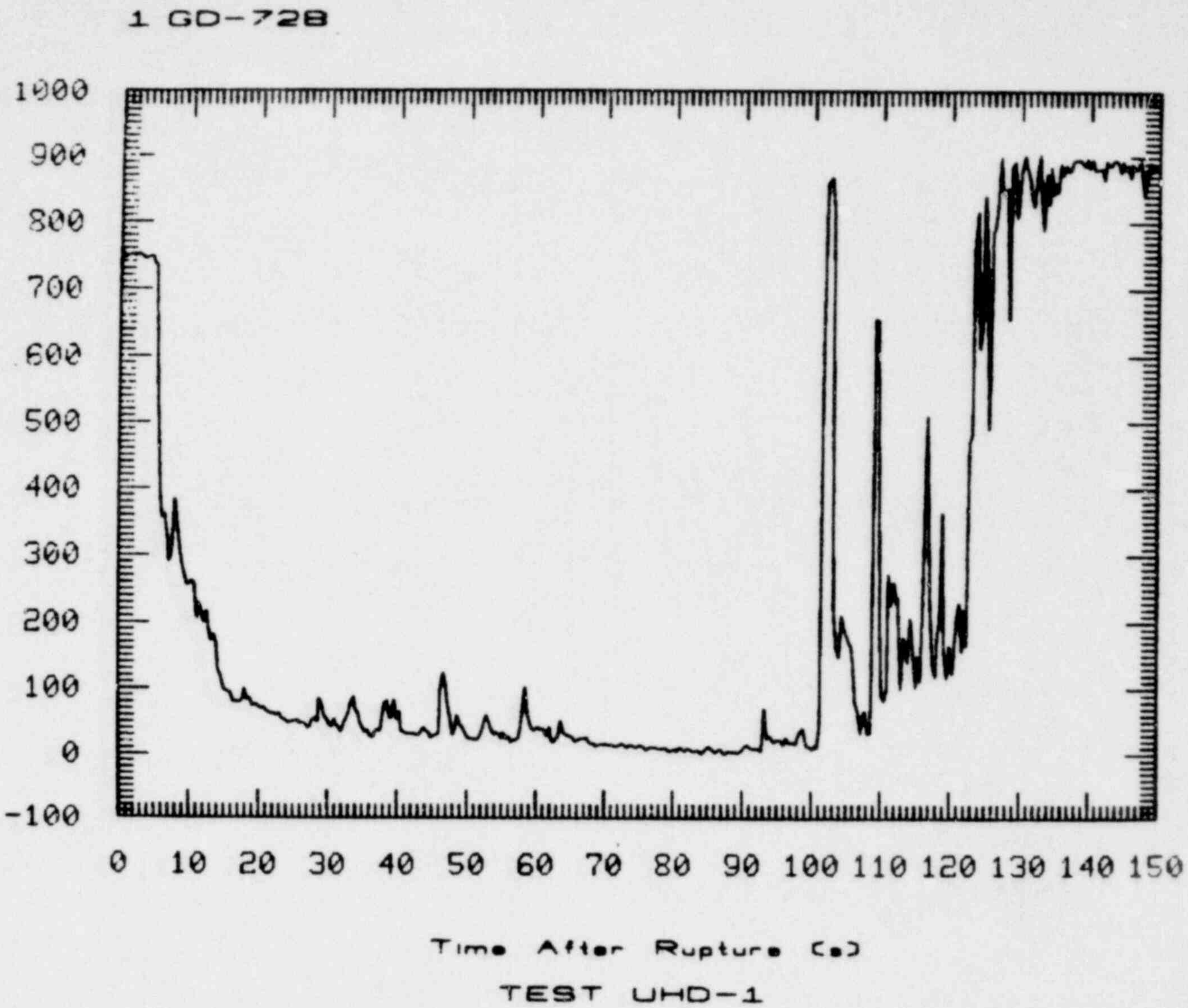

Fig. 37 Fluid density near the top of the downcomer for Test UHD-1.

PRELIMINARY

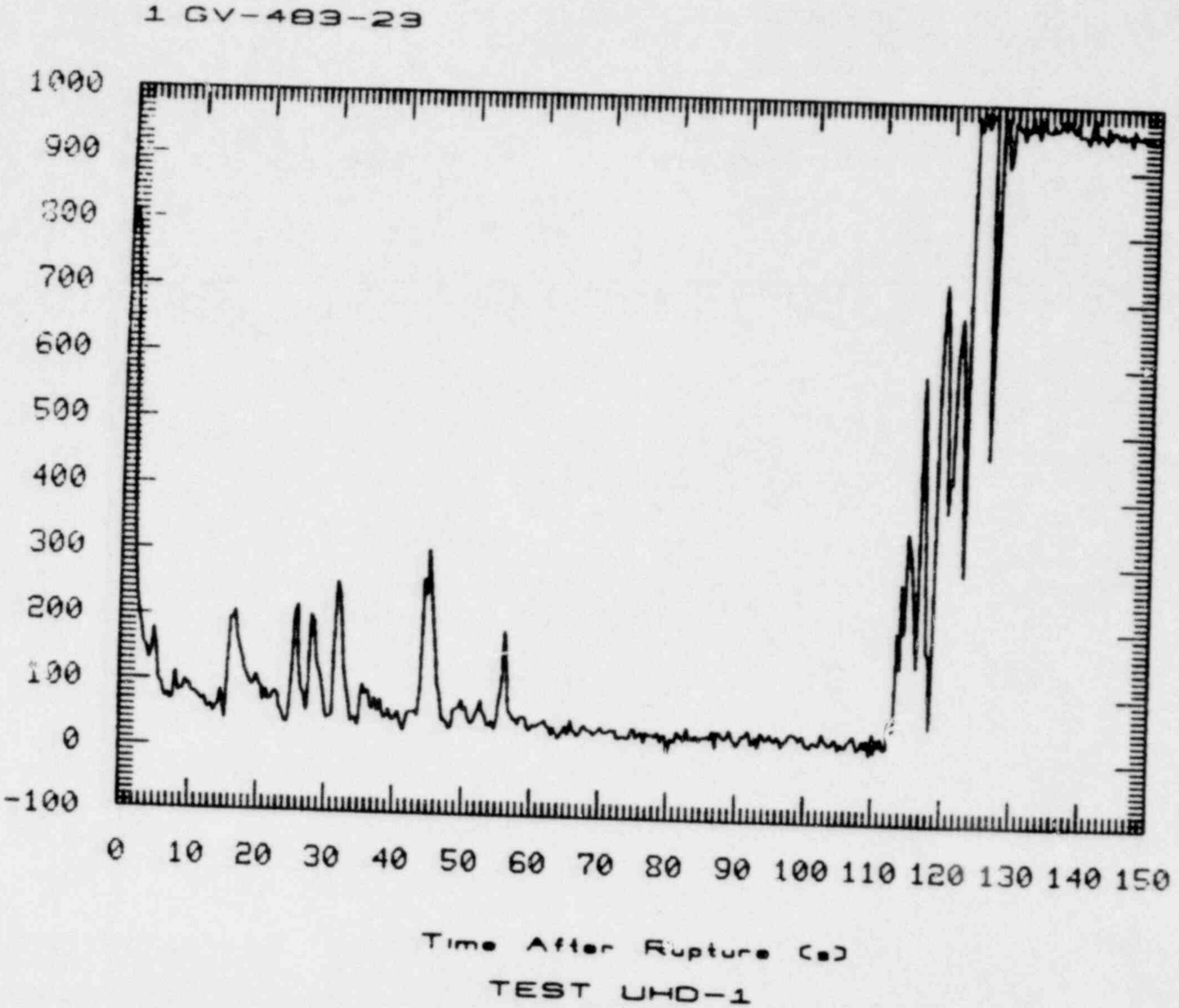

Fig. 38 Fluid density near the inlet to the core for Test UHD-1.

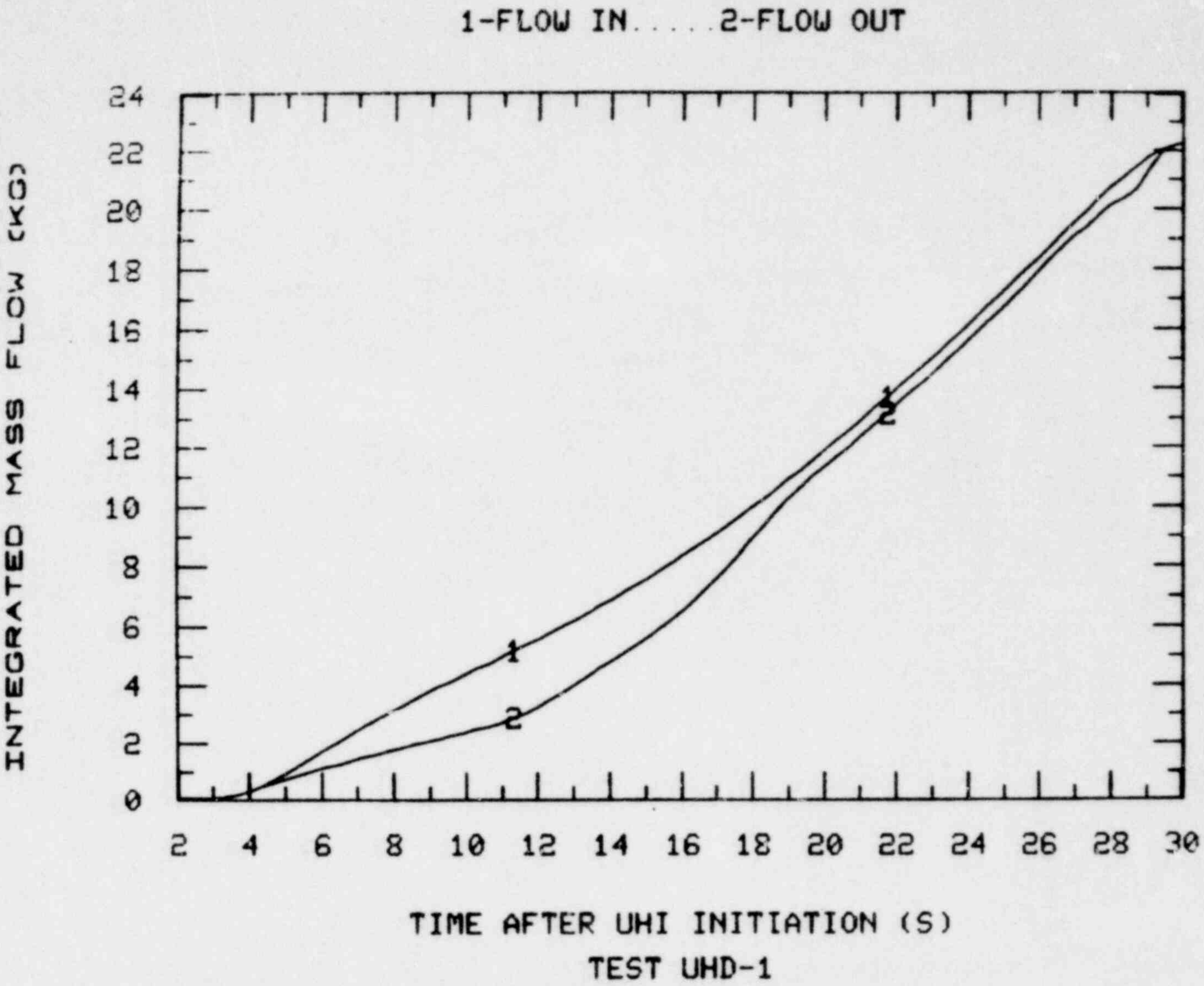

Fig. 39 Comparison of the integrated mass flow rate into the upper head (via the injection line) with the integrated mass flow rate out of the upper head (via the guide tube and support columns) for Test UHD-1.

PRELIMINARY