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BWR Refill-Reflood Program Task 4.4 — CCFL/Refill System Effects Tests (30° Sector) Evaluation of Parallel Channel Phenomena

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Prepared for
U.S. Nuclear Regulatory Commission

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March 1982

BWR REFILL-REFLOOD PROGRAM

CONTRACT NRC-04-79-184

TASK 4.4 - CCFL/REFILL SYSTEM EFFECTS TESTS (30° SECTOR) EVALUATION OF PARALLEL CHANNEL PHENOMENA

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SUMMARY

This report evaluates parallel channel flow phenomena observed in the multi-channel SSTF tests. Parallel channel effects are evidenced by three different channel flow regimes that may occur simultaneously. They occur when there is a level in the lower plenum which allows redistribution of steam to the channel inlet orifices. Most channels exhibit a counter-current flow regime, controlled by counter-current flow limiting (CCFL) at the inlet orifice, similar to single channel experiments. Co-current upflow channels reduce the inlet orifice steam flow to the counter-current flow channels allowing stabilizing levels to form. The smaller orificed peripheral channels are usually in a liquid downflow regime controlled by friction at the inlet orifice.

The impact of parallel channel flow is to drain the upper plenum mass quickly and as a result keep the bottom of the jet pumps covered. With less steam escaping out the jet pumps, more water is held up in the multi-channel core and lower plenum during the pre-ECCS phase of the LOCA than in a single channel test. Every channel contains a steam-water mixture while parallel channel flow exists. Parallel channel phenomena observed in the SSTF tests indicate beneficial effects on the assessment of BWR LOCA refill-reflood performance.

ABSTRACT

This report interprets the results from SSTF separate effects tests and system response tests and evaluates the parallel channel flow phenomena.

Parallel channel flow of interest occurs when there is a level in the lower plenum which allows redistribution of steam to the channel inlet orifices. Parallel channel effects are evidenced by three different channel flow regimes that may occur simultaneously. These regimes, identified from the SSTF tests, are: (1) counter-current flow, (2) co-current upflow, and (3) liquid downflow.

Most channels exhibit a counter-current flow regime, controlled by counter current flow limiting (CCFL) at the side entry orifice (SEO), similar to single channel experiments. When the level in an individual counter-current channel reaches the top the resulting imbalance in total pressure drop, due to overflow from the channel, causes a transition to co-current upflow. This controls the core pressure drop and maintains a stabilizing level in the other counter-current channels. In most instances the liquid draining through the peripheral channels prevents steam from entering these smaller inlet orifices. A liquid downflow regime controlled by friction, not by CCFL at the SEO, is the result.

In the reference refill-reflood system response test, the bypass and channels reflood rapidly. Although all channels start in counter-current flow, the peripheral channels experience early CCFL breakdown at the upper tie plates and transition to liquid downflow. The instrumented channel nearest the core center transitions to co-current upflow within 10 to 20 seconds of test initiation. It remains in this flow regime, progressively increasing in water content, until the lower plenum fills.

The impact of some channels being in liquid downflow and some in co-current upflow is to drain the upper plenum mass to the lower plenum more quickly than in the case of a single channel. As a result, the lower plenum level does not uncover the bottom of the jet pumps, less liquid is lost out the jet pumps, and the lower plenum refills sooner than in corresponding one dimensional test facilities. With less steam escaping out the jet pumps, more water is held up in the multi-channel core during the pre-ECCS phase of the LOCA than in a single channel core. Every channel contains a steam-water mixture. Thus, the parallel channel phenomena observed in the SSTF tests indicate a positive impact on the assessment of BWR LOCA refill-reflood performance.

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ACRONYMS

BWR	Boiling Water Reactor
BP	Bypass
CCFL	Counter-Current Flow Limiting
CE	Conductivity Element
DP	Pressure Difference
ECCS	Emergency Core Cooling System
GPM	Gallons Per Minute
GT	Guide Tubes
HPCS	High Pressure Core Spray
LOCA	Loss of Coolant Accident
LP	Lower Plenum
LPCI	Low Pressure Coolant Injection
LPCS	Low Pressure Core Spray
LTP	Lower Tie Plate
PSIA	Pounds Per Square Inch Absolute
SEO	Side Entry Orifice
SSTF	Sector Steam Test Facility
TC	Thermocouple
TRAC	Transient Reactor Analysis Code
UP	Upper Plenum
UTP	Upper Tie Plate

1.0 Introduction

1.1 SSTF Multi-Dimensional Facility

The 30 Sector Steam Test Facility (SSTF) tests are the first full scale, multi-dimensional BWR refill-reflood simulations. The uniqueness of these tests can be emphasized by noting the three dimensional simulations in the SSTF, as contrasted to the one dimensional simulations of previous test facilities. The SSTF three dimensional simulations, shown in Figure 1, include: (a) a three dimensional bypass surrounding the channel boxes, with peripheral LPCI injection (BWR/6) and twelve guide tube volumes connected to the bottom of the bypass: (b) a full scale upper plenum with core spray headers positioned prototypically at the periphery: and (c) multiple channels (58 including the partial channels), allowing different inlet orifice diameters to be used on the peripheral and central channels, and making use of a radial peaking pattern for the core steam injection simulation of bundle heat transfer.

1.2 Parallel Channel Phenomena

The conditions and procedures for the several tests evaluated in this report are discussed more thoroughly in a companion document (Reference 1). The side entry orifice CCFL tests, the initial mass distribution tests, and the system response refill-reflood tests showed parallel channel flow effects that, although postulated as possible, had not previously been observed. This report provides an evaluation of these results.

These tests have been analyzed to explain and quantify the parallel channel phenomena, and to determine the effects on the transient behavior of the system. "Parallel channel effects" refers to the interactions observed such that all core channels are not in the same flow regime during a portion of the refill-reflood phase of the BWR LOCA. Instead, while most channels are in counter-current flow, some may be in co-current upflow and others in liquid downflow.

Parallel channel flow was first observed in side entry orifice test SE1-4 (Reference 2). The purpose of this test was to measure the CCFL leakage flow from all 58 side entry orifices for given lower plenum steam updraft rate. As shown in Figure 2, these steady-state tests were run by setting the lower plenum steam updraft and increasing the rate of water injection into the upper plenum and bypass until the CCFL limit at the SEO was reached. In these tests, even with liquid injection far exceeding single channel model predictions of CCFL flow at the SEO, no mass accumulated in the upper plenum (although mass did accumulate in the core), and drainage rate equaled liquid injection rate. These data are shown in Figure 3-a.

Channel pressure drop measurements indicate clearly that three distinct flow regimes exist, as shown in Figure 3-b. These regimes are: (1) counter-current flow, (2) co-current upflow, and (3) liquid downflow. Six channels, see Figure 4 for locations, have differential pressure measurements as shown in Figure 5. These measurements for the SE1-4 test are plotted in Figure 6 as a function of lower plenum steam

Figure 1

SSTF TEST SECTION SCHEMATIC

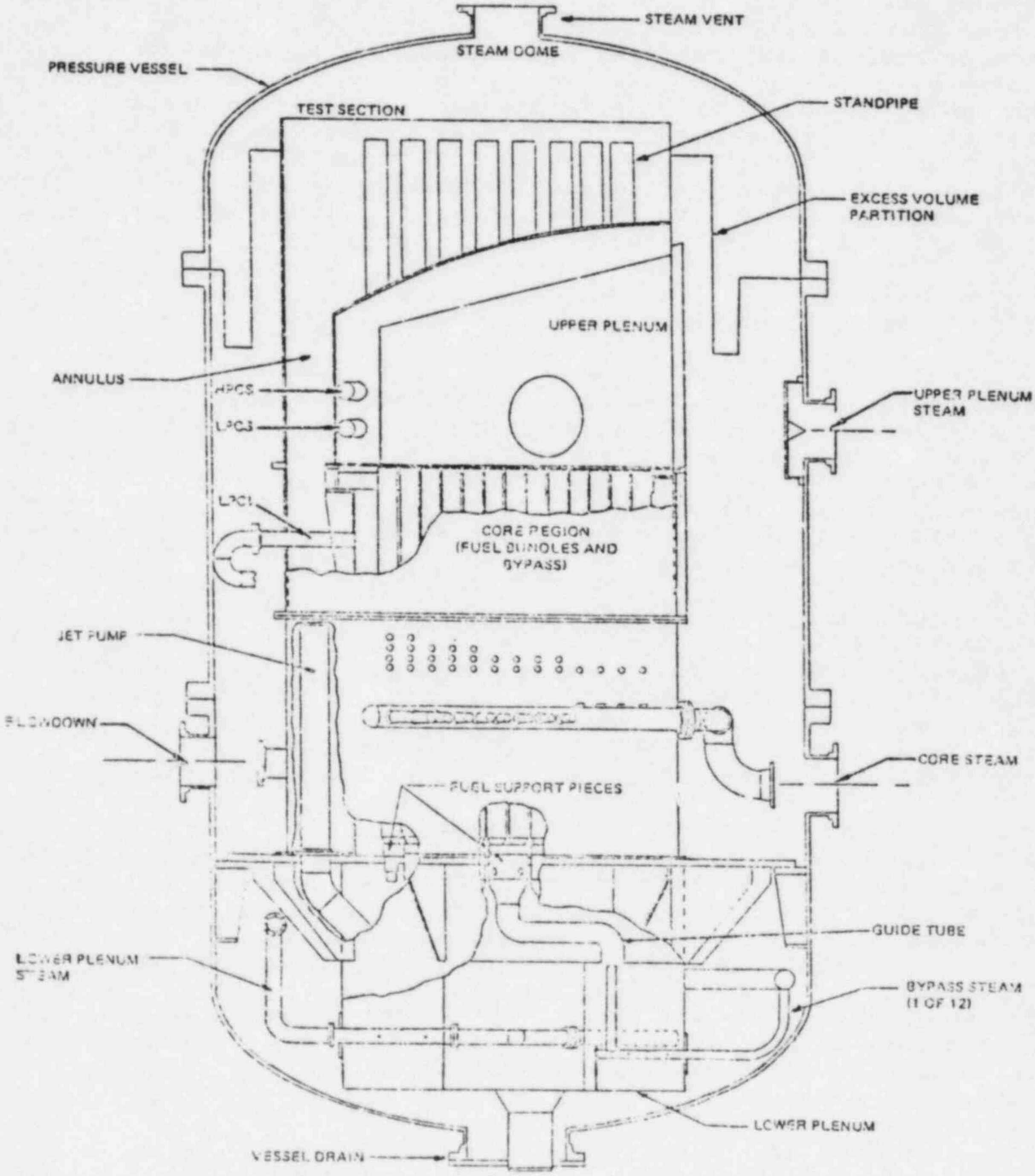


Figure 2

SYSTEM DIAGRAM

SIDE ENTRY ORIFICE CCFL TEST SE1-4

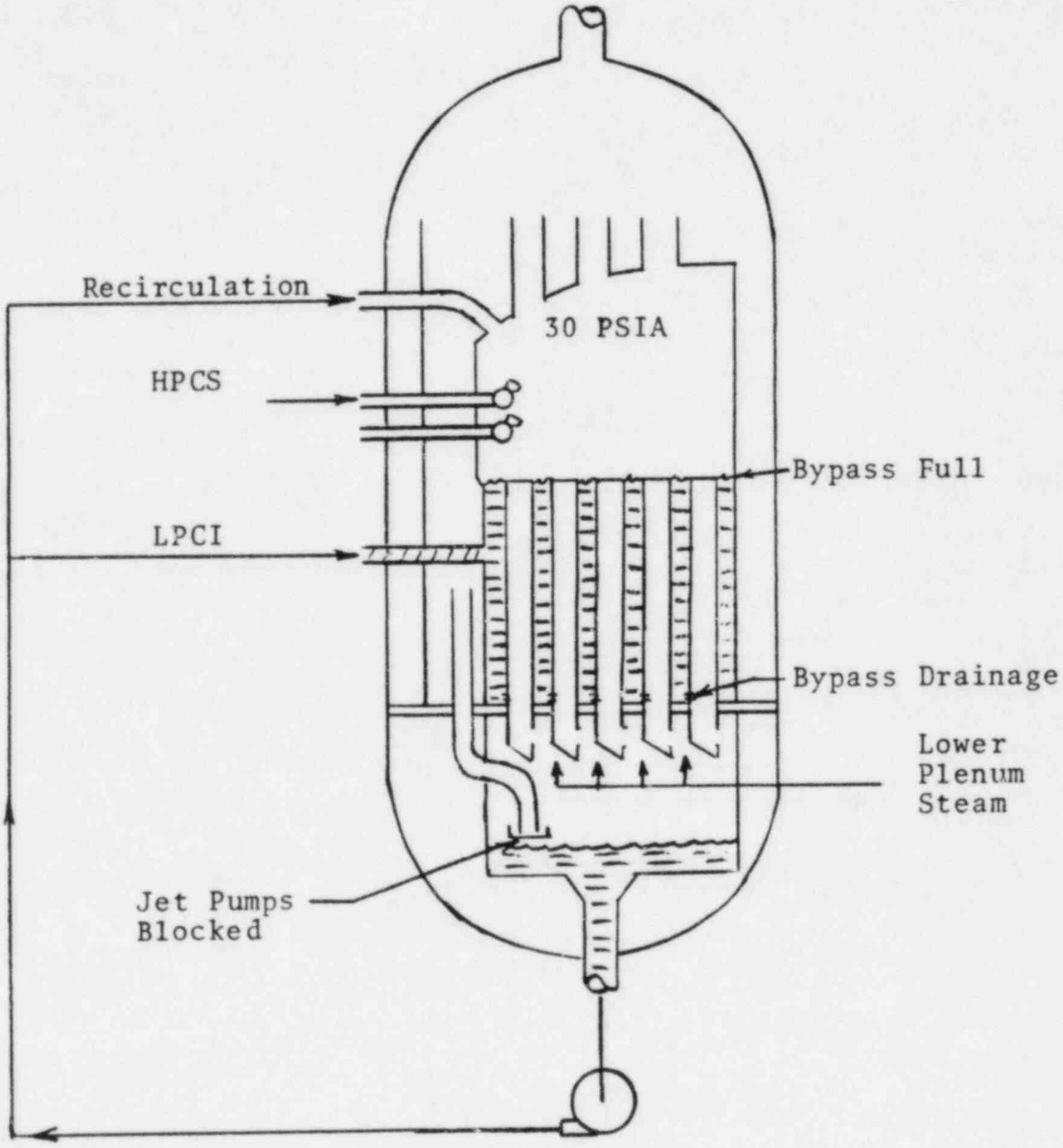


Figure 3

PARALLEL CHANNEL FLOW RESPONSE
(SEO CCFL Test SEI-4)

Figure 3-a
Multi-Channel SEO Drainage
vs. Steam Updraft

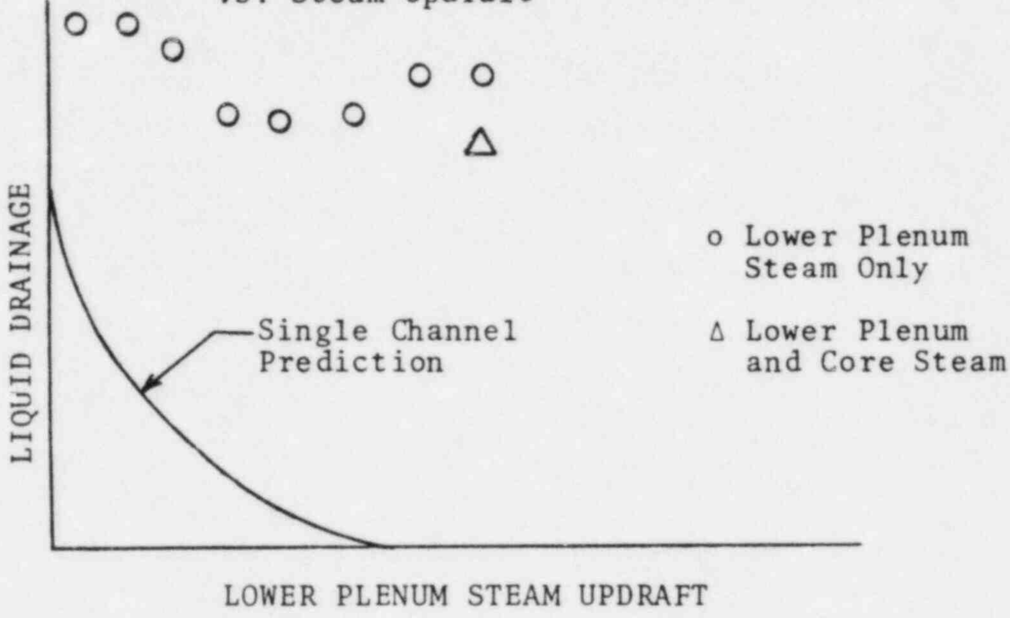


Figure 3-b
Parallel Channel
Flows Regimes

(1) Counter-Current Flow

(2) Co-Current Upflow

(3) Liquid Downflow

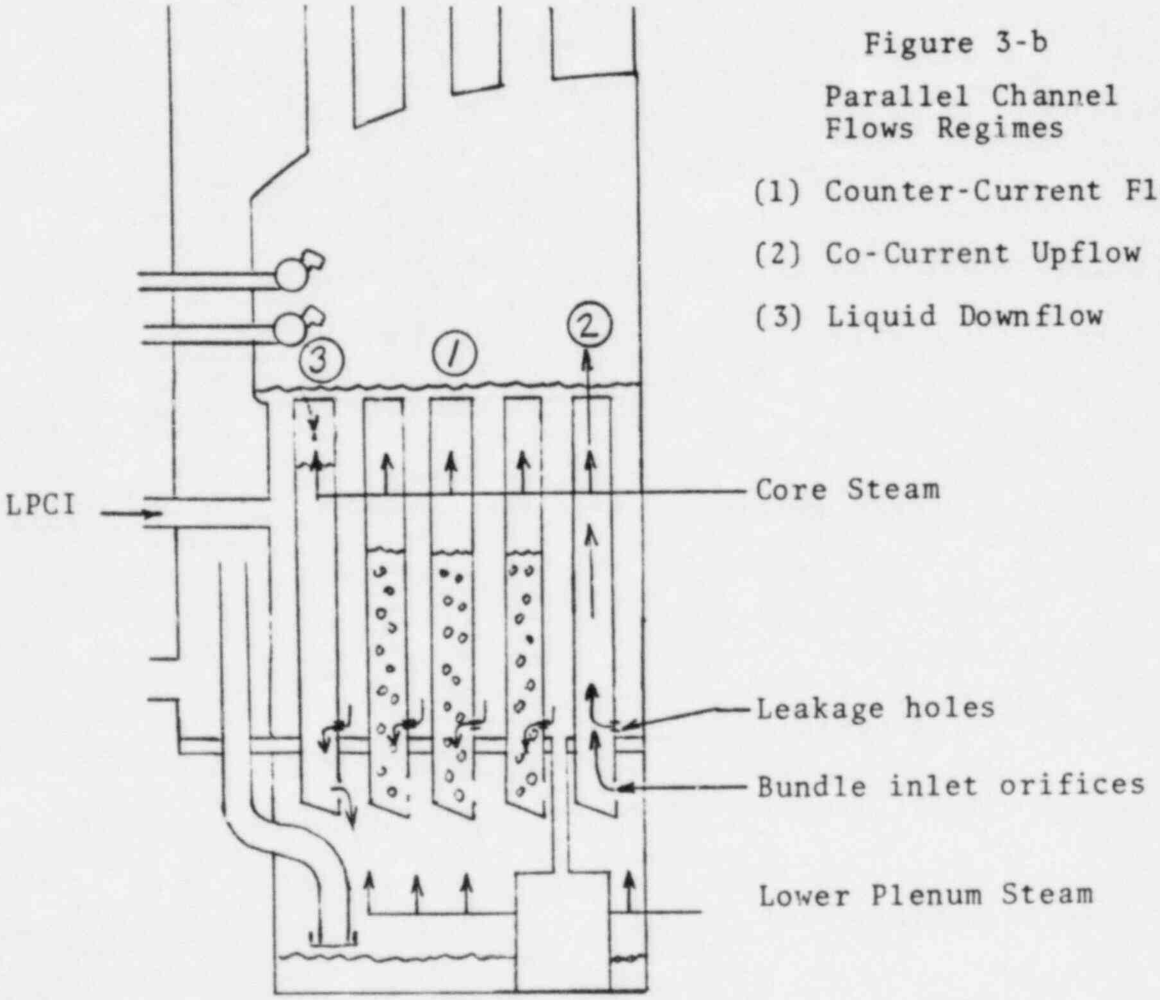


Figure 4

LOCATION OF INSTRUMENTED BUNDLES

ΔP - Pressure Transducers

CE - Conductivity Elements

TC - Thermocouple Banks

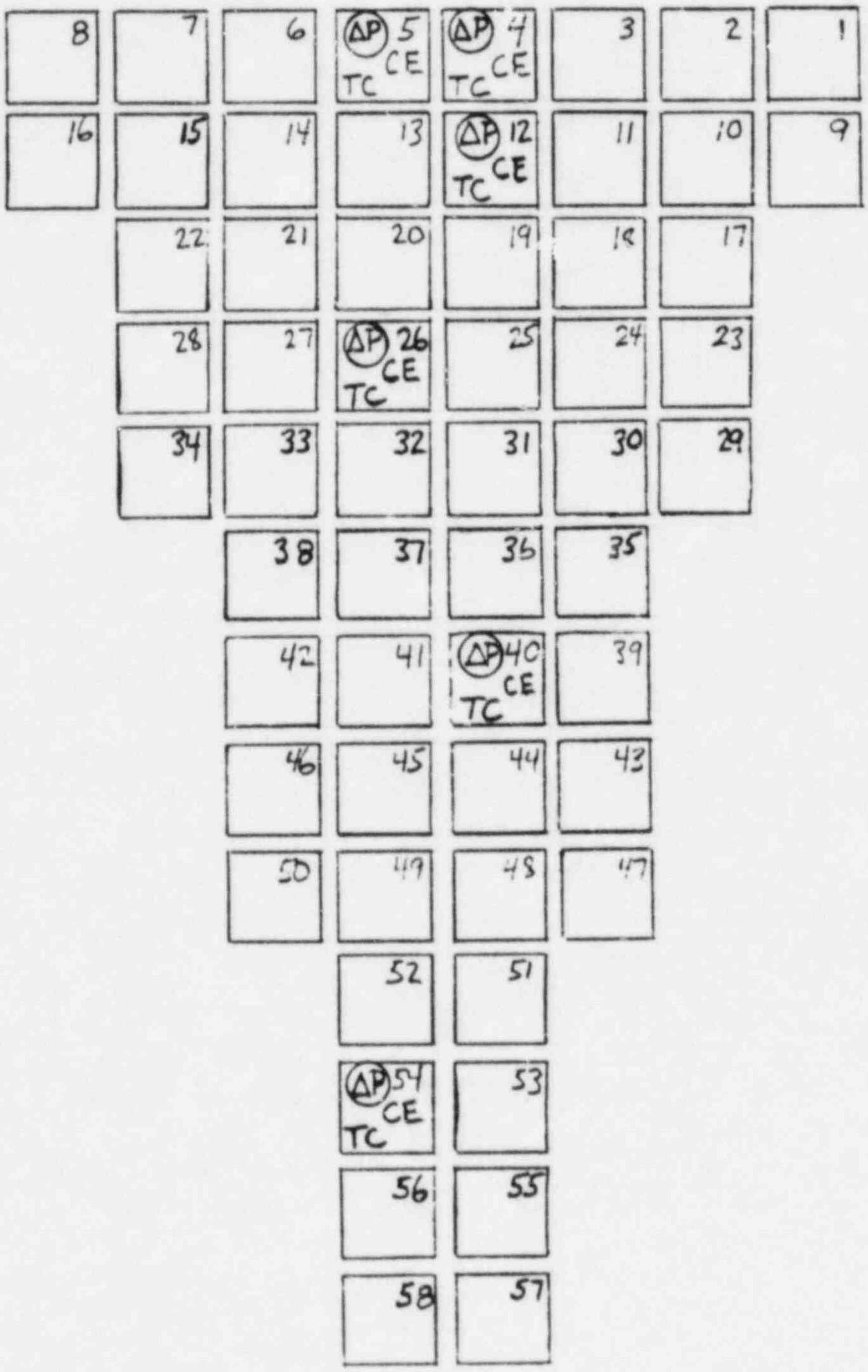


Figure 5
CHANNEL INSTRUMENTATION

ΔP - Pressure Transducers
CE - Conductivity Elements

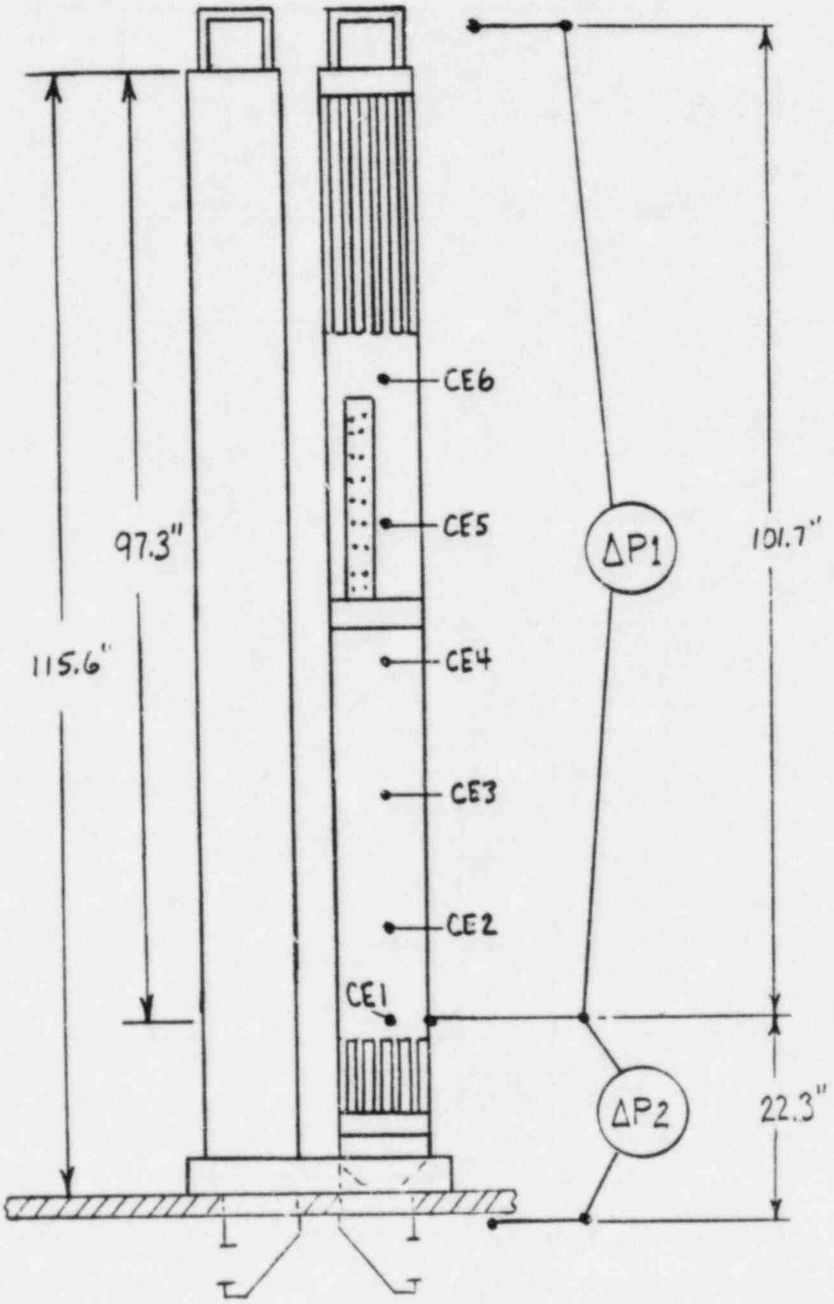
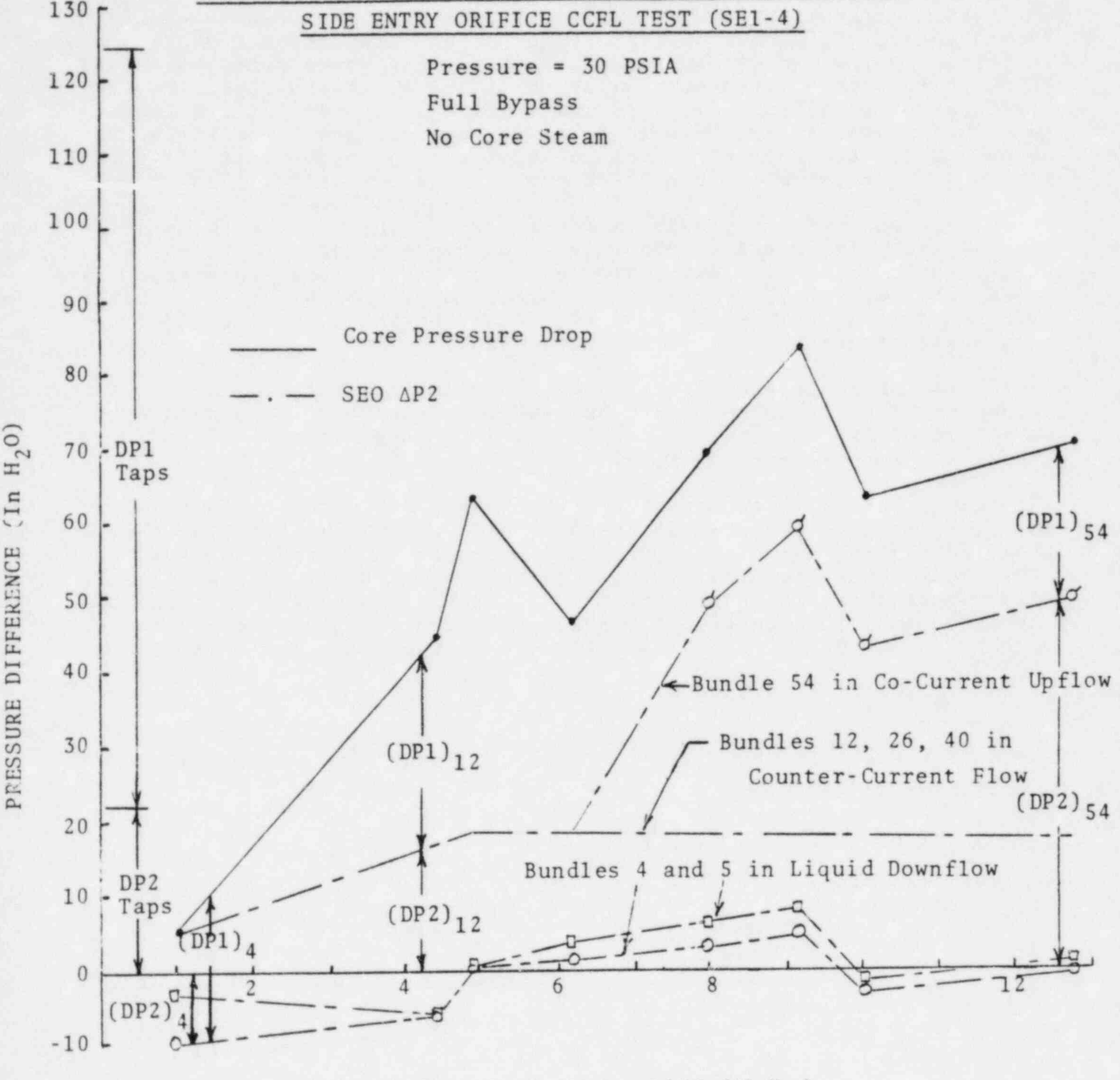


Figure 6

CHANNEL PRESSURE DROPS vs. LOWER PLENUM STEAM RATE
SIDE ENTRY ORIFICE CCFL TEST (SE1-4)



rate. The negative DP2 readings in channels 4 and 5 identify liquid downflow friction through the SEO. The DP1 readings indicate the liquid static head (no core steam injection) in the upper 97.3 inches of these downflow channels. The DP2 readings for the counter-current flow channels 12, 26 and 40 (and 54 for steam rates below 6,000 lb/hr) indicate a low void fraction static head. For steam rates exceeding 6,000 lb/hr a transition occurs for channel 54. Thereafter the DP2 readings for this channel exceed the maximum liquid head (22.3 inches) for the pressure taps, due to steam upflow friction through the SEO. Concurrently, the low DP1 readings indicate a high void fraction mixture consistent with this co-current upflow condition.

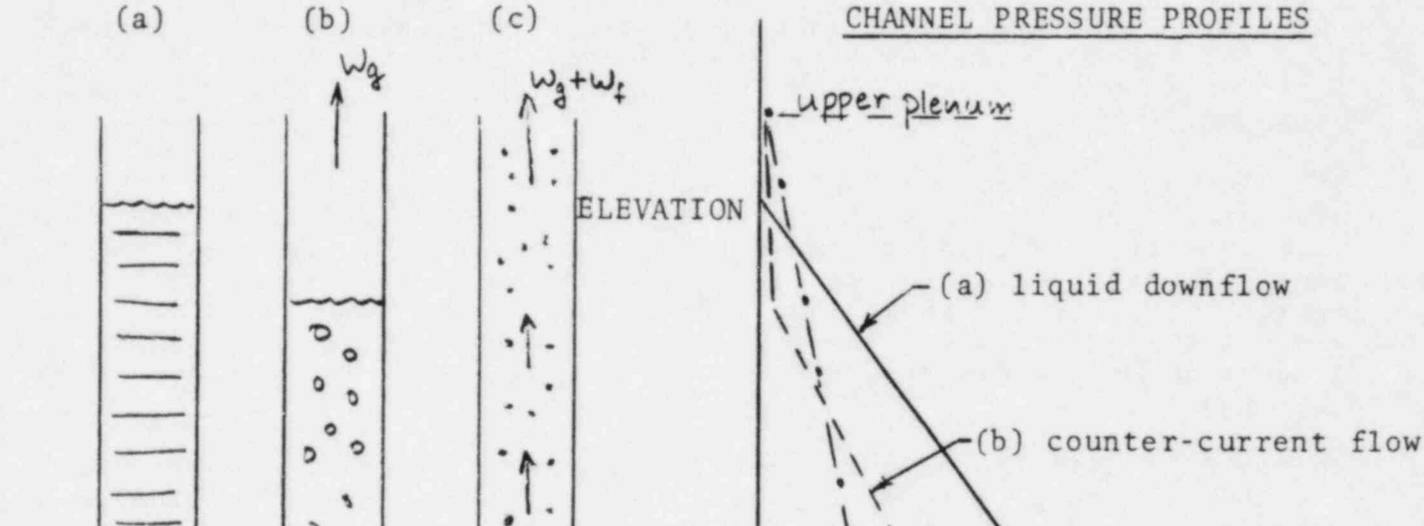
Figure 7 schematically depicts the pressure profiles for these three flow regimes. The downflow channels are represented by curve (a), while the counter current and co-current channels are represented by curves (b) and (c), respectively. Figure 7 shows that although different flow regimes may occur simultaneously, the pressure drop across all of the channels must be the same.

Based on these observations and data interpretation, the test procedure for SEO-CCFL test SE1-5D was designed to measure the threshold of CCFL at the SEO and to confirm the mechanism for the transition to co-current upflow.

Section 2.0 presents an overview of the tests evaluated in this report and the unique results obtained from each. This is followed by a detailed explanation of the parallel channel phenomena, in Section 3.0, that makes the data interpretation more meaningful. The separate effects tests are then discussed in Section 4.0 and the system response tests in Section 5.0. Appendix A summarizes the determination of the initial mass distribution for the system response tests.

Figure 7
PARALLEL CHANNEL FLOW REGIMES

- Communication at Inlet Orifices
- Equal Channel Pressure Differentials
- Flow Regimes
  - (a) Liquid Downflow $\Delta P_{SEO} < 0$
  - (b) Counter-Current Flow $\Delta P_{SEO} = 0$, SEO CCFL
  - (c) Co-Current Upflow $\Delta P_{SEO} > 0$



2.0 Overview of Test Observations

The SSTF tests evaluated in this report are listed in Table 1, and further summarized below. The purpose for SEO-CCFL tests SE1-4 and SE1-5D are discussed above. Both of these tests were run with lower plenum steam only (i.e. no core steam injection) and, therefore, no upper tie plate CCFL restricted flow into the top of the channels. The result was that no liquid was held up in the upper plenum. Test SE1-5D demonstrates that there is a CCFL threshold SEO steam flow below which the channels drain and above which the channels fill. This test also shows that when a counter-current flow channel fills to the top it undergoes a transition to co-current upflow.

The purpose of SEO CCFL tests SE1-5A, B, C is to assess the effects of core steam injection on the upper plenum and core drainage. A high void fraction two-phase mixture was held in the upper plenum due to the upper tie plate CCFL induced by the core steam. Overall drainage from the upper plenum and core was reduced. Since saturated liquid was injected into the upper plenum, no upper tie plate CCFL breakdown occurred.

The three transient shakedown tests (TST) were run to establish the best procedure for setting the initial mass conditions for the blowdown tests. Each of these tests demonstrated a unique aspect of parallel channel behavior and are included in this study for that reason. TST 8(204) showed that for non-typical steam injection rates and saturated liquid recirculation, subcooled spray injection condenses some upper plenum steam and can increase the mass holdup in this region.

In TST 8-3 (369) the core spray injection is cycled on and off. This results in the peripheral channels cycling between UTP CCFL breakdown with transition to the liquid downflow regime, and CCFL with counter-current flow re-established. The core pressure drop also increases and decreases in consort with the spray flow.

The results of TST 9-6 (16) are very important because this test demonstrates that co-current upflow occurs as soon as a lower plenum level begins forming. Thus, within seconds of initial lower plenum flashing, parallel channel flow becomes an important system phenomenon.

Two other parallel channel phenomena are observed in the initial conditions phase of test SRT-3 (26). Following the rapid draining of the upper plenum, which occurs when injection of saturated water to this region is reduced, the channels drain slowly. During this period of falling core pressure drop, one of the instrumented channels experiences a transition to co-current upflow. Later, as the core level drops further, all of the channels are in, or transition to, counter-current flow. The lower plenum level never uncovers the jet pumps and most of the steam updrafts through the channels. The system response blowdown test SRT-3 (26), in addition to demonstrating a rapid reflood of the channels, experiences a transition to co-current upflow of channel 54 before it fills. This is the first test in which this phenomenon is observed. The expected subcooled UTP CCFL breakdown and transition to liquid downflow occurs in the peripheral channels. The counter-current channels do not drain even when subcooling is measured at some of the side entry orifices. This contrasts with

TABLE 1

PARALLEL CHANNEL EXPERIMENTS

EXPERIMENT	OBJECTIVE	RESULTS
A. SEO CCFL Tests		
SE1 - 4A, B, C, D (30 psia)	SEO Downflow vs. L.P. Steam Injection	No upper plenum mass; Downflow equal to upper plenum injection.
SE1 - 5D (30 psia)	SEO CCFL threshold transient	Threshold measured; transient transition to co-current upflow.
SE1 - 5A, B, C (30 psia)	Effects of Core Steam Injection	Upper plenum mass holdup with UTP CCFL and full bypass.
B. Initial Conditions Tests		
TST 8 (204) (136 psia)	Target on Masses	Increased upper plenum mass with subcooled ECCS injection.
TST 8-3 (369) (150 psia)	Target on Steam Flows	Transient effects of lower plenum steam and ECCS injection observed.
TST 9-6 (16) (150 psia)	Simulated Flashing Redistribution of Liquid Mass	Lower Plenum level forms, leading to parallel channel flow and draining of upper plenum.
C. Reference System Response Test		
SRT - 3 (26) (150 psia)	Set Initial System Masses	Rapid upper plenum draining. Slow core draining. Transition to counter-current flow.
SRT - 3 (26) (Blowdown)	Refill-Reflood System Response	Rapid core reflooding. Upper tie plate CCFL breakdown. Parallel channel flow.

observations in single channel facilities, and is a consequence of the requirement that all parallel channel pressure drops must be equal, as discussed in Section 3.

3.0 Controlling Parallel Channel Phenomena

3.1 Channel Flow Regimes

Figure 7 schematically summarizes the three observed channel flow regimes and the respective pressure profiles, which are important for data interpretation. The three regimes are described as follows:

(a) Liquid Downflow - Liquid downflow and no steam upflow through the orifice. Friction pressure drop across the inlet orifice in the downward direction. Primarily liquid static head in channel when steam is not injected into the channels or when subcooled CCFL breakdown condenses the core steam.

(b) Counter-Current Flow - Drainage flow controlled by side-entry orifice CCFL. No pressure drop across the SEO. Two-phase static head in channel, (i.e. no flow friction). Two-phase interface level below top of channel.

(c) Co-Current Upflow - Steam only upflow through SEO. Friction pressure drop across the SEO in the upward direction. Large pressure differential driving liquid leakage from bypass to channel at lower tieplate (LTP) holes. Co-current liquid vapor upflow in the channel. Combined two-phase static head and friction pressure drop in channel.

3.2 Transition to Liquid Downflow

The flow regime present in most channels during the refill-reflood phase of the LOCA is counter-current flow. Transition to the liquid downflow regime can occur for the following reasons: (1) the inlet orifice drainage rate exceeds the maximum CCFL liquid flow (i.e. no steam can flow up through the inlet orifice), and (2) inlet orifice subcooled CCFL breakdown (i.e. the steam is condensed before it can flow up through the SEO).

For the peripheral channels, with their smaller inlet orifices, leakage from the bypass can be sufficient to produce a total liquid downflow condition. Upper tie plate subcooled CCFL breakdown flow can also produce the liquid downflow regime, even in the channels with larger inlet orifices.

In single channel tests the occurrence of SEO subcooled CCFL breakdown usually results in rapid draining of the channel. In a multi-channel facility, CCFL breakdown at the SEO usually does not increase the drainage rate significantly. The pressure drop across this channel must remain equal to the drop across the core. Therefore, the momentary static head reduction with liquid drainage must be compensated with an increased vapor flow to that channel. The increased vapor flow can saturate the liquid and establish CCFL at the inlet orifice again. This cyclic process apparently happens repeatedly and results in only minor changes in liquid drainage when subcooling is present at the SEO in a multi-channel array. The resultant SEO temperature oscillations for the reference system response test SRT-3 Run 26 are illustrated in Figure 8.

3.3 Threshold for Core Side-Entry Orifice CCFL

The interaction of the parallel channels, and the threshold for the various flow regimes can best be described by considering the simple situation depicted in Figure 9. In this example the liquid flow into each channel is controlled externally and the lower plenum steam flow is too small to restrict the channel drainage. The core pressure drop will be zero for this case.

If a liquid leakage rate, Wfi, is greater than the maximum liquid flow on the SEO CCFL curve, Figure 9, then that channel will be in liquid downflow. The liquid level in this channel can be found from the following core pressure drop relationship.

(1.1) $$\Delta P_{core} = \rho_f Z_i - (K/A^2)_{SEO} (W_{fi}^2/2g\rho_f) = 0$$

The threshold for CCFL at the SEO's is the value of lower plenum steam flow which, when reached, will cause the counter-current flow channels to start filling. If the liquid drainage for each channel, Wfj, is known then the threshold is found by determining the steam flow from the SEO CCFL curve for each channel, as shown in Figure 10. The sum of these steam flows is the threshold value, i.e. for the three channels of Figure 10,

(1.2) $$W_{gLP} = W_{gj} + W_{gK}$$

The lower plenum steam rate will not be at exactly this value. Either it will be below the threshold and the channels will drain, or above the threshold and channels will start filling, as in Figure 11.

As the channels fill, the static head in the counter-current flow channels are equal since the inlet orifice pressure drop is zero.

(1.3) $$\Delta P_j = \Delta P_{core}$$

Since the flow area, Ach, is uniform over most of the channel length, the static head is directly proportional to the mass in each channel,

(1.4) $$\Delta P_j = \rho_f \int (1 - \alpha_j)\ dZ + \rho_g \int \alpha_j\ dZ = M_j/A_{ch}$$

Therefore, the mass in each counter-current flow channel is the same during the filling transient. The filling rate of these channels is determined by the balance between drainage from the side entry orifices and the combined drainage into the top of the channel and

Figure 8

SIDE ENTRY ORIFICE SUBCOOLING (ONE LPCI)

TEST SRT-3 RUN 26

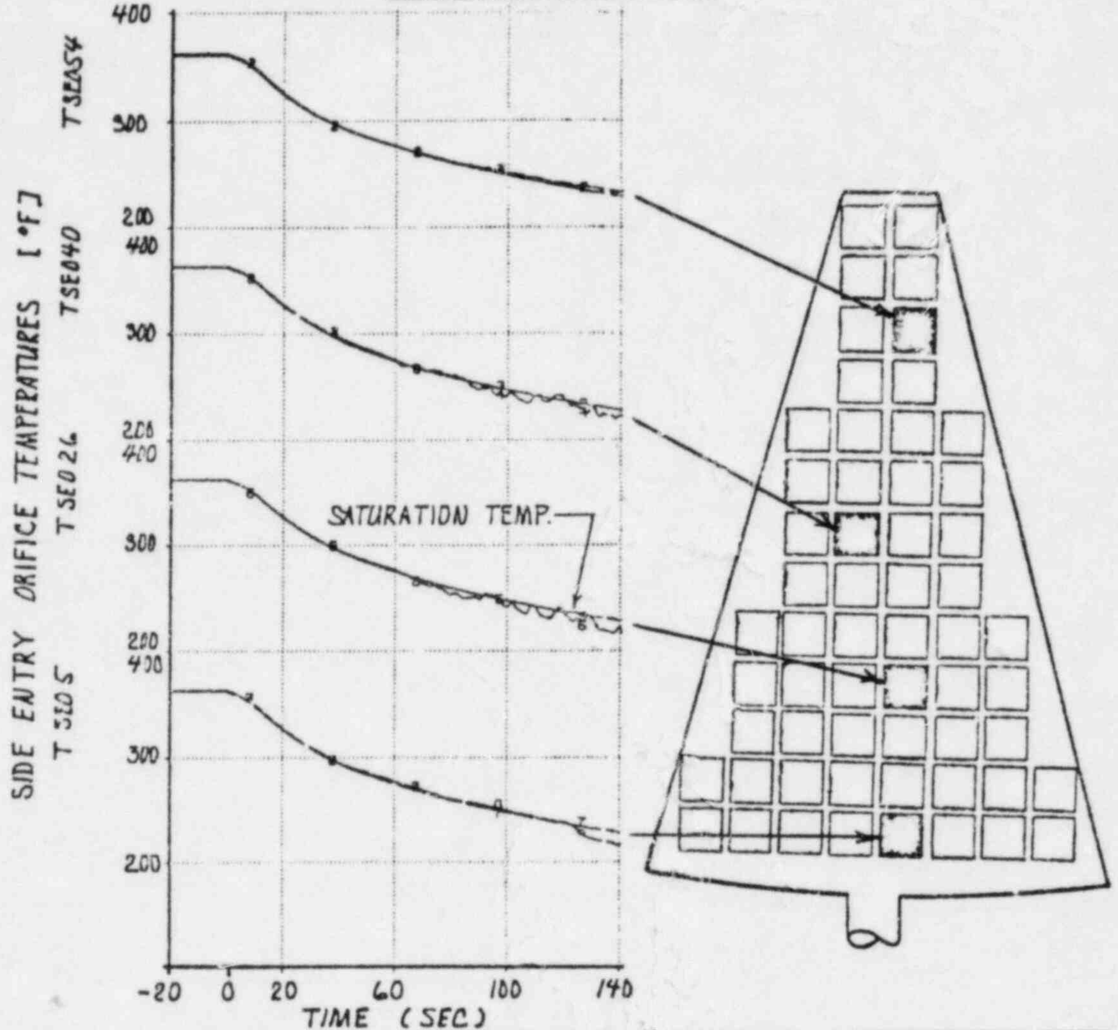


Figure 9

BELOW INLET ORIFICE CCFL THRESHOLD

- $\Delta P_{core} = 0$
- Channels Drained
- Liquid Downflow When W_{fi} > CCFL W_{fmax}

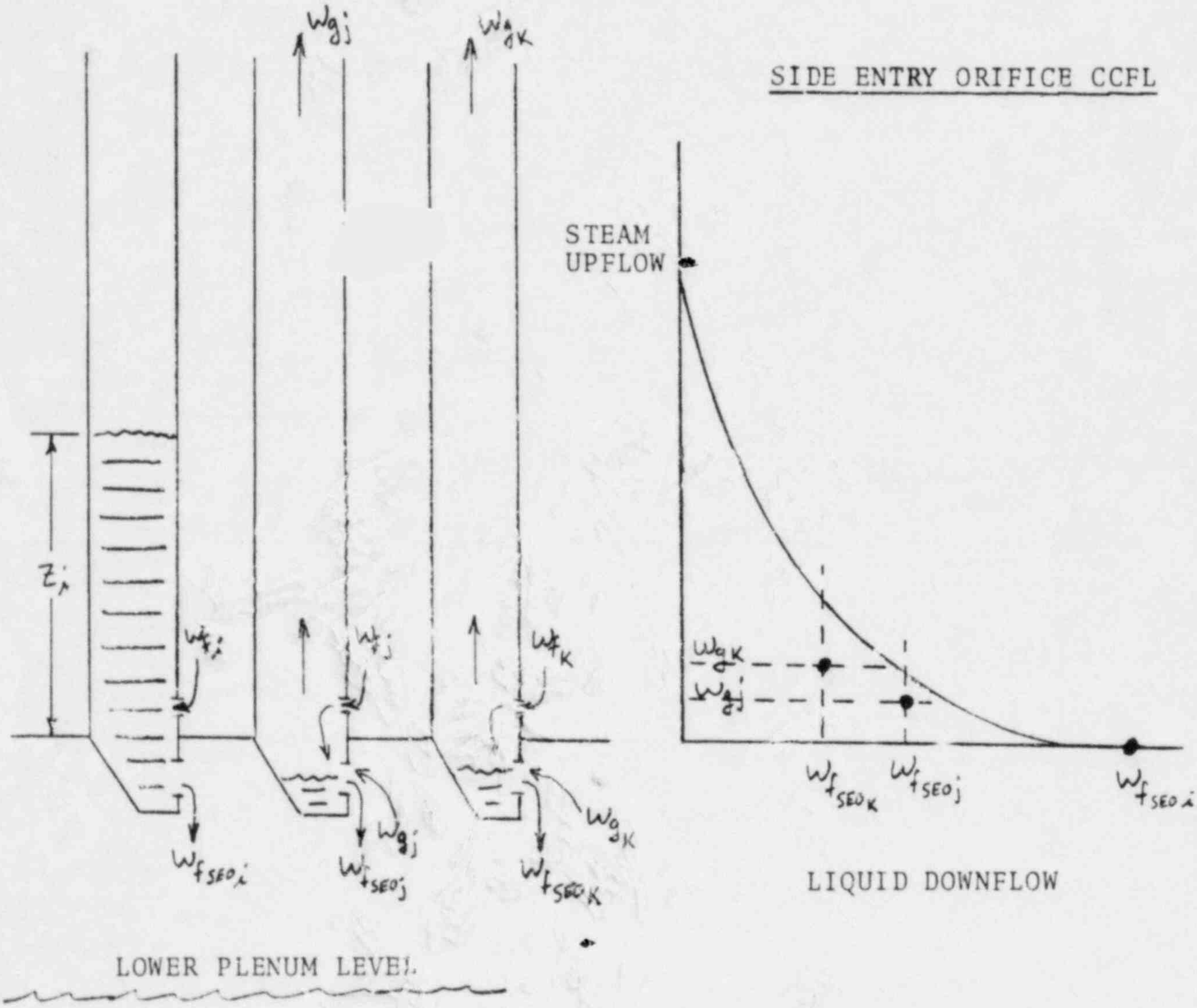


Figure 10

INLET ORIFICE CCFL THRESHOLD

- Independent Variable, $W_{fj} = W_{fseoj}$
- Dependent Variable, W_{gj}
- Lower Plenum Steam Redistributes, $W_{gj} = F_{CCFL}(W_{fj})$
- SEO CCFL Threshold, $(W_g)_{LP} = (W_{gj} + W_{gk})$

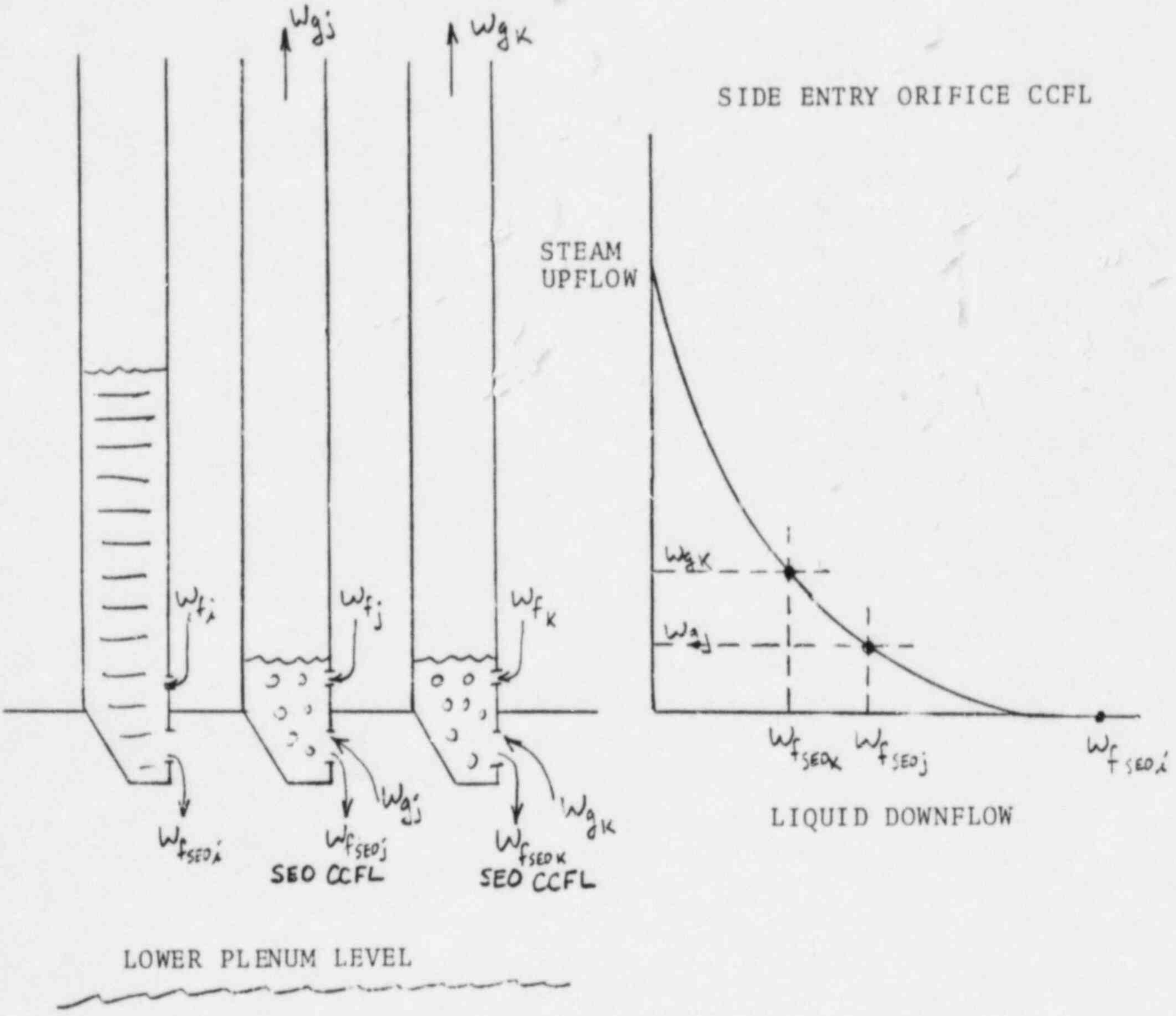
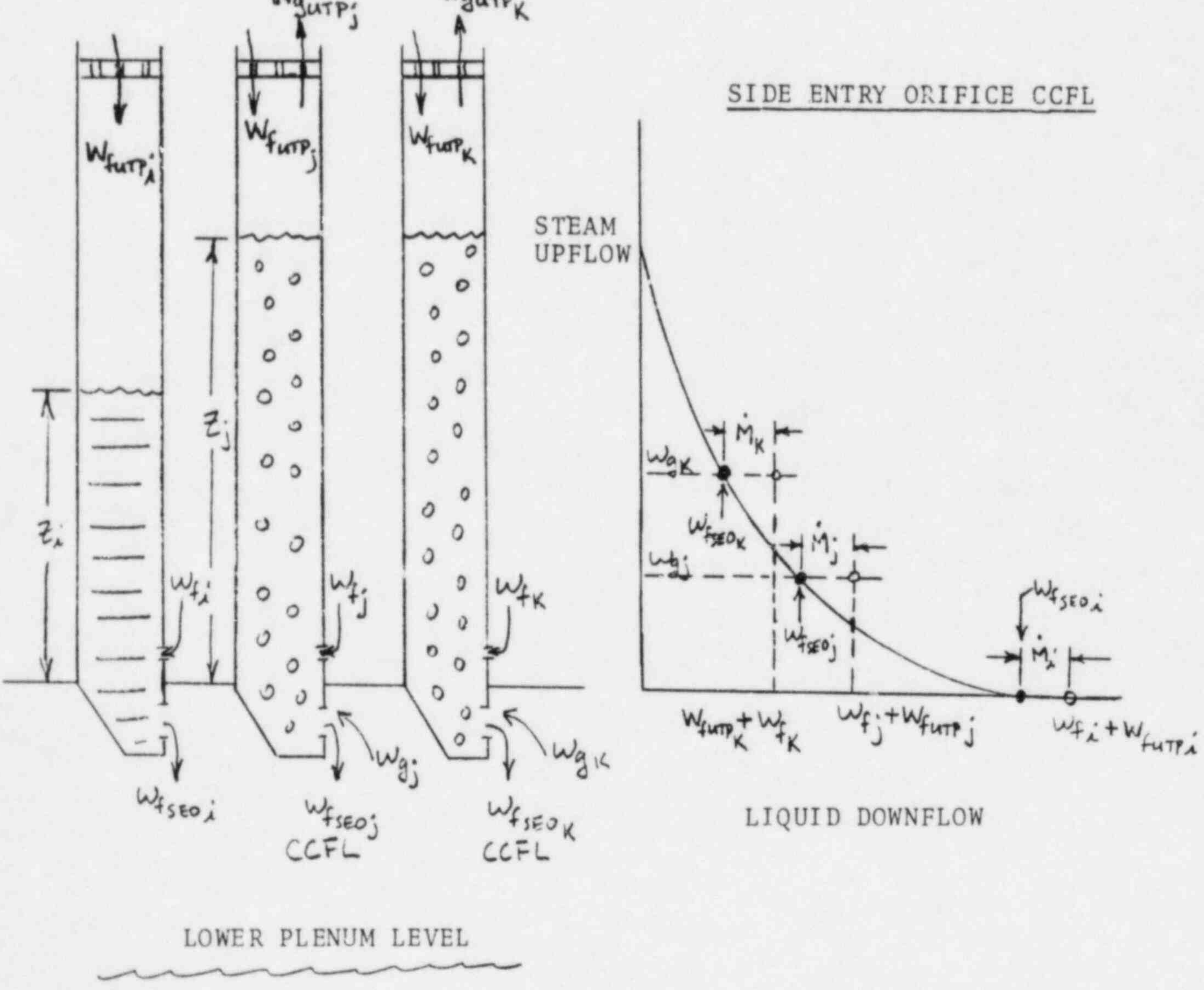


Figure 11

ABOVE INLET ORIFICE CCFL THRESHOLD

- Above Threshold, $(W_g)_{LP} > \Sigma F_{CCFL} (W_{fj})$
- Channels Filling, $\dot{M}_j = W_{fj} - W_{fSEOj} + W_{fUTPj}$
- Equal Channel ΔP's, $\dot{M}_j = \dot{M}_k$ = Channel Filling Rate (lb/sec)
- Stabilizing Level, $\Delta P_j = \rho_f (1 - \alpha_j) Z_j$

(Note: $\Delta P_j = M_j/A_{ch}$ if $\Delta P_j = \Delta P_k$, then $\dot{\Delta P}_j = \dot{\Delta P}_k$.)



leakage from the bypass into the channels. The driving potential for this leakage decreases as the channel head of equation 1.4 increases. Therefore, the channel fluid conditions are specified by the upper tieplate and bypass leakage liquid flows and the following relations:

$$(1.5) \qquad \dot{M}_{ch} = \dot{M}_j = W_{fj} - W_{fSEOj} + W_{fUTPj}$$

$$(1.6) \qquad W_{gSEOj} = F_{CCFL} (W_{fSEOj}); \; (F_{CCFL} = \text{CCFL Correlation})$$

$$(1.7) \qquad \sum_j W_{gSEOj} = W_{gLP}$$

The two-phase level in each channel is determined by the average void fraction,

$$\alpha_j = F_\alpha (W_{gj}), \; (F_\alpha = \text{Void Fraction Correlation}) \qquad (1.8)$$

$$Z_j = (M_{ch} / A_{ch}) / \{\rho_f (1 - \bar{\alpha}_j) + \rho_g \bar{\alpha}_j\} \qquad (1.9)$$

3.4 Transition to Co-Current Upflow

As the channels fill their levels, Zj, adjust to perturbations in flow to maintain equal static heads in all the counter-current flow channels. When a counter-current flow channel fills completely it no longer has an adjustable level: therefore, it cannot respond to an increase in core pressure drop caused by the continued filling of the other channels. This channel will then undergo a transition from counter-current flow to co-current upflow in order to balance the increasing core pressure drop. That is, the channel will have a transition from a static head dominant regime to a friction dominant regime, as shown in Figure 12. This transition produces a large friction pressure drop across the SEO which, in turn, increases the driving head and resultant liquid leakage from the bypass to the channel. Hence, the co-current upflow regime includes a high liquid content. This process is demonstrated experimentally in Sections 4.0 and 5.0.

Enough channels go through this transition to co-current upflow to allow the remaining counter-current flow channels to steady out with stabilizing levels. This is accomplished with the counter-current flow channels operating at their collective SEO CCFL threshold, and the two-phase pressure drop across the co-current upflow channels low enough to permit a static level in the counter-current channels, below the top of the channels. The resulting steady-state conditions, as shown in Figure 13, can be described as follows: (1) The steam flow up the counter-current flow channels is determined by the liquid flow into the channels (UTP and bypass) and the CCFL characteristics of the SEO (eq. 1.6): (2) The remaining lower plenum steam flows through the

Figure 12

TRANSITION TO CO-CURRENT UPFLOW

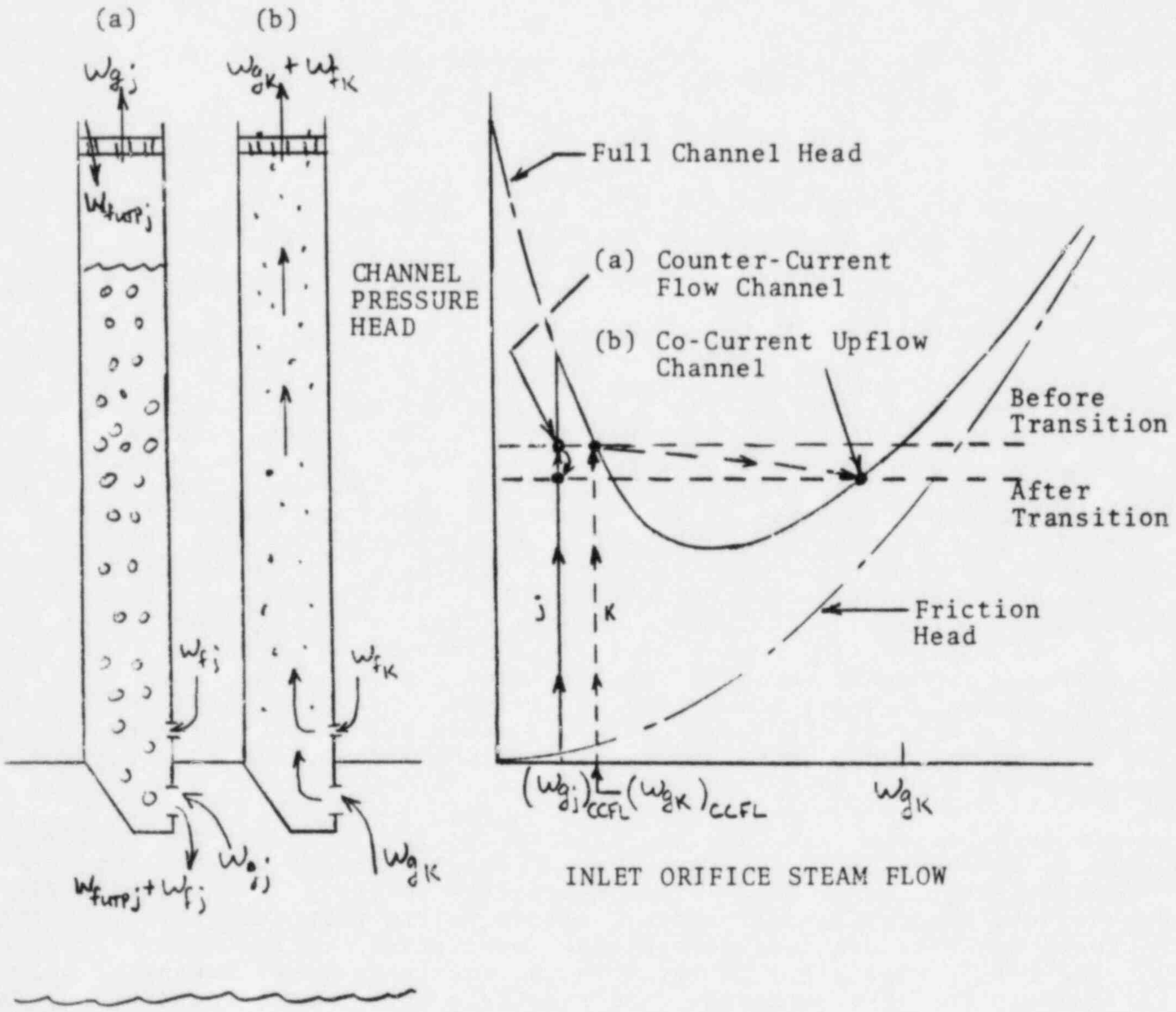
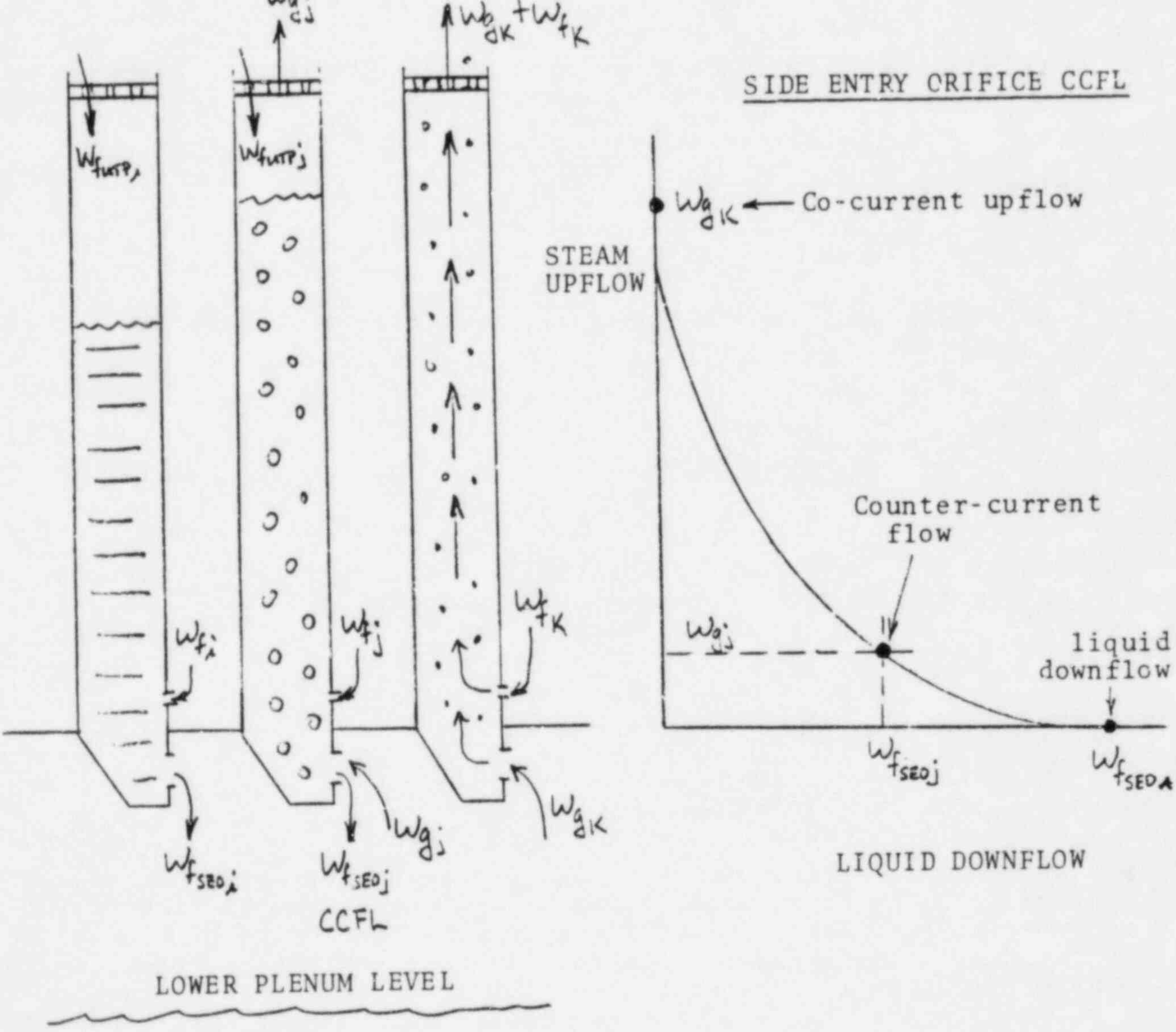


Figure 13

CO-CURRENT UPFLOW

- Transition from Full CCFL Channel
- Stabilizing Level in CCFL Channels
- CCFL Channels at Threshold
- All Liquid Drains
- No Upper Plenum Mass (No Core Steam)



co-current upflow channels,

$$W_{gK} = W_{gLP} - W_{gj}; \tag{1.10}$$

(3) The core pressure drop is determined by the co-current upflow channels,

$$\begin{aligned} \Delta P_{core} &= \Delta P_k = F\ (W_{gk}) \\ &= (K/A^2)_{SEO}\ (W_{gk}^2/2g\rho_g) + \phi_{1o}^2\ (K/A^2)_{ch} \\ &\quad (W_{gk} + W_{fk})^2/2g\rho_f + \int \left[\rho_f(1 - \alpha_k) \right. \\ &\quad \left. + \rho_g\alpha_k \right] dZ; \end{aligned} \tag{1.11}$$

(4) The two-phase level in the counter-current flow channels is a function of the channel void fraction, j, and the core pressure drop,

$$Z_j = \Delta P_{core} \ / \ \{\rho_f\ (1 - \bar{\alpha}_j) + \rho_g\bar{\alpha}_j\}; \tag{1.12}$$

(5) The counter-current flow channels must have a stabilizing level, i.e., not be full,

$$Z_j < Z_{ch}. \tag{1.13}$$

The level in the liquid downflow channels, Zi, is determined by the core pressure drop, the flows into the channel (UTP and bypass) and the inlet orifice loss characteristics.

$$\begin{aligned} Z_i = \Big[&(K/A^2)_{SEO}\ (W_{fSEOi}^2 \ / \ 2g\rho_f) + (K/A^2)_{ch} \\ &(W_{fUTPi}^2 \ / \ 2g\rho_f) + \Delta P_{core} \Big] / \rho_f. \end{aligned} \tag{1.14}$$

Two other modes of transitioning to co-current upflow are discussed in Section 5.0. The first mode is preceeded by the channel first filling, as already discussed, but during a period when the core pressure drop is falling. This transition occurs because the SEO steam flow to this channel, which is controlled by the SEO leakage, is increasing the level faster than the drainage can lower it. The second transition mode observed in Section 5.0, occurs when the bypass and channels start filling. The radial gradient in the static head of the bypass, caused by the peripheral LPCI injection, prevents the center channel from filling as fast as the other channels. The static head in this channel thus falls behind the core pressure drop. The lower plenum steam then flows to this path of lower resistence and co-current upflow results.

3.5 Channel Interaction

Figure 13 depicts a stable core flow condition. It is instructive to consider the effects of varying the independent variables in this situation. When the lower plenum steam flow is increased, this increase will flow to the co-current upflow channels as seen by equation (1.10). This increases the core pressure drop and the level in the counter-current flow channels. This rising pressure drop is illustrated in Figure 14 by the solid curves for one to four channels in co-current upflow. If during this process any channel completely fills, it undergoes a transition to co-current upflow as illustrated by the vertical dashed lines in Figure 14. With an additional channel in upflow, the core pressure drop will decrease as shown. Continuing to increase the lower plenum steam flow will again increase the core pressure drop on the next solid curve (Figure 14) until the next transition occurs.

For a decreasing lower plenum steam rate, the core pressure drop will decease along the right hand segment of one of the dot-dashed curves in Figure 14. These curves represent the overall pressure head curve for various numbers of channels simultaneously in co-current upflow. Figure 12 shows a similar curve for one channel. When the core pressure drop reaches the bottom of the dot-dashed curve (Figure 14) it is operating on, all of the co-current upflow channels will undergo a transition back to counter-current flow. Thus there is a hysteresis effect in this process. A transition from upflow to counter-current flow is observed in the test discussed in section 5.2.

If instead of varying the lower plenum steam flow, the liquid drainage into the counter-current flow channels is first increased and then decreased, the same process as described above also occurs. The reason for this is that increased drainage from the counter-current flow channels allows less steam to flow into these channels. The excess steam is available to flow up the co-current upflow channels, thus increasing their pressure drop.

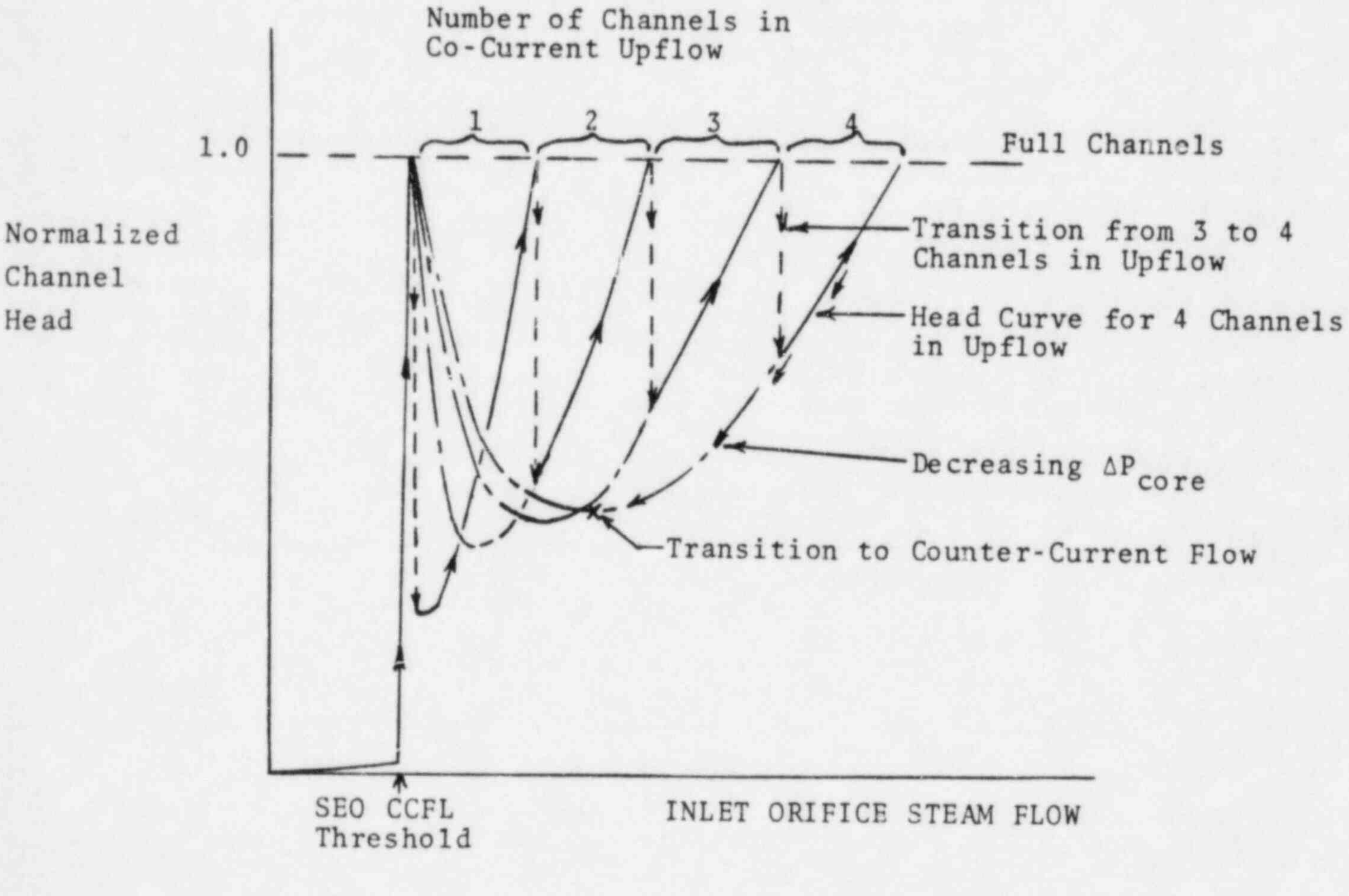
3.6 Effects of Core Steam Injection

When no steam is injected into an SSTF channel, liquid flow into the top of the channel is not limited by CCFL. For this situation, no liquid is held in the upper plenum.

With core steam injection, simulating bundle heat transfer, CCFL at the upper tie plate (UTP) is an important factor. With this steam injection present, liquid can be held in the upper plenum if the bypass is full. The CCFL controlled drainage through the UTP is determined by both the core steam injection and the steam entering the the channel through the inlet orifice. This is shown schematically in Figure 15. This figure also demonstrates that the inlet orifice steam flow is a function of the upper tie plate CCFL drainage and the

Figure 14

PROGRESSIVE TRANSITION OF CHANNELS INTO CO-CURRENT UPFLOW

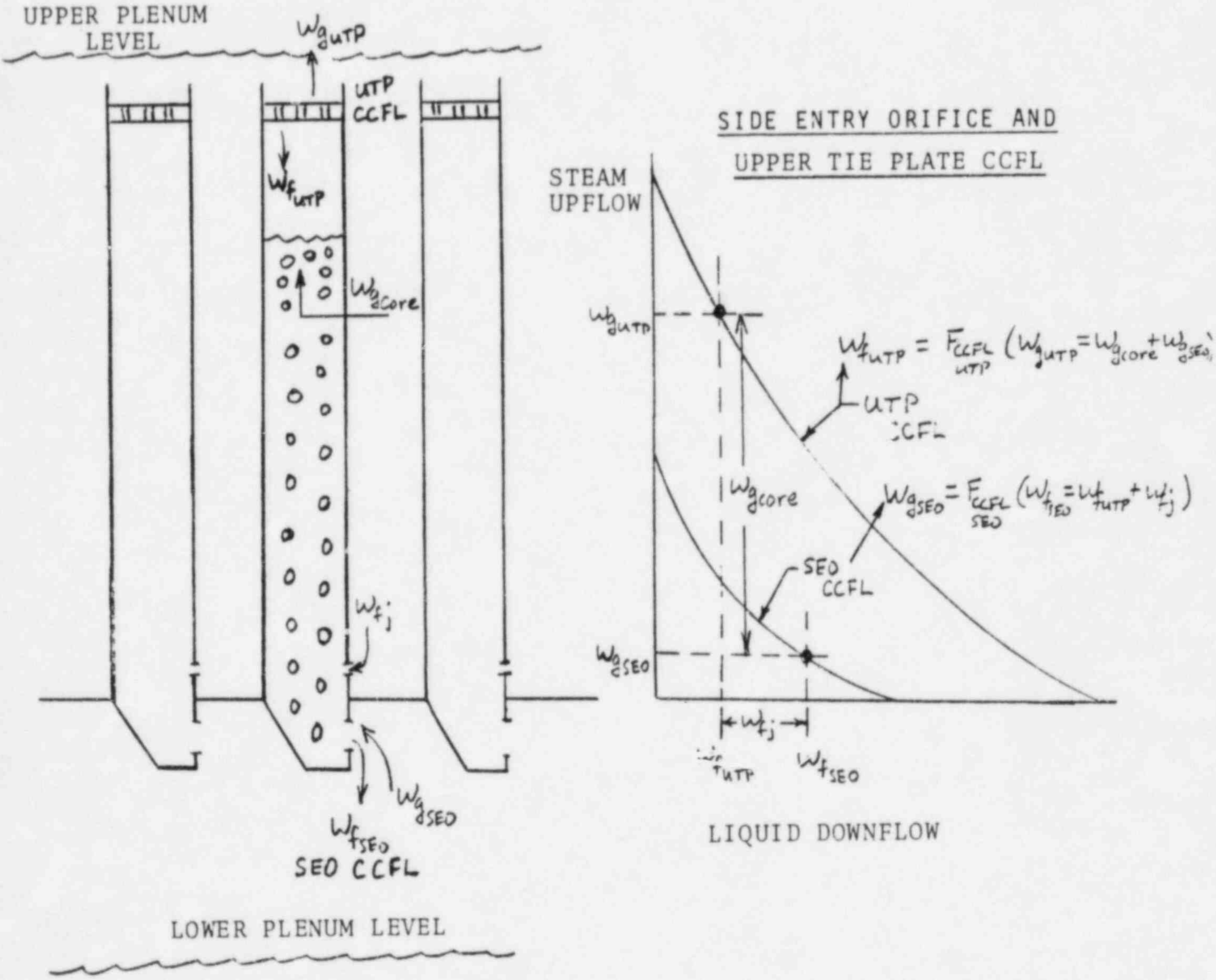


(Reference 3 demonstrates a similar behavior for straight pipes in parallel.)

Figure 15

EFFECTS OF CORE STEAM INJECTION

- Upper Plenum Mass
  - UTP CCFL/Full Bypass
- Stable Level in CCFL Channels
- Upper Plenum Liquid Redistributes
- Lower Plenum Steam Redistributes
- SEO CCFL Channel Mass Holdup
- Assume $W_{g_{core}}$ and W_{fj} are known



SIDE ENTRY ORIFICE AND UPPER TIE PLATE CCFL bypass-to-channel drainage.

Thus, these effects are interactive. For example, if the core steam injection is reduced, the UTP drainage and the orifice drainage are both increased. This decreases the inlet orifice steam flow which further increases the UTP and channel drainage rates. The drainage from the bypass is a function of the channel static head so it will interact also.

Figure 15 demonstrates how channel drainage, and subsequent redistribution of the inlet orifice steam, can be altered by core steam injection. It also demonstrates how the net core drainage is reduced by core steam injection, and how that drainage rate can be calculated.

4.0 Separate Effects Parallel Channel Tests

4.1 SEO-CCFL Test SE1-4A, B, C, D (No Upper Plenum Mass)

The purpose of this series of tests is to measure the CCFL characteristic of the side entry orifices of the SSTF core. A schematic of the test set-up used is shown in Figure 2. The procedure for performing this series of tests is to set the steam injection to the lower plenum and, while holding this rate constant, increase the liquid injection to the bypass and upper plenum until CCFL at the SEO limits the drainage to the lower plenum. It was expected that an accumulation of mass in the upper plenum would confirm that this limit had been reached. The resulting drainage would be measured and correlated with the steam injection rate.

The results of this test show no mass accumulation in the upper plenum, even with liquid injection rates far exceeding the rate predicted using single channel models. The core drains all injected liquid for all lower plenum steam rates tested.

An evaluation of the data shows that the three channel flow regimes discussed in Section 3.1, and shown in Figure 3, exist in these tests. The occurrence of these parallel channel flow regimes allows the channels to drain all the liquid flowing into them. With no core steam injection, there is no flow limitation at the upper tie plates and the bypass liquid overflows into the tops of the channels unimpeded.

As the channels fill, the peripheral channels go into liquid downflow while a small number of the central channels go into co-current up flow. The lower plenum steam flow to the remaining counter-current flow channels is decreased by this effect, thus increasing the drainage to equal the liquid injection rate.

Interpretation of channel pressure drop measurements is aided by noting the pressure tap locations in the instrumented bundles, Figure 5. The core location of the six instrumented bundles is shown in Figure 4.

The total core pressure drop, (DP1 + DP2), and the side-entry orifice pressure drop, DP2, measurements are plotted in Figure 6 as functions of lower plenum steam flow rate. The maximum DP2 static head is the 22.3 inch span of the pressure taps. Therefore, a two-phase static head will be somewhat less than 22.3 in., as indicted by the counter-current flow bundles 12, 26 and 40 in Figure 6. A DP2 measurement greater than 22.3 in. can only occur for upflow friction, as is the case for bundle 54. A negative DP2 reading indicates liquid downflow friction across the inlet orifice (bundles 4 and 5). When the DP2 pressure difference lies between 0 and 22.3 in., other measurements, such as DP1 and the bundle conductivity elements, are evaluated to determine the flow regime of the channel.

4.2 SEO CCFL Test SE1-5D (SEO CCFL Threshold)

Based on the evaluation of test SE1-4 discussed above, the side-entry orifice CCFL test procedure was modified to further investigate the parallel channel phenomena. A liquid injection of 557 GPM of saturated water through the LPCI into the bypass was set and held constant. Lower plenum steam injection was initially set at a value well below the predicted SEO CCFL threshold (equation 1.2) and then was increased in steps until the CCFL threshold was exceeded.

The test results confirm that the channels have no level (Pcore = 0)below the SEO CCFL threshold, and start filling as the threshold steam flow is exceeded. Subsequent filling and transition to co-current upflow in some of the channels was also observed. The core level response to increasing lower plenum steam rates are shown schematically in the system diagram, Figure 16.

Pressure drop traces for bundles 54, 40 and 26 are shown in Figure 17. Initially the channels are draining with no level, and when the lower plenum steam injection is increased to exceed the threshold they all start to fill at the same time. As the level in each bundle exceeds the 22.3 inch tap location, DP1 starts to register while DP2 levels out at 16 - 18 in. of water. At approximately 325 seconds bundle 54 transitions to co-current upflow, as indicated by the sudden increase in DP2 (exceeds 22.3 in.) due to upflow friction, and decrease in DP1 due to increased void fraction.

Conductivity element (CE) traces shown in Figure 18 confirm the transient filling of bundle 54 and the transition to co-current upflow. These conductivity element traces (conductivity element locations given in Figure 5) show the bundle starting empty (high reading), and then filling with a two-phase mixture (intermediate oscillating readings). A rapid increase in the CE readings is due to liquid being carried out of the bundle by the upflowing steam and water. Traces for bundles 40 and 26 show that they do not fill past the top conductivity element, i.e. they retain a stabilizing level.

Reducing the lower plenum steam rate below the CCFL threshold of the SEO allowes the channels to drain empty.

4.3 SEO-CCFL Test SE1-5A, B, C (Core Steam Effects)

Having no core steam injection, the above tests SE1-4 and SE1-5D did not accumulate any mass in the upper plenum. Tests SE1-5A, B, and C were performed to assess the effects of core steam injection on upper plenum mass hold-up and core drainage. A system schematic of this test series is shown in Figure 19.

Upper tie plate CCFL due to core steam injection is required along with a full bypass before mass can accumulate in the upper plenum. UTP CCFL limits the liquid flow from the upper plenum into the channels and consequently reduces the core drainage to match the flow into the core. With that, the upper plenum is filled with a highly voided two-phase mixture and mass is carried out the standpipes. The magnitude of the upper plenum mass is a function of the steam flow to this region and the injection rate of subcooled spray water. Tests SE1-5A and 5B (Table 2) have the same subcooled spray rate (1650 GPM). Test SE1-5B, having a higher total steam flow, has a smaller mass as indicated in Table 2 by its upper plenum head. Test SE1-5C has the same total steam flow as SE1-5B but only half the subcooled spray flow (830 GPM) to condense steam voids. Consequently its upper plenum head

Figure 16

SYSTEM DIAGRAM

SIDE ENTRY ORIFICE CCFL THRESHOLD

(TEST SE1-5D)

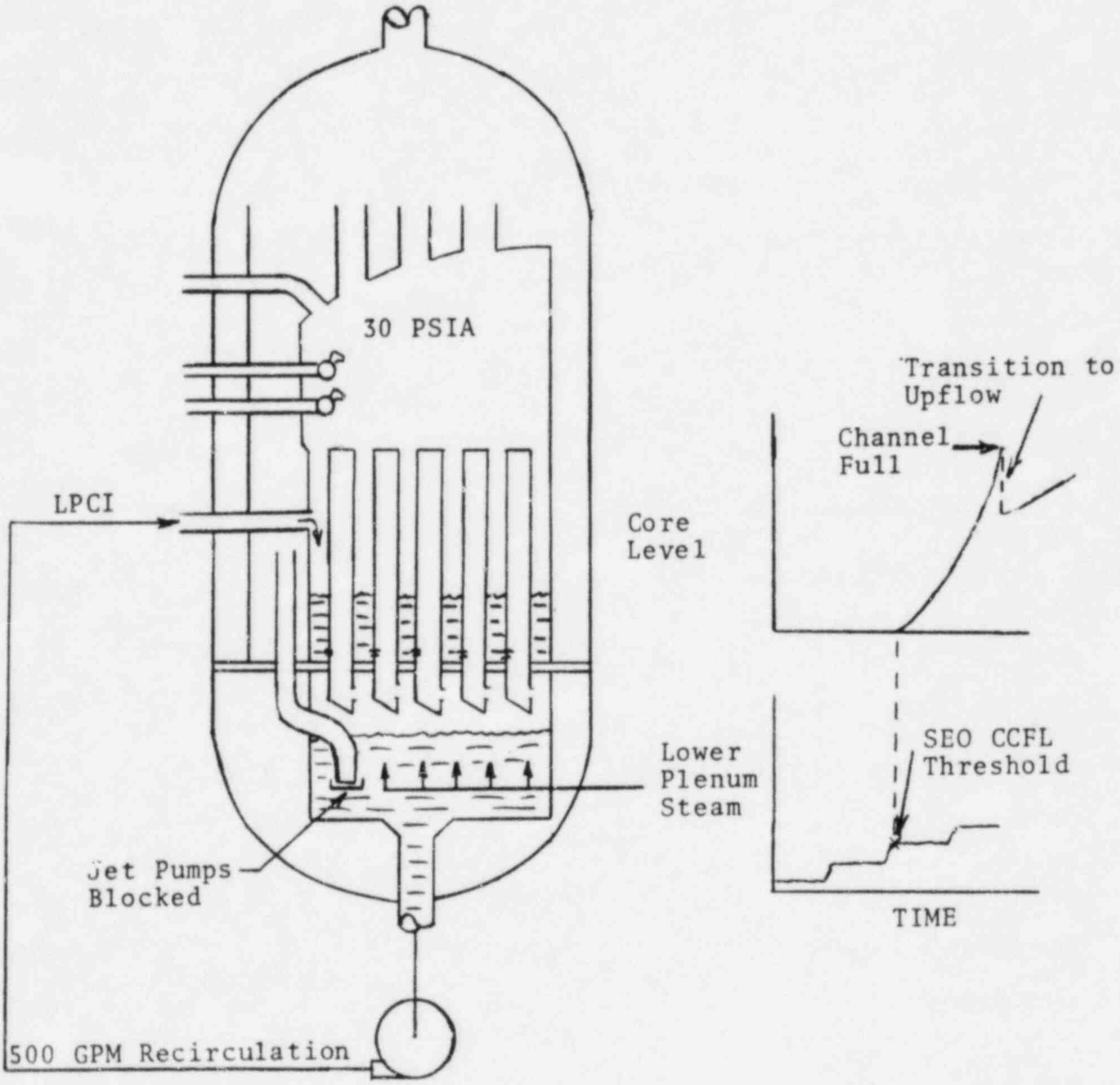


Figure 17

SIDE ENTRY ORIFICE CCFL THRESHOLD AND TRANSITION TO CO-CURRENT UPFLOW

(SEO CCFL TEST SE1-5D (329)

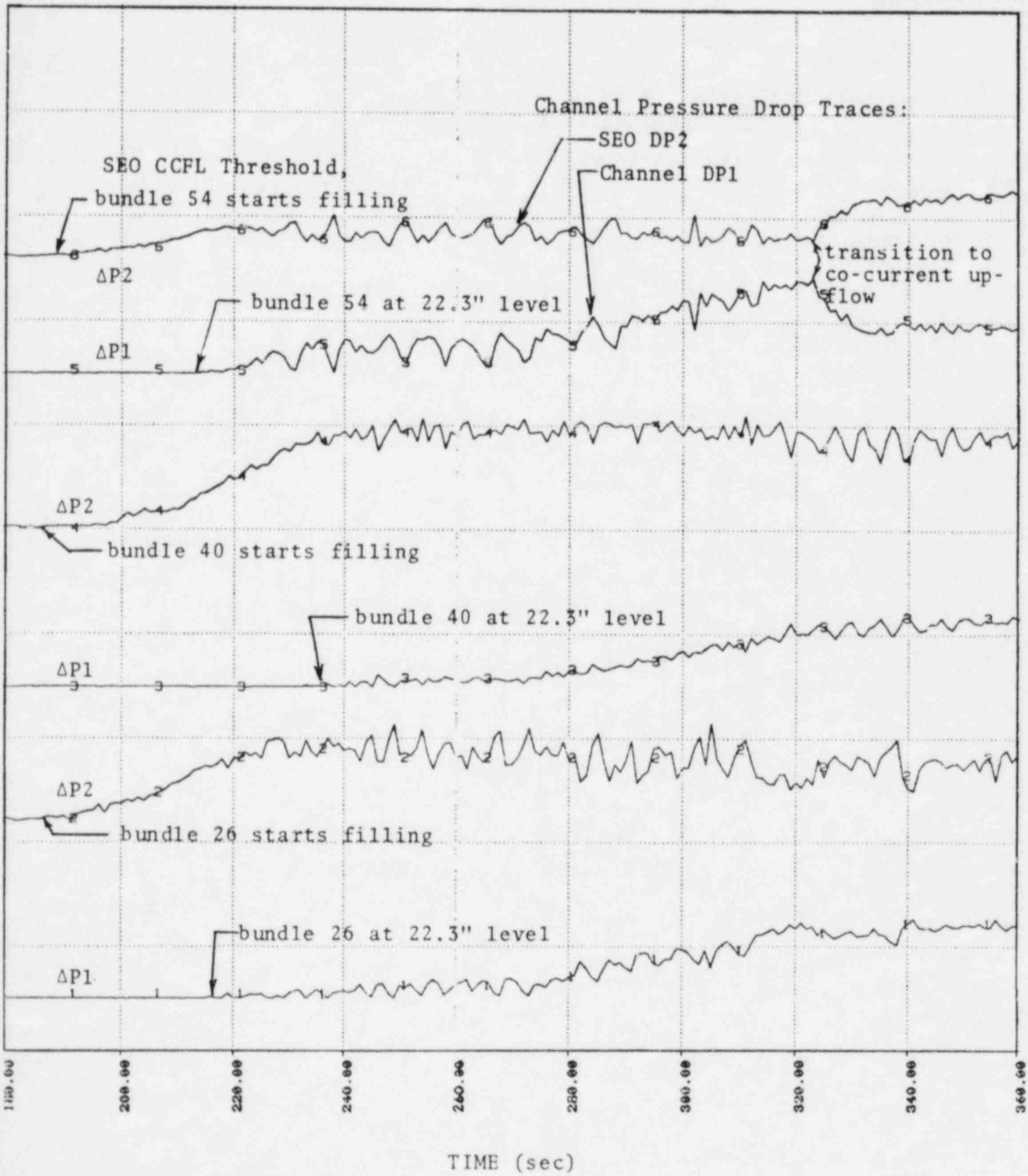


Figure 18

TRANSITION TO CO-CURRENT UPFLOW

(TEST SE1-5D (329) CHANNEL 54 CONDUCTIVITY ELEMENTS)

- COUNTER-CURRENT CHANNEL FILLS
- TRANSITION TO CO-CURRENT UPFLOW
- STABLIZING LEVEL

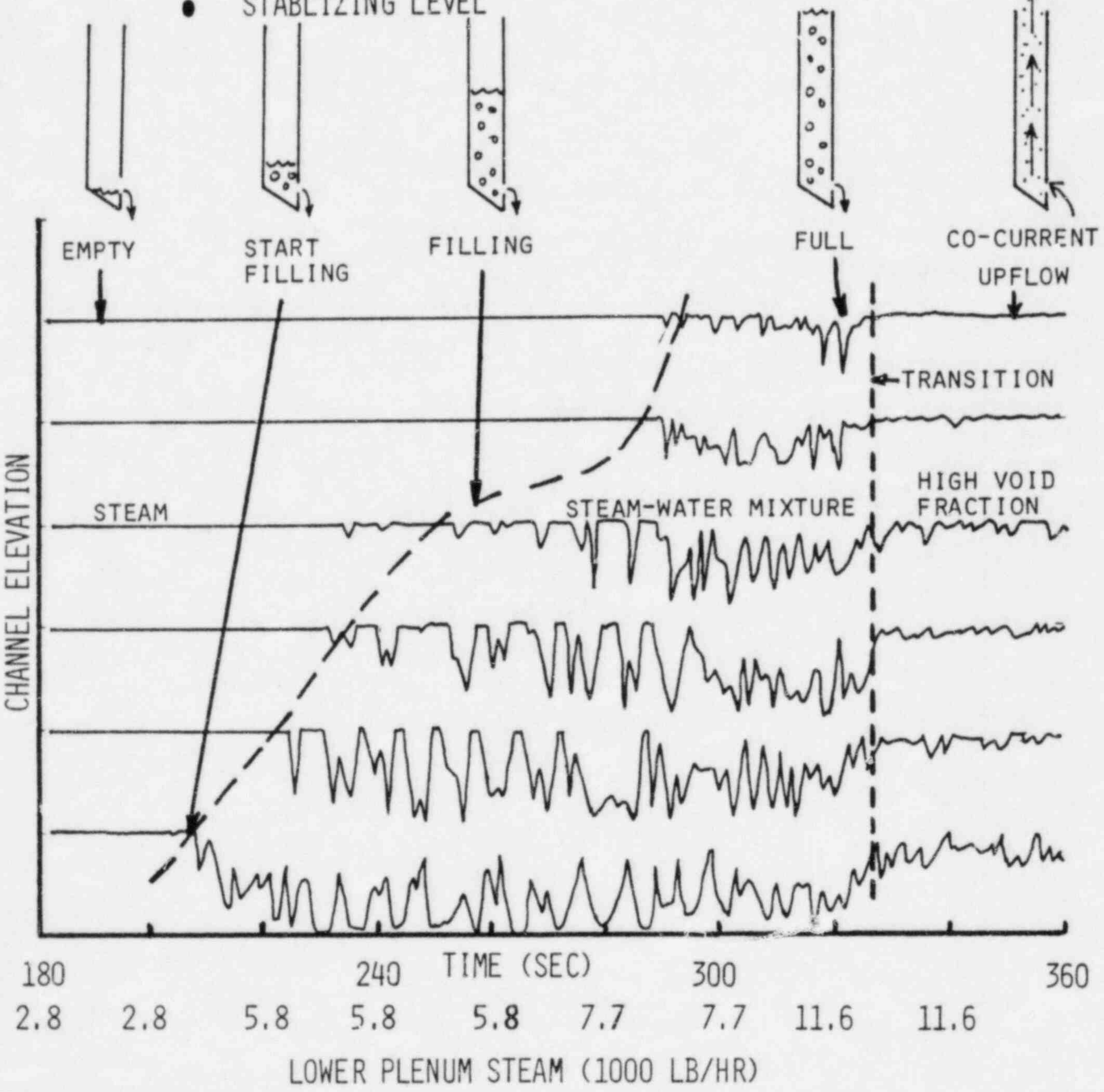


Figure 19

SYSTEM DIAGRAM

EFFECTS OF CORE STEAM INJECTION

(SEO CCFL TEST SE1-5A, B, C)

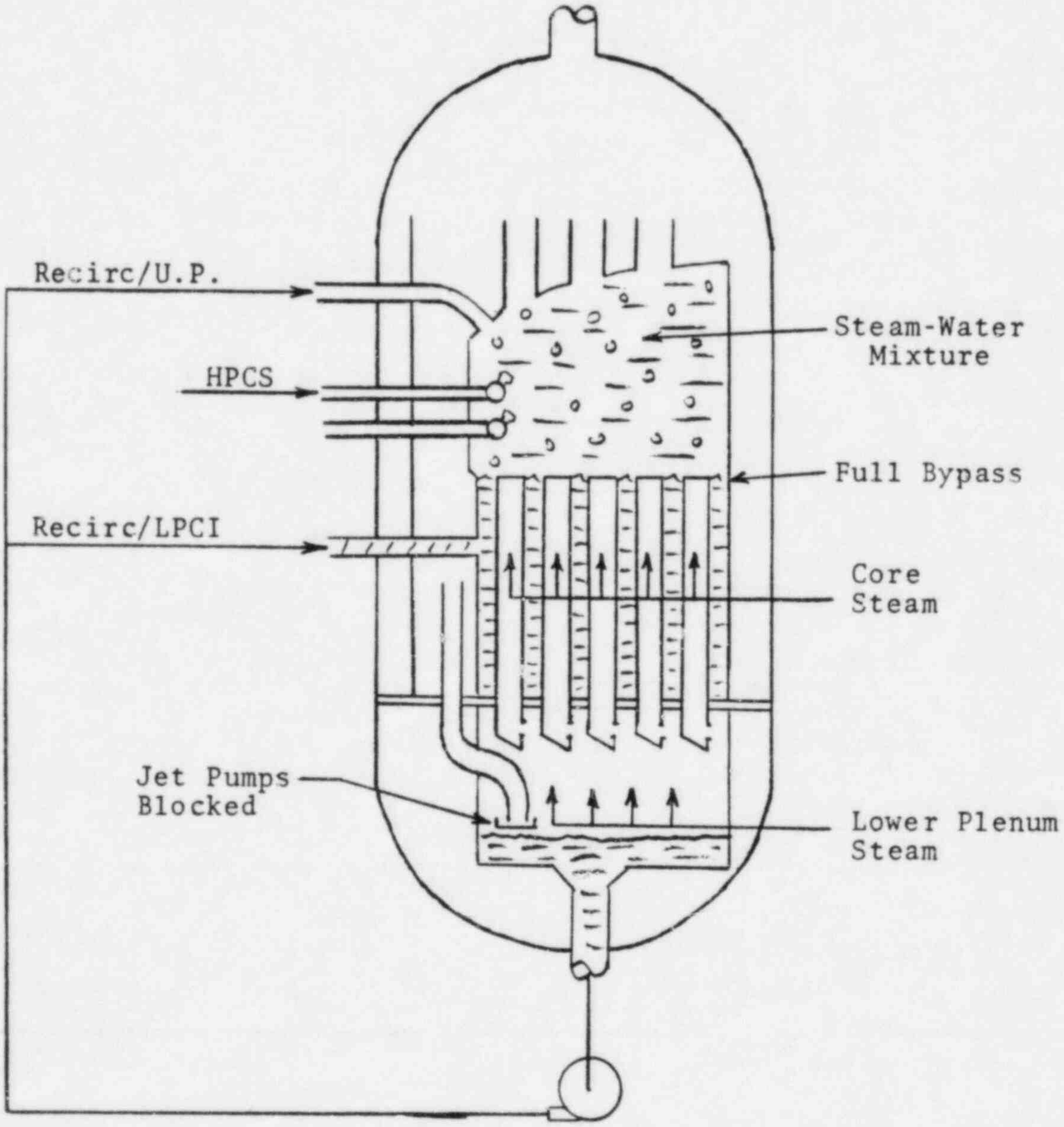


TABLE 2

EFFECTS OF CORE STEAM INJECTION ON UPPER PLENUM MASS

(30 PSIA)

TEST	LOWER PLENUM STEAM FLOW (lb/hr)	CORE STEAM FLOW (lb/hr)	TOTAL STEAM FLOW (lb/hr)	UPPER PLENUM ΔP (In. H_2O)
SE1-5A	13,400	25,100	38,500	10"
SE1-5B	13,100	40,300	53,400	8"
SE1-5C	33,000	20,000	53,000	4"
SE1-4D	12,730	0	12,730	1"

is less. Table 2 summarizes this effect. Test SE1-4D is included in Table 2 to contrast the effects of core steam on upper plenum mass hold-up.

The effects of core steam injection on the core pressure drops and flows are highlighted in Table 3. A lower plenum steam flow of 13,000 lb/hr was used for each of these three experiments. Test SE1-4D, with no core steam flow, had a much greater core pressure drop due to its lower void fraction. The DP2 measurements in bundles 4 and 5 for tests SE1-4D and SE1-5A imply a liquid downflow friction drop of 22" across the side entry orifice. In test SE1-5B the increased core steam flow limits the drainage into bundles 4 and 5 due to UTP CCFL. This reduces the liquid downflow through the side entry orifice and the friction pressure drop is decreased to 11".

More details of the core pressure drops are shown in Figure 20. The lower plenum steam injection was increased to 33,000 lb/hr in test SE1-5C. This drove four of the six instrumented bundles into co-current upflow, including peripheral bundle 4.

4.4 Initial Conditions Test TST - 8 Run 204 (Large U.P. Mass)

Experiment TST-8, Run 204 was the first of the initial conditions tests. The purpose of this test was to determine the flexibility of the facility to achieve target initial masses. The procedure used was to sequentially set the mass in each region by adjusting the steam and liquid injections (or drainage) to the regions. The final masses achieved are shown in Figure 21 along with the required steam and water flow rates.

The test demonstrates that the mass accumulation in the upper plenum can be increased by the injection of subcooled water to decrease the void fraction. The upper plenum static head is 32 in. of water as shown in Figure 22.

Upper tieplate subcooling and liquid downflow was measured in bundles 4, 5 and 12 (Figure 22). No co-current upflow was observed in any of the six instrumented channels, which is consistant with SE1-4 for 6,000 lb/hr of lower plenum steam.

4.5 Initial Conditions Test TST 8-3 Run 369 (Flow Regime Transitions)

The purpose of this experiment was to achieve the target initial masses using pre-calculated steam and liquid injection rates. Figure 23 shows a schematic of this experiment. The sequence of steam and water injections for this test is shown in Figure 24. Transient pressure drop traces in Figure 25 for the core, bypass, and DP2 for bundles 4, 5, 26 and 54, show a number of interesting parallel channel and system interactions.

The test was started with no lower plenum steam injection and, therefore, with the channels draining empty. As lower plenum steam injection was ramped up, the channels started filling and the bypass level increased. Before the channels filled completely the upper

TABLE 3

EFFECTS OF CORE STEAM INJECTION ON CORE PRESSURE DROP

(30 PSIA)

LOWER PLENUM STEAM = 13,000 lb/hr

TEST	CORE STEAM FLOW (lb/hr)	CORE ΔP IN. H_2O	SEO DOWNFLOW FRICTION DP (CHANNELS 4 & 5)	SEO UPFLOW FRICTION DP (CHANNEL #)
SE1-4D	0	70"	22"	50" (#54)
SE1-5A	25,100	49"	22"	25" (#12 & #54)
SE1-5B	40,300	47"	11"	24" (#12)

Figure 20

CHANNEL PRESSURE DROPS vs. CORE AND LOWER PLENUM STEAM RATES
SIDE ENTRY ORIFICE CCFL TESTS SE1-5A, B, C

Pressure = 30 PSIA
Full Bypass

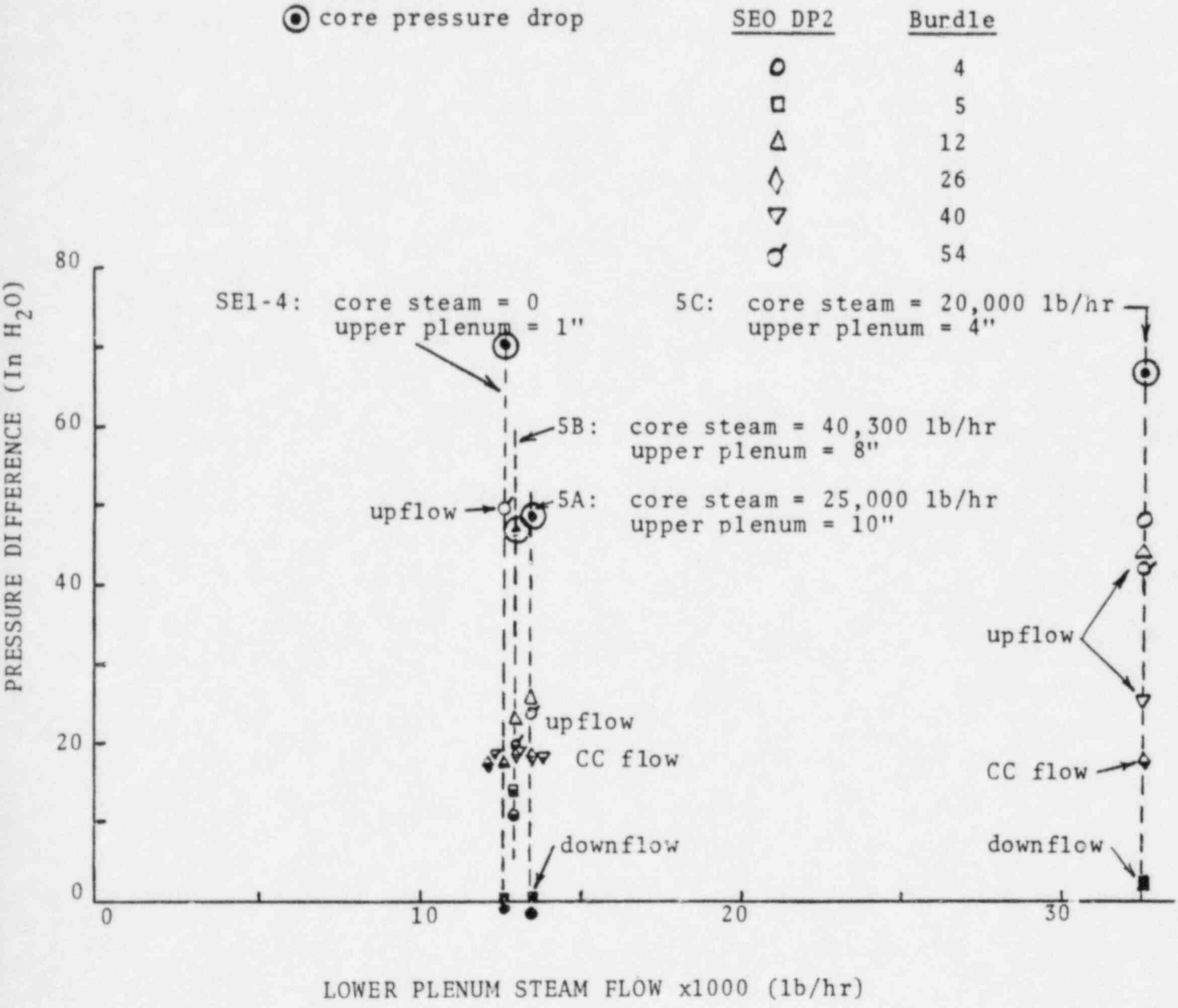


Figure 21

SYSTEM DIAGRAM

INITIAL CONDITIONS TEST TST 8 RUN 204

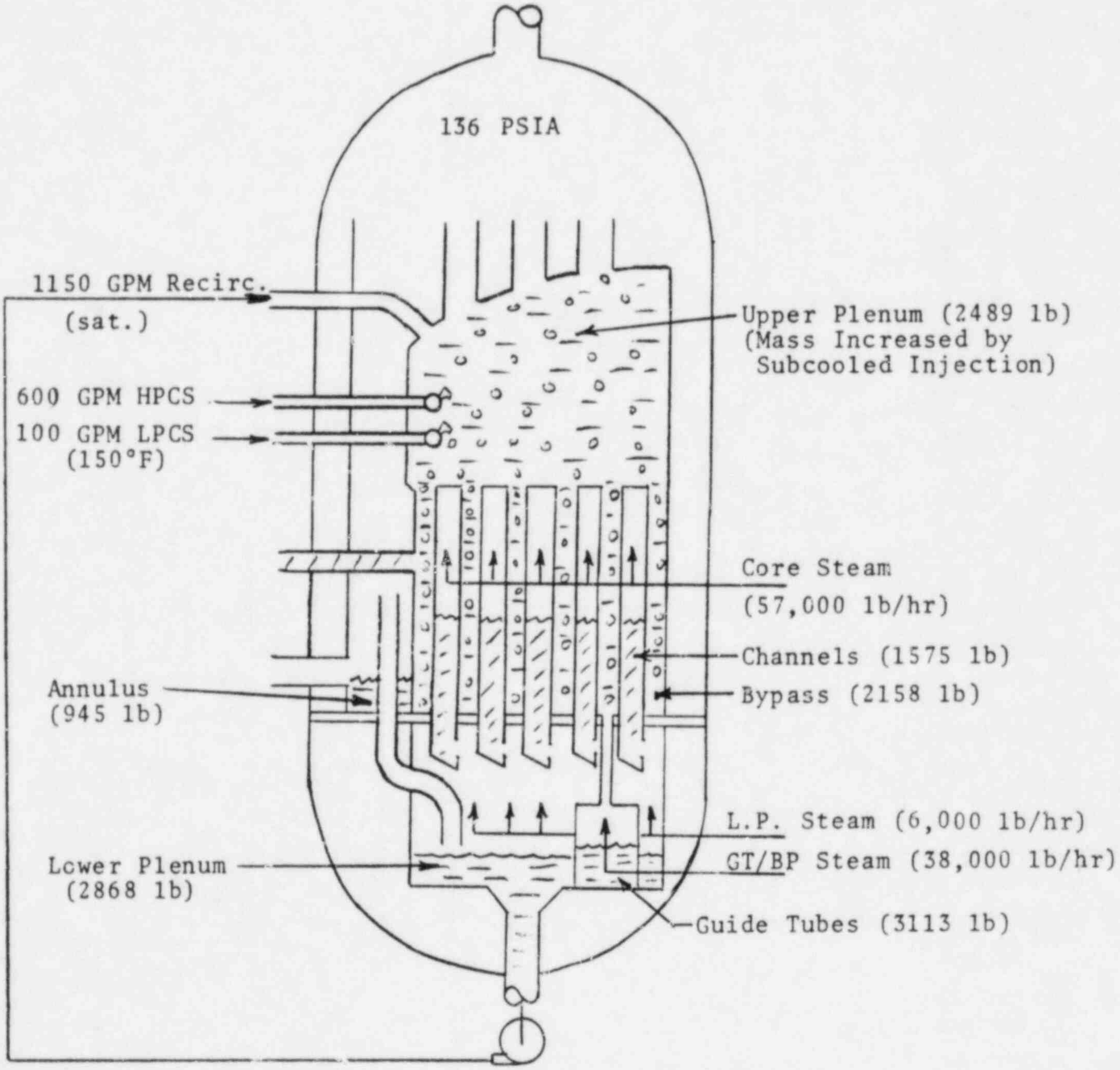


Figure 22

INITIAL CONDITIONS TEST TST 8 RUN 204

TEST READINGS

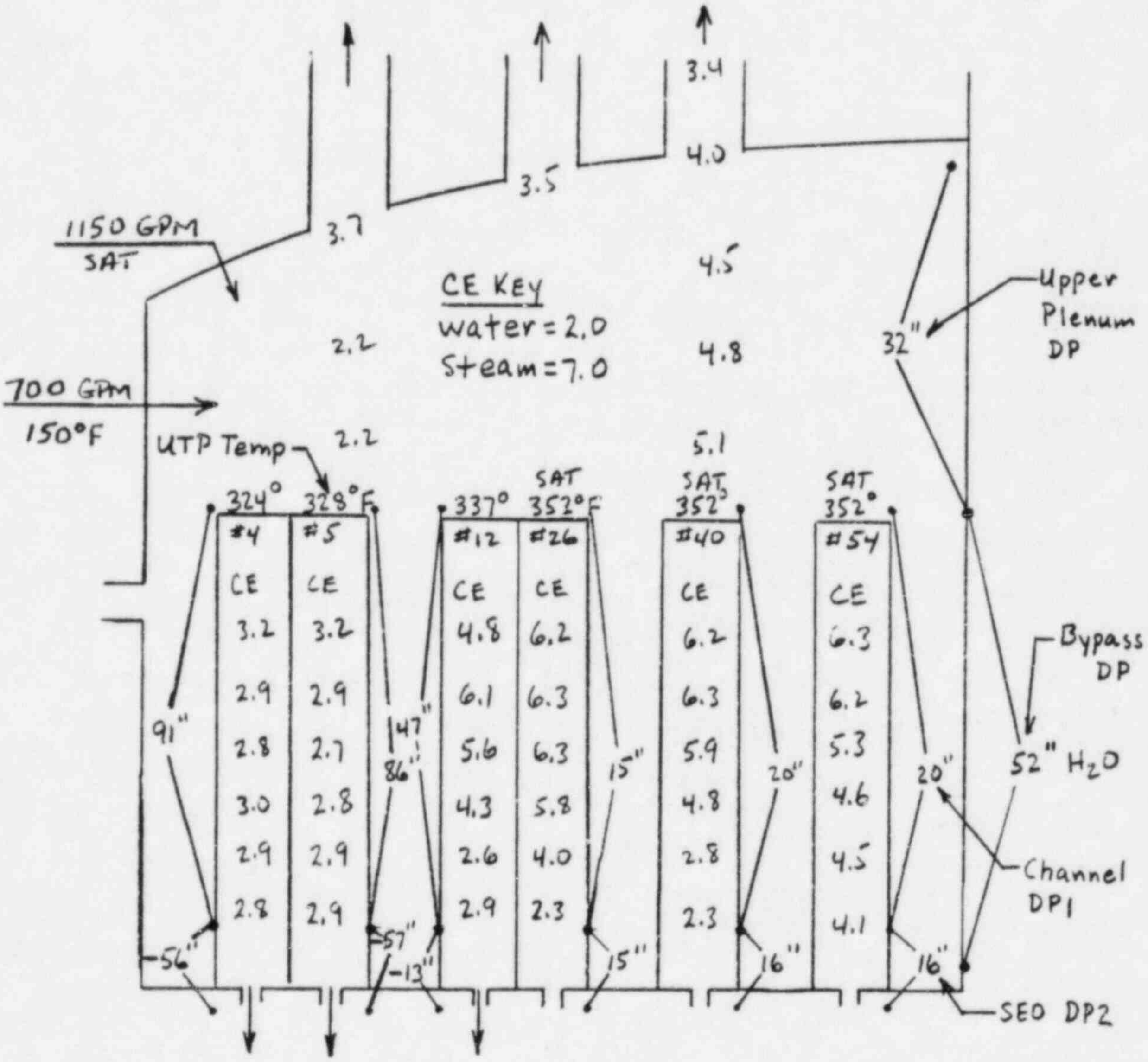


Figure 23

SYSTEM DIAGRAM

INITIAL CONDITIONS TEST TST 8-3 RUN 369

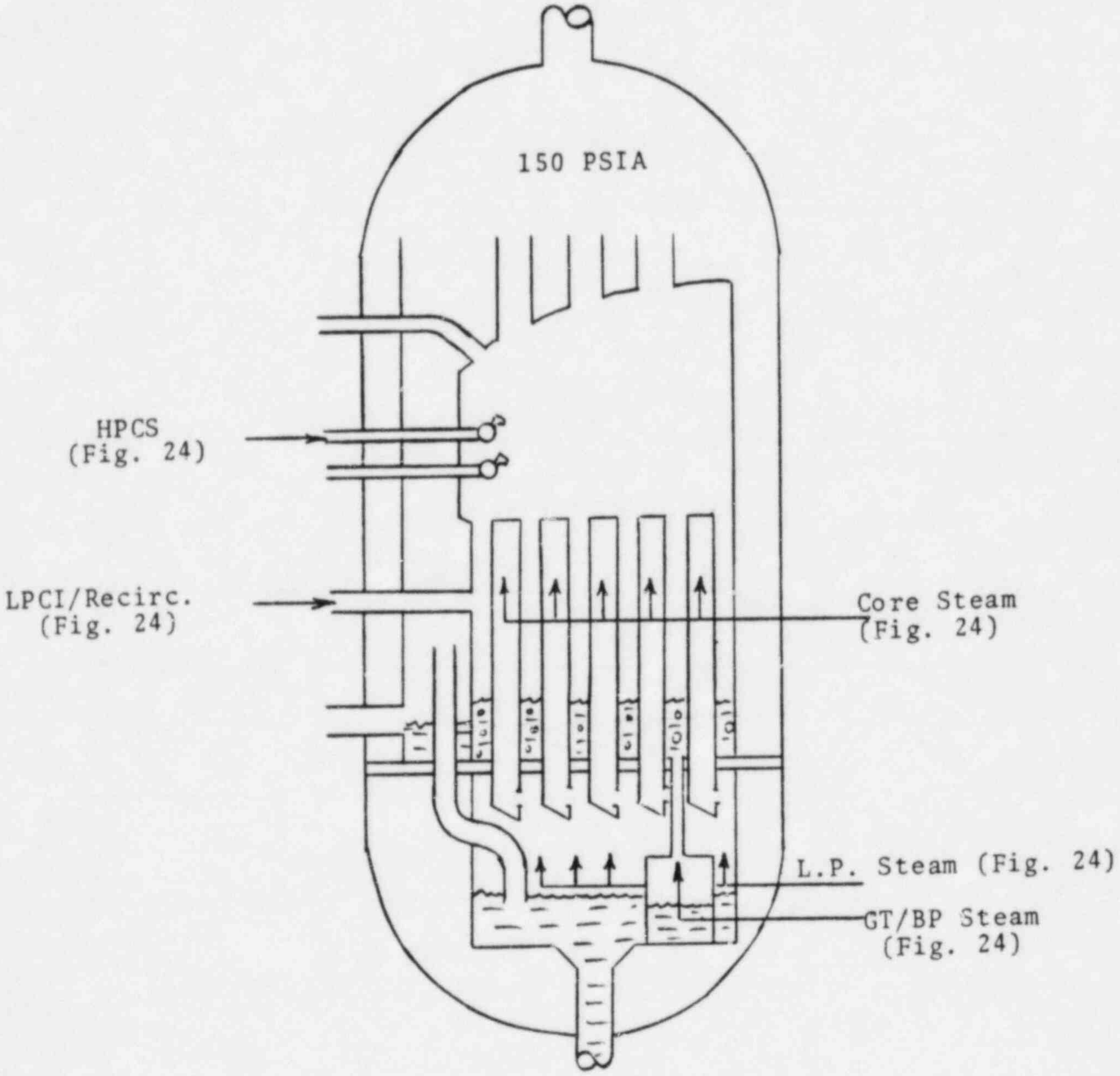


Figure 24

TEST TST 8-3 RUN 369
STEAM AND WATER FLOW

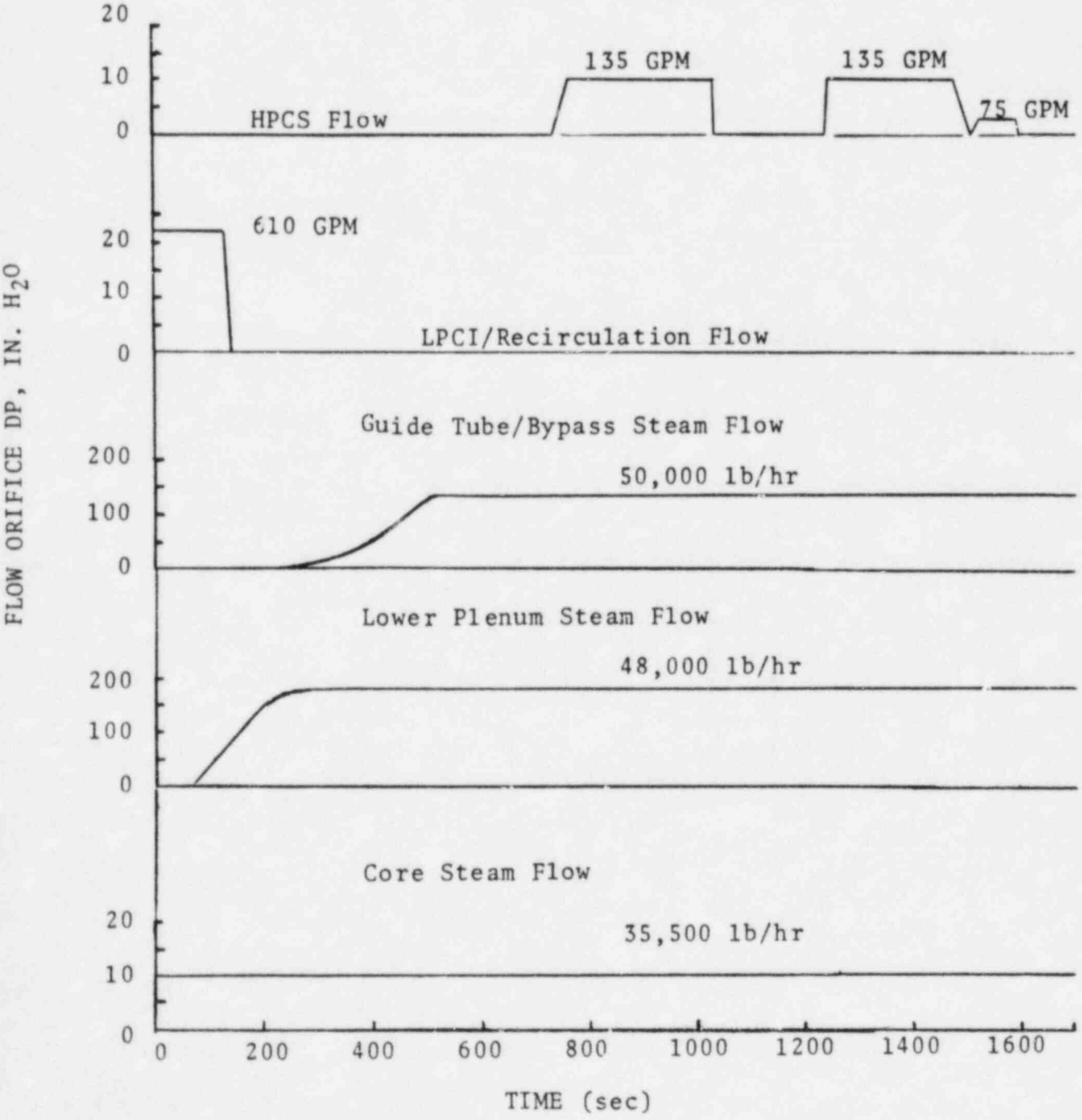
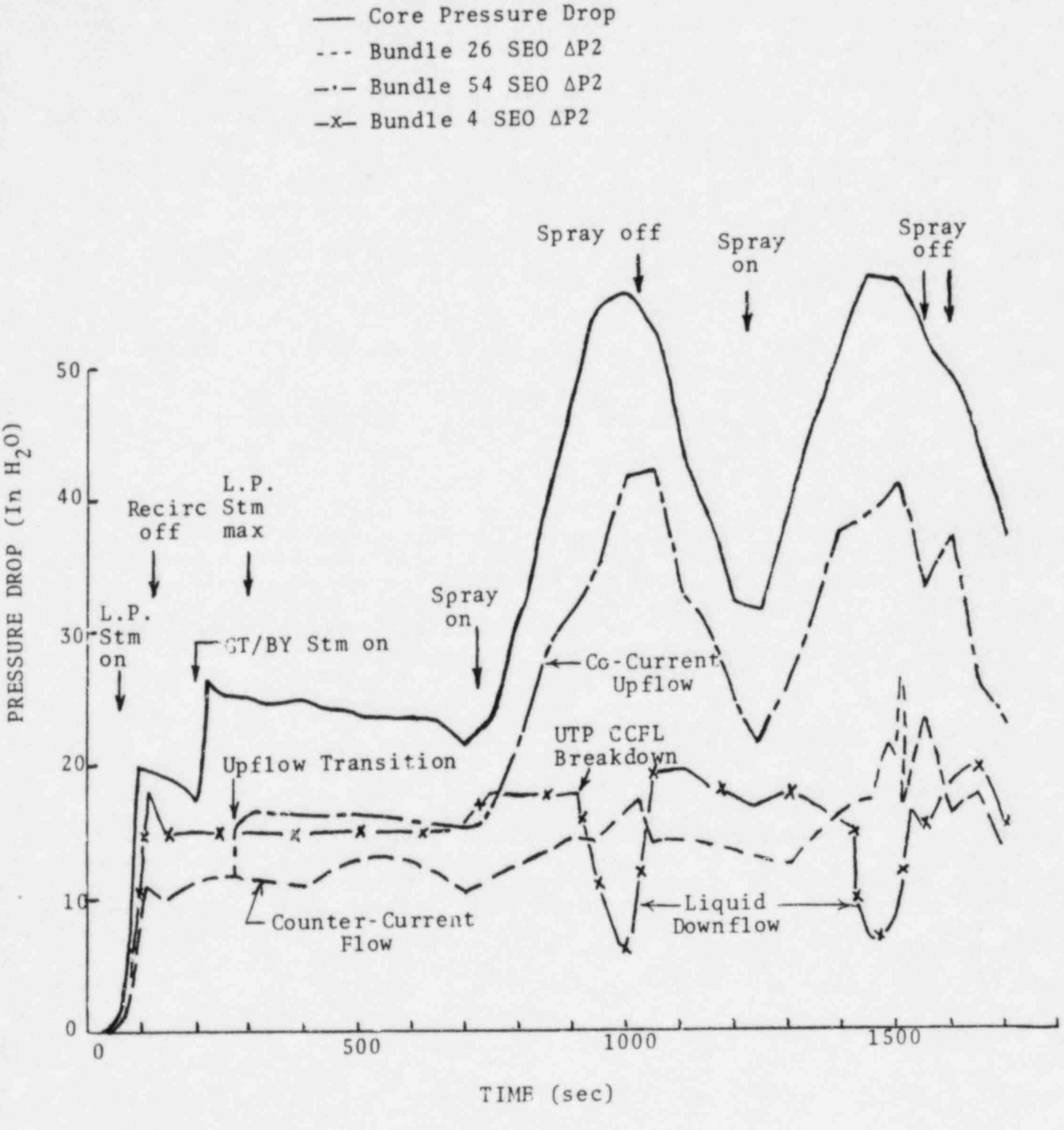


Figure 25

CORE RESPONSE FOR INITIAL CONDITIONS TEST TST 8-3 RUN 369



plenum liquid injection was turned off, and the channels and bypass started draining. The guide tube steam injection started at about 200 seconds and forced water from the guide tube pipes into the bypass, thus increasing the bypass head. As the lower plenum steam reached its maximum, bundle 54 transitioned to co-current upflow at 270 seconds. Up to this time, the DP2 traces for bundles 54 and 26 were the same.

No injection changes were made between 500 and 730 seconds, and with no liquid injection, the slowness of the bypass and channel draining was evident from the core pressure drop curve.

At 730 seconds the subcooled core spray was started. There was an immediate increase in the core DP and the DP2 for bundle 54 as steam was diverted from the counter-current flow channels to the co-current upflow channels. There was a delay before upper tieplate subcooling and CCFL breakdown were observed for bundles 4 and 5. The liquid downflow in these two bundles is evident from their DP2 traces.

When the core spray was turned off, bundles 4 and 5 returned to counter-current flow and the core pressure drop decreased as it drained. This cycle was repeated.

With a level in the bypass, no mass was held in the upper plenum.

4.6 Initial Conditions Test TST 9-6 Run 16 (Simulated Lower Plenum Flashing)

The procedure used in this third of the series of initial conditions experiments, was to fill the test section with saturated water up into the core and bypass. The steam injection rates were then turned on to their predetermined values. The objective was to let the steam redistribute the water. The system schematic for this test is similar to Figure 23, but with different mass distribution. The important aspect for this discussion is the transient response measured in this experiment and the occurrence of parallel channel flow effects when a lower plenum level forms.

The test procedure used roughly simulates initial lower plenum flashing. Figure 26 shows the bypass level swell (curve a) shortly after 80 seconds and a lower plenum level starting to form (curve b) at 110 seconds. The level swell in channel 54 is shown by the pressure drop measurements and conductivity element readings in Figure 27. This channel fills and goes into co-current upflow at 120 seconds. This demonstrates that initiation of parallel channel flow is coincident with the formation of a lower plenum level. This is an important model consideration because it is a controlling phenomenon in the LOCA transient from this time onwards.

Figure 26

LOWER PLENUM LEVEL FORMATION

(TEST TST 9-6 RUN 16)

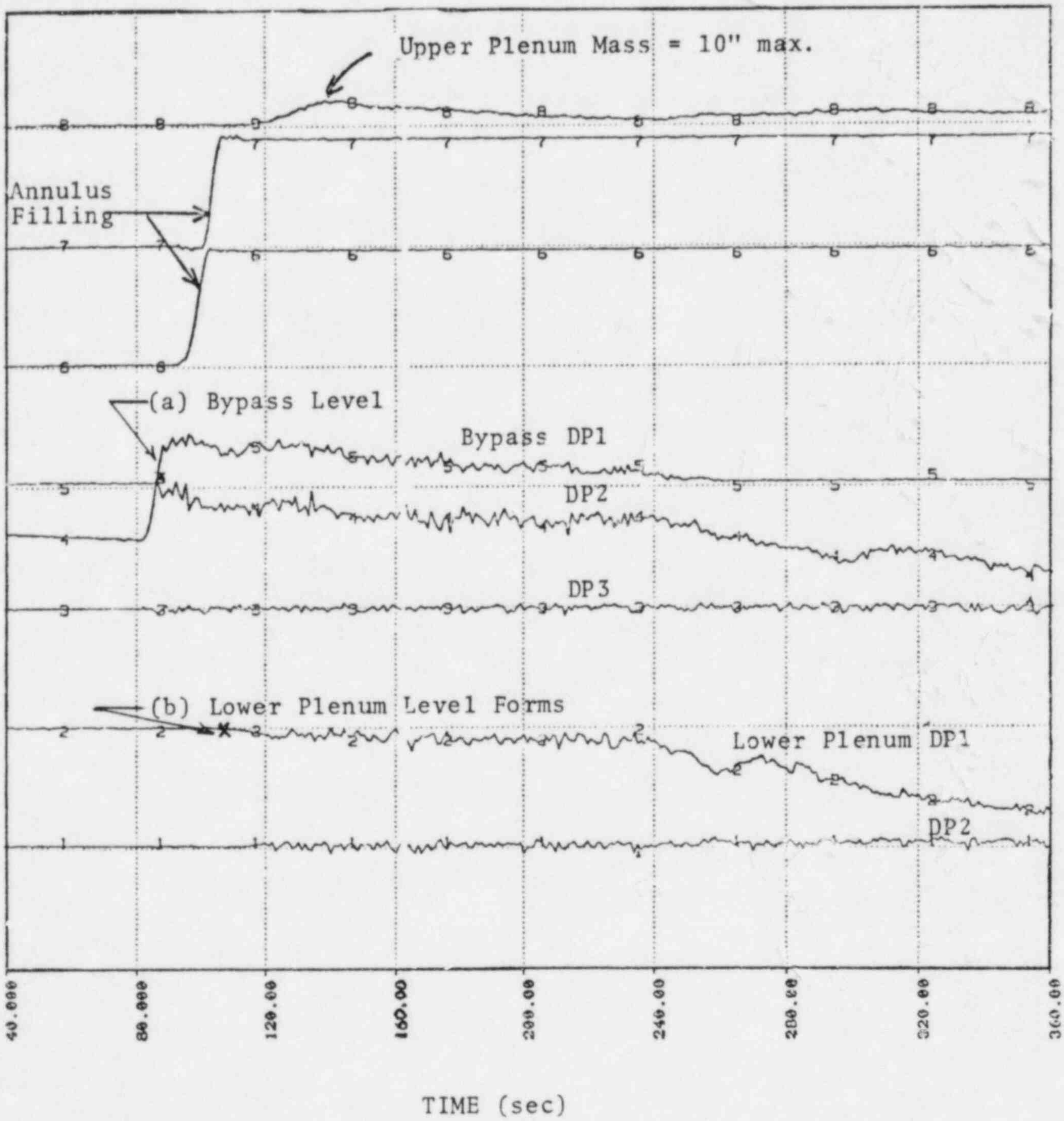
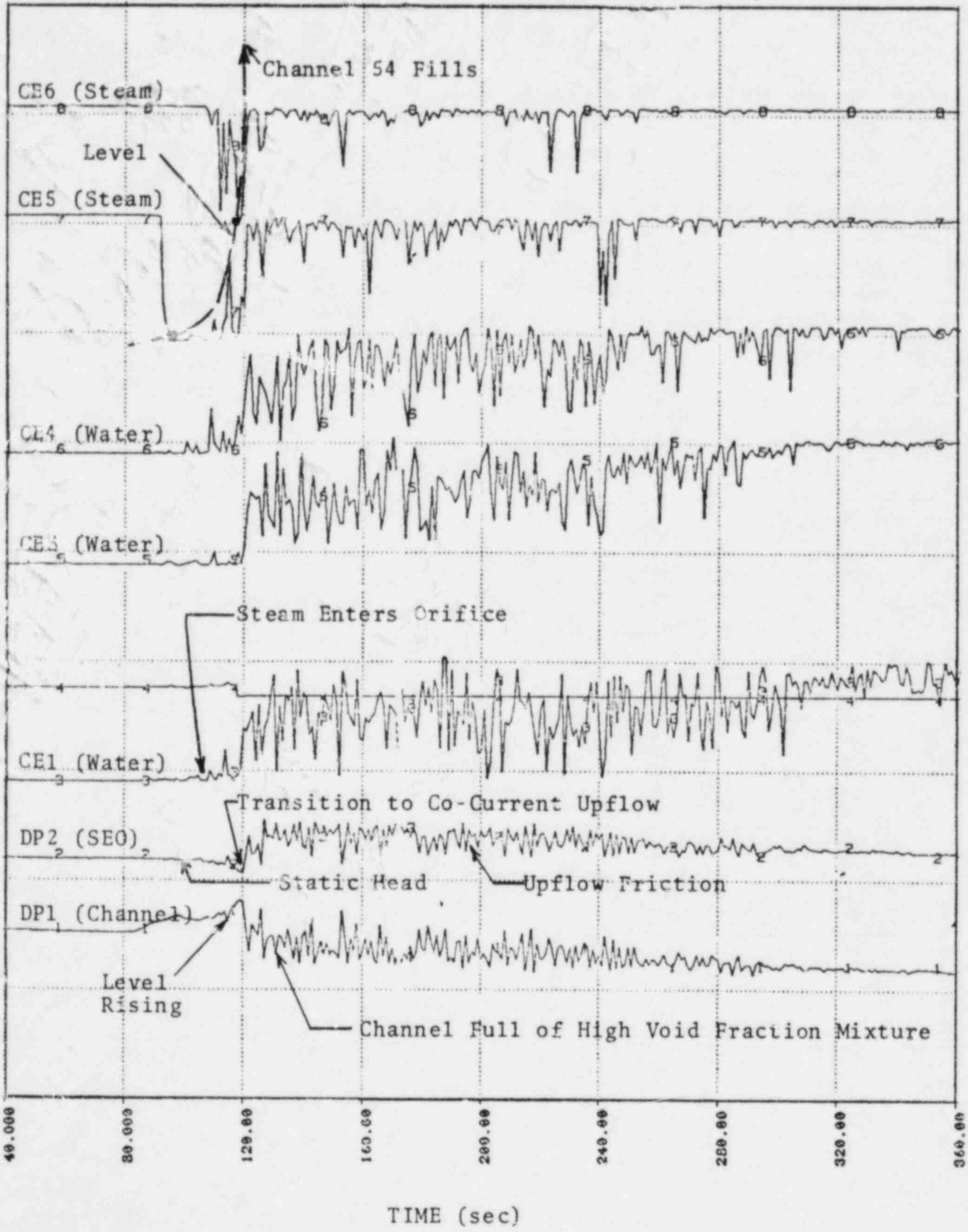


Figure 27

TRANSITION TO CO-CURRENT UPFLOW
AS LOWER PLENUM LEVEL FORMS
(TEST TST 9-6 RUN 16 Channel 54 Level and DP's)



5.0 LOCA Transient Parallel Channel Tests

5.1 Introduction

The purpose of this section is to evaluate the parallel channel phenomena for transient response tests. The focus is on the channel and system interactions. The tests that are discussed are actually two phases of the same reference LOCA transient, SRT-3 Run 26.

The first phase sets the initial conditions for the blowdown transient while holding the system pressure constant. This test demonstrates the draining of the upper plenum and core before the ECCS flow comes on. Flashing is simulated with steam injection.

The second phase is the depressurization refill-reflood transient of the reference BWR/6 DBA LOCA with two core spray systems and one LPCI system active. This test demonstrates the refilling of the system and reflooding of the channels.

5.2 Reference Initial Conditions Test SRT-3 Run 26

The purpose of this test is to set the system initial conditions in preparation for the refill-reflood blowdown transient. The test consists of three periods: (1) simulating post lower plenum flashing (300-630 sec), (2) upper plenum drainage (630-640 sec), and (3) core and bypass drainage (640-1400 sec).

Period 1 - is accomplished by filling the test section with water to a level in the core and bypass. Steam is then injected into the lower plenum, guide tube/bypass, and core to simulate depressurization flashing and vaporization due to decay heat. Water is pumped from the lower plenum into the upper plenum to simulate the liquid transfered to this region during lower plenum flashing. A level forms in the lower plenum which leads to parallel channel interactions. This level, which adjusts itself to system conditions, is higher than the jet pump tailpipe openings, thus preventing steam from venting out through this flow path. The bypass and upper plenum becomes filled with mixtures of steam and water. Figure 28 shows that prior to 630 seconds, while liquid is still being injected into the upper plenum, the following parallel channel flow regimes exist: (a) peripheral channels 4 and 5 are in liquid downflow, (b) channels 26 and 54 are in co-current upflow, and (c) channels 12 and 40 are in counter-current flow. The core pressure drop is 44 in. water.

Period 2 - begins when the liquid injection into the upper plenum is turned off at 630 seconds. The upper plenum drains very rapidly as can be seen in Figure 28. This liquid drains through three flow paths. They are: (1) the liquid downflow channels, (2) upper tie plate CCFL drainage to the counter-current flow channels, and (3) to the bypass and then through the lower tie plate holes to the channels.

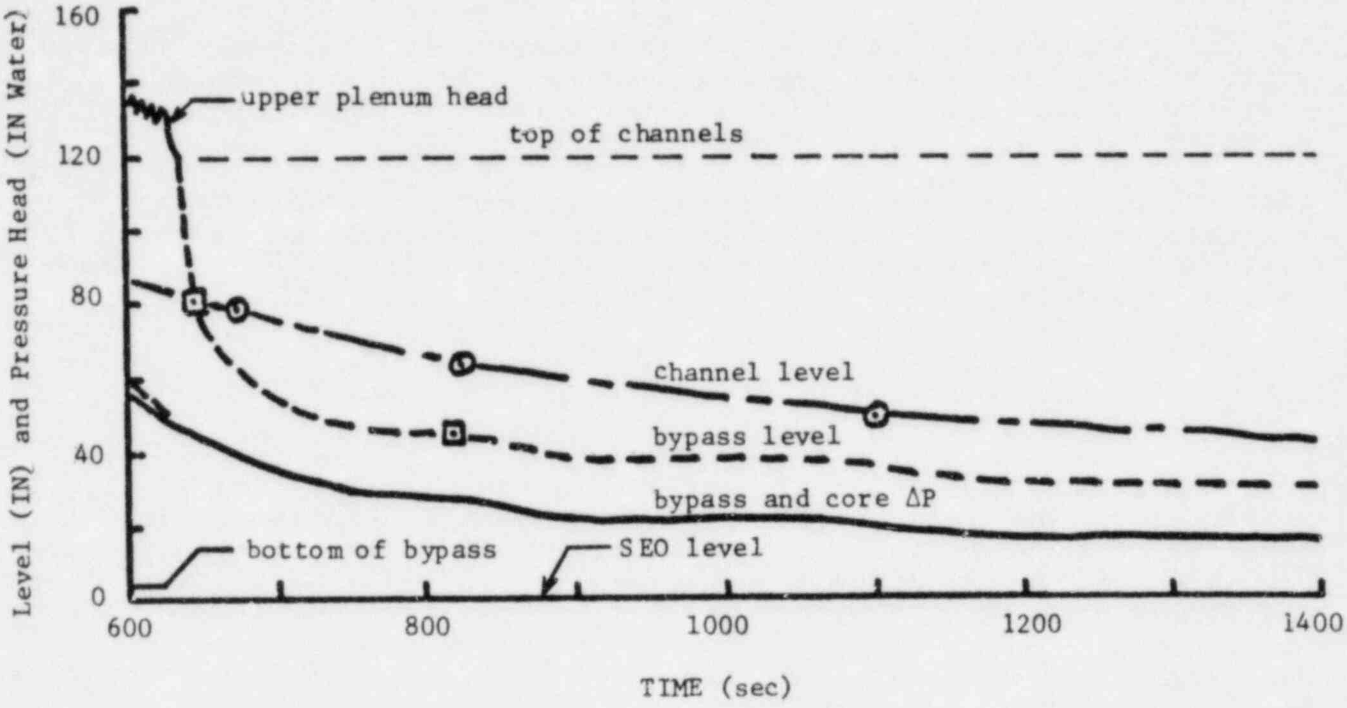
Parallel channel flow effects produce this rapid upper plenum draining. The peripheral downflow channels drain liquid from the upper plenum directly to the lower plenum. Less obvious are the effects of co-current upflow. The co-current upflow channels vent some of the

Figure 28

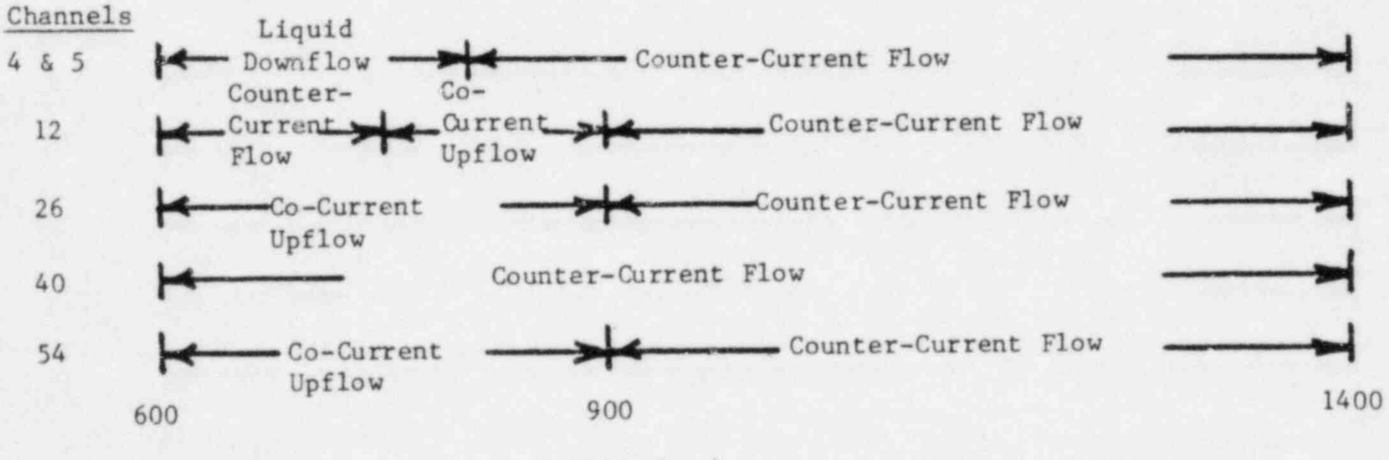
DRAINING OF UPPER PLENUM, CORE, AND BYPASS

(SRT-3 RUN 26)

(a) Pressure Heads and Levels



(b) Parallel Channel Flow Regimes



steam out of the lower plenum thus allowing more CCFL drainage from the counter-current flow channels. This increases the upper plenum drainage rate while still maintaining a liquid inventory in the channels.

These phenomena can be illustrated by applying the principles discussed in section 3.0 (see Figure 15). Without any co-current upflow channels, the 46,000 lb/hr of lower plenum steam injection used in test SRT-3 Run 26, would reduce the CCFL drainage through the inlet orifices to approximately zero. Thus the channels would be full and the upper plenum would not drain.

As discussed earlier, in a multi-channel core, this condition forces some of the channels to undergo a transition to co-current upflow, thus diverting steam away from the counter-current flow channels. The impact of this steam redistribution on the upper plenum drainage can be conservatively estimated by balancing the upper tie plate CCFL drainage from the upper plenum into the channels, with the orifice CCFL drainage out of the channels. This is illustrated in Figure 29. The bypass to channel flow has been neglected. For a core steam injection rate of 55,000 lb/hr (SRT-3, Run 26) the estimated lower plenum steam flow to the counter-current flow channels is reduced from 46,000 lb/hr to 9,000 lb/hr. This increases the upper plenum and SEO drainage estimate from zero to 490 GPM, thus draining the 888 lb of upper plenum mass in an estimated 15 seconds. The test data in Figure 28 shows this draining actually occurring in 10 seconds, due to the additional effects of bypass to channel flow.

In this test, as in all of the SSTF tests, the lower plenum level is always high enough to prevent steam from venting out the jet pumps. This phenomenon continues to hold liquid in the channels even after the upper plenum has drained. This is illustrated in the next period.

During period 3 - the upper plenum is empty and no longer supplying water to the channels through the upper tie plates. Liquid drains from the bypass to the channels and these two regions drain slowly together as shown in Figure 28. In the first 100 seconds after the upper plenum drains, the core pressure drop declines from 44" water to 31.6" water, a loss of approximately 28% of the core mass. The ECCS injection and start of refill-reflood in the BWR would occur within 30 seconds after the upper plenum has drained. Therefore, it is estimated that a smaller per cent of the core mass would be lost in the BWR.

To obtain a more bounding test result, the SSTF core was allowed to drain for 750 seconds to a collapsed level of 16.5" water before blowdown was initiated. Over the last 200 seconds, SEO CCFL shut off all channel drainage. All of the channels had by this time transitioned to counter-current flow as seen in Figure 28.

After the upper plenum drained, the core pressure drop curve in Figure 28 shows a declining core drainage rate as the mass decreases. This is consistent with the channel interaction phenomena discussed in section 3.0. As the core pressure drop decreases, as shown in Figure 30, less lower plenum steam vents through the co-current upflow channels. More steam now flows to the counter-current flow channels thus reducing the CCFL drainage rate through the SEO. Eventually the core pressure drop decreases to point (2) in Figure 30 where the co-current upflow channels transition back to the counter-current flow regime. This occurs at 900 seconds into the core drainage period of the test as

Figure 29

UPPER PLENUM DRAINAGE

- NO ECCS INJECTION
- NEGLECT BYPASS DRAINAGE; $W_{FSEO} \approx W_{FUTP}$
- DRAINAGE CONTROLLED BY UTP CCFL; $-\dot{M}_{UP} \approx W_{FUTP}$
- LOWER PLENUM STEAM SPLIT; $W_{G_{LP}} = W_{G_{SEO}} + W_{G_K}$

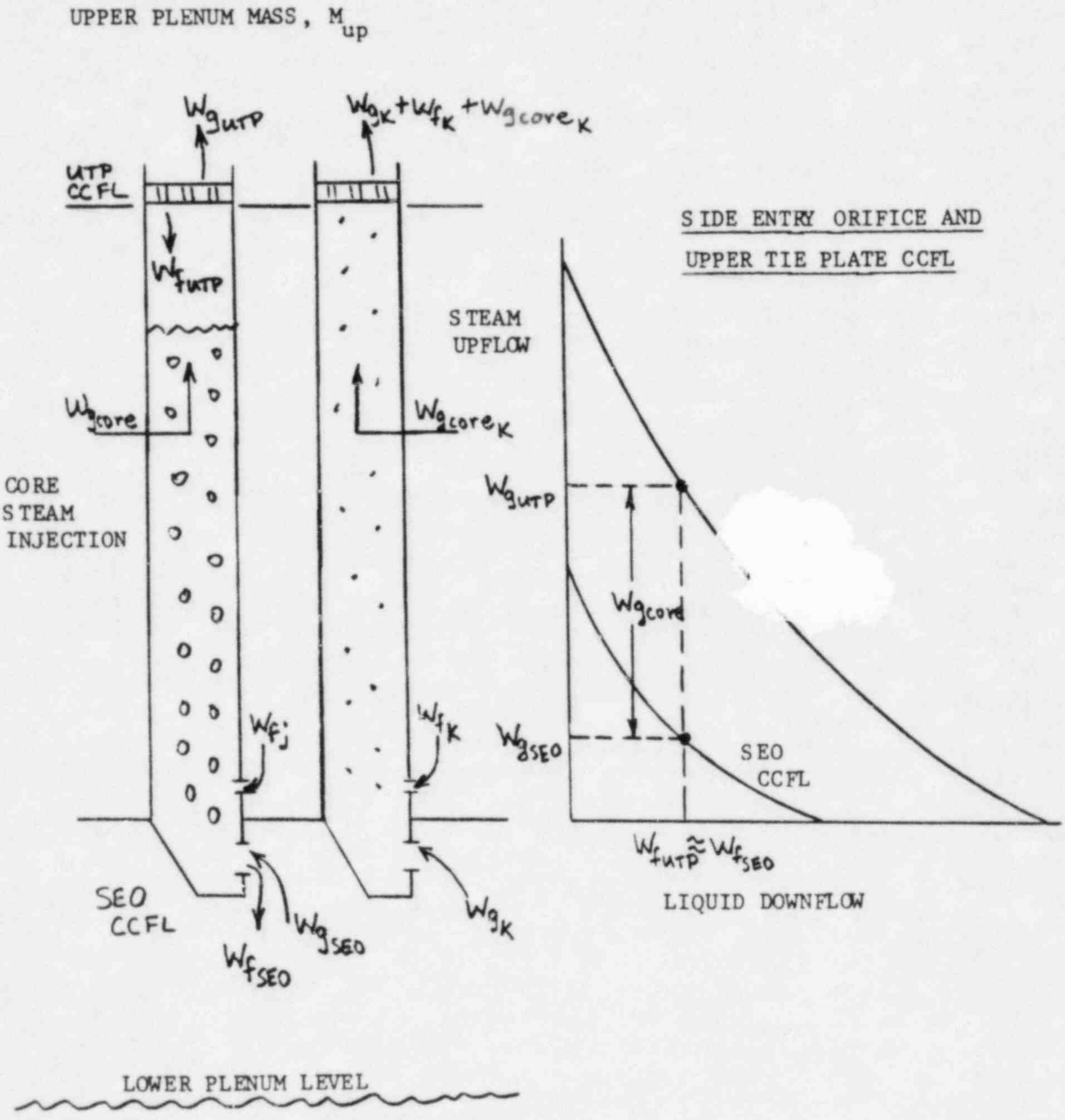
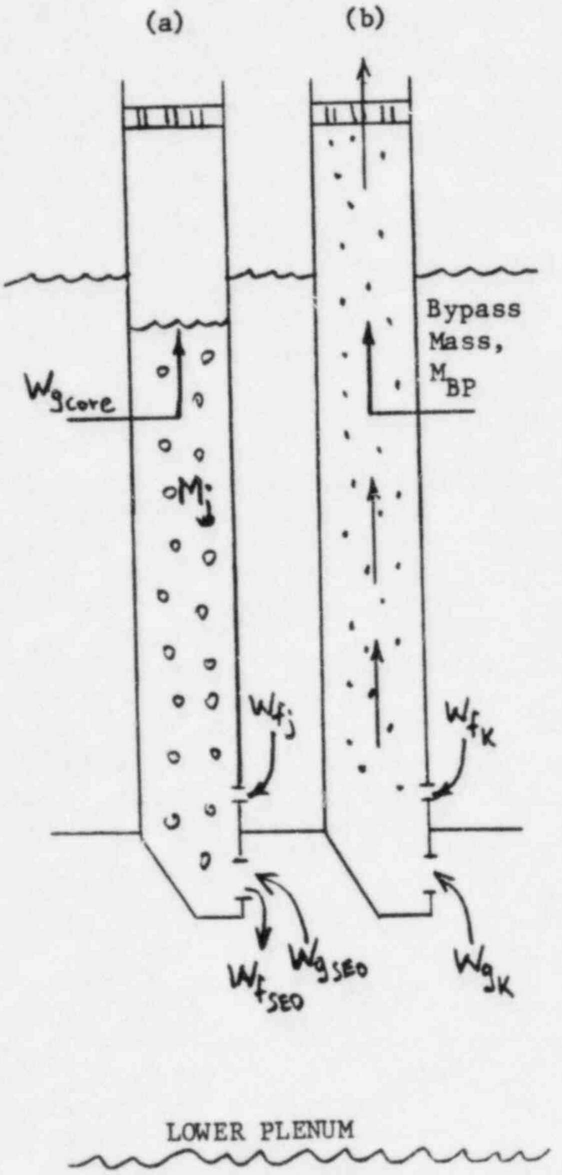


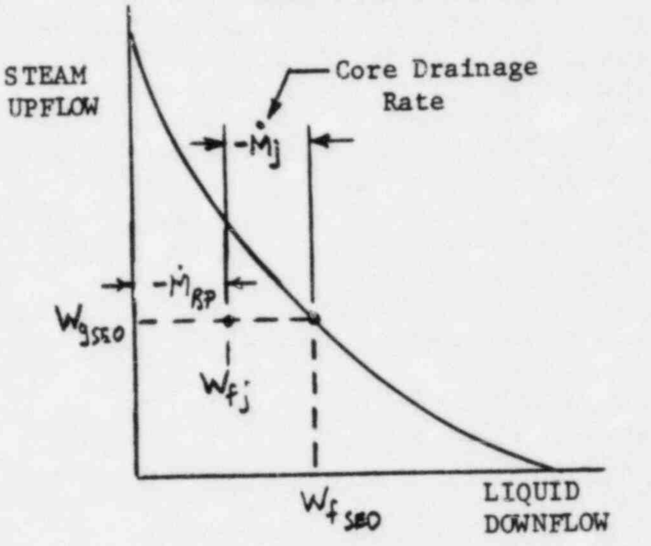
Figure 30

CORE AND BYPASS DRAINING

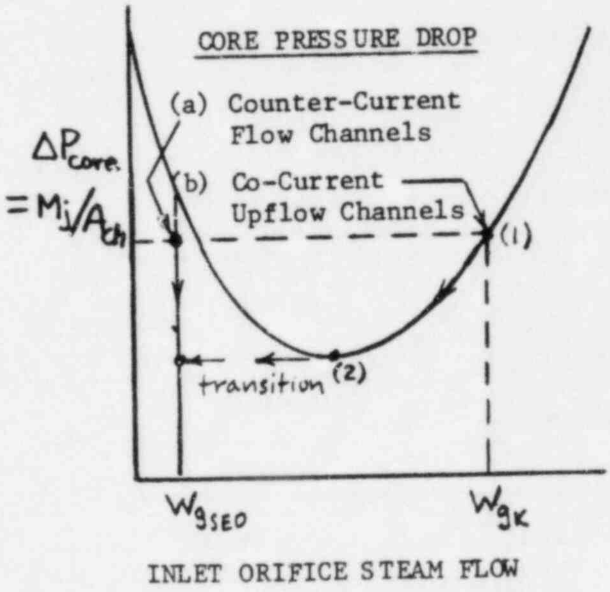
- NO ECCS INJECTION
- BYPASS, CORE DRAIN SIMULTANEOUSLY; $-\dot{M}_j/A_{CH} \approx -\dot{M}_{BP}/A_{BP}$
- DRAINAGE RATE; $-\dot{M}_j - \dot{M}_{BP} = W_{F_{SEO}}$
- LOWER PLENUM STEAM SPLIT; $W_{G_{LP}} = W_{G_{SEO}} + W_{G_K}$
- DECREASED LEVEL (ΔP_{CORE}), SLOWER DRAINAGE (W_{FSEO})



SIDE ENTRY ORIFICE CCFL



CORE PRESSURE DROP



seen in Figure 28. The rate at which the core is draining declines to almost zero at this point where CCFL at the SEO dominates.

This test illustrates the effects of parallel channel flow during the post lower plenum flashing phase of the LOCA prior to ECCS initiation. Rapid upper plenum drainage and slow core drainage are observed and verified as being consistent with the parallel channel phenomena discussed in section 3.0.

5.3 Reference System Response Test SRT-3 Run 26

This test is the reference BWR/6 refill-reflood transient. It is the continuation of the initial conditions test discussed in section 5.2, and commences when the break flow and ECCS injection are initiated. The system conditions at the beginning of the transient blowdown are shown in Figure 31. The core and bypass are partially drained and the steam injection rates simulate the depressurization flashing and decay heat transfer vaporization. As the system starts depressurizing after break initiation, the steam injection that simulates the flashing for initial set-up is turned off.

The purpose of this discussion is to define the parallel channel phenomena during the refill-reflood transient. As will be seen, core reflooding occurs rapidly. Figure 32 summarizes the reflooding response of the channels.

Initiation of the LPCI injection into the bypass at its periphery, very rapidly fills this region as seen in Figure 32. The spray flow, which comes on at the same time as the LPCI, also contributes to the rapid filling of the bypass. The multi-dimensional characteristics of the top of the bypass prevent any counter-current flow limitation of the upper plenum drainage to the bypass, as previously observed in steady pressure tests.

Filling of the bypass is an important step in the refill-reflood process. The bypass liquid flows into each of the channels through the lower tieplate holes and finger spring flow paths. A large portion of this liquid is held in the channels by CCFL at the side-entry orifices. This leads to the rapid re-flooding of the channels as illustrated in Figure 32. Test measurements confirm that all channels have the same pressure drop (Pcore). This insures that each channel contains a coolant mixture.

The counter-current flow channels each contain an equal amount of mass because their pressure drops are entirely static head. Refilling of these channels is speeded by CCFL controlled drainage into the channels from the upper plenum. The rate at which they reflood is determined by the difference between the flow into the channels and the CCFL drainage out at the SEO, as illustrated by Figure 33. The total SEO steam flow to the counter-current flow channels is determined by how much of the lower plenum steam vents through the co-current upflow channels and out the jet pumps. The rising core level must, of course, be supported by the jet pump head. This head limits the final core reflood head. The final level is a function of the channel void fraction.

Initially all of the SSTF channels are in counter-current flow.

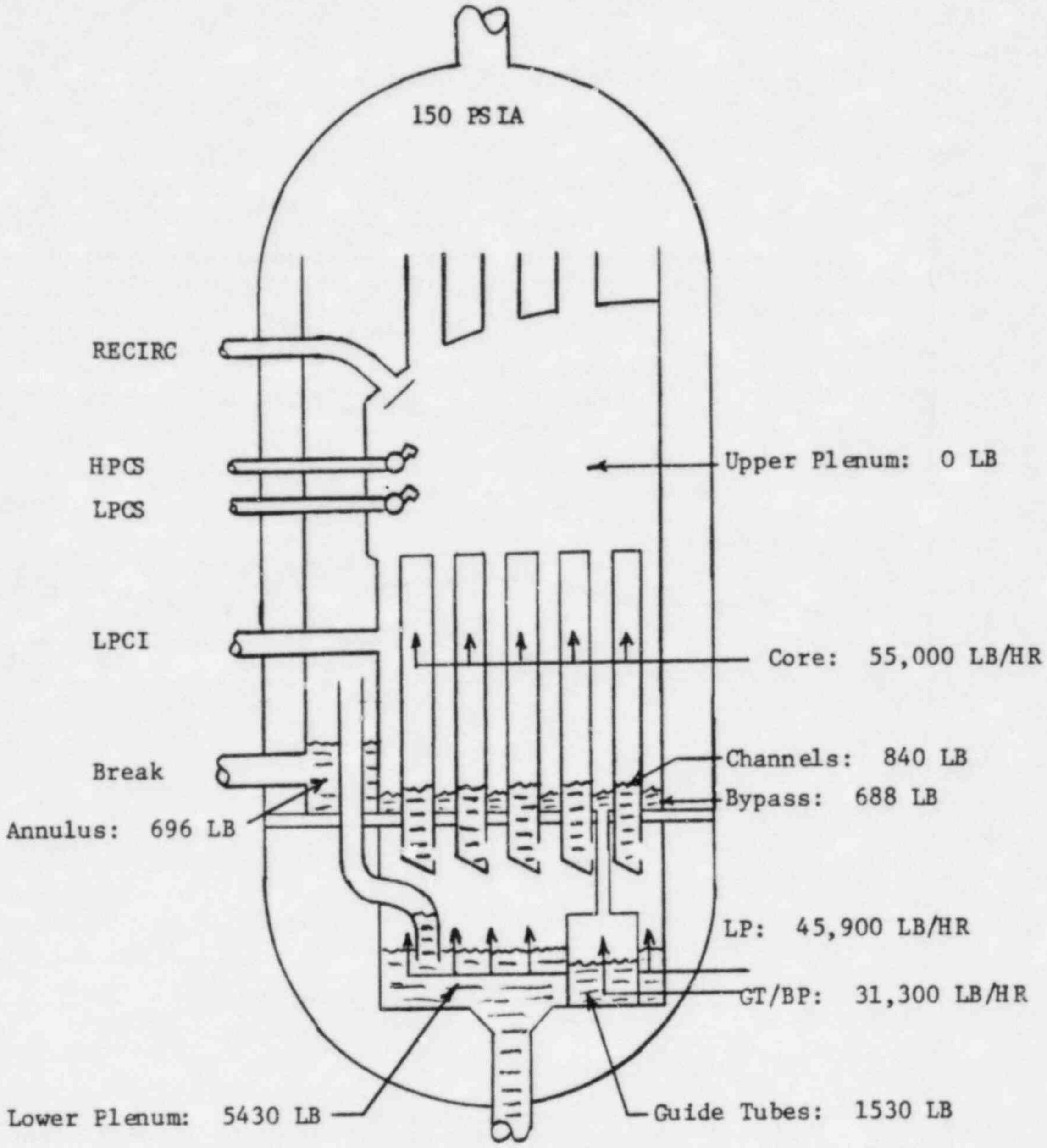


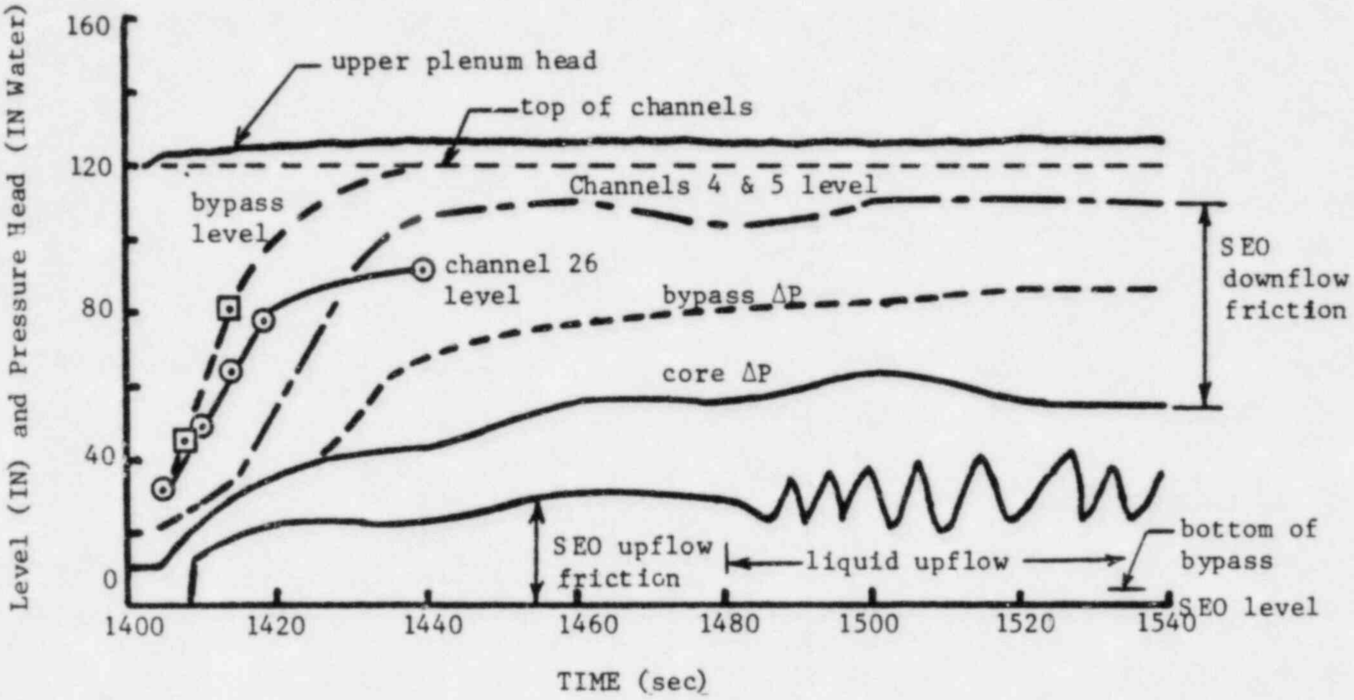
Figure 31

INITIAL CONDITIONS FOR REFERENCE SYSTEM RESPONSE TEST SRT-3 RUN 26

Figure 32

REFILL-REFLOOD SYSTEM RESPONSE TEST SRT-3 RUN 26

(a) Pressure Heads and Levels



(b) Parallel Channel Flow Regimes

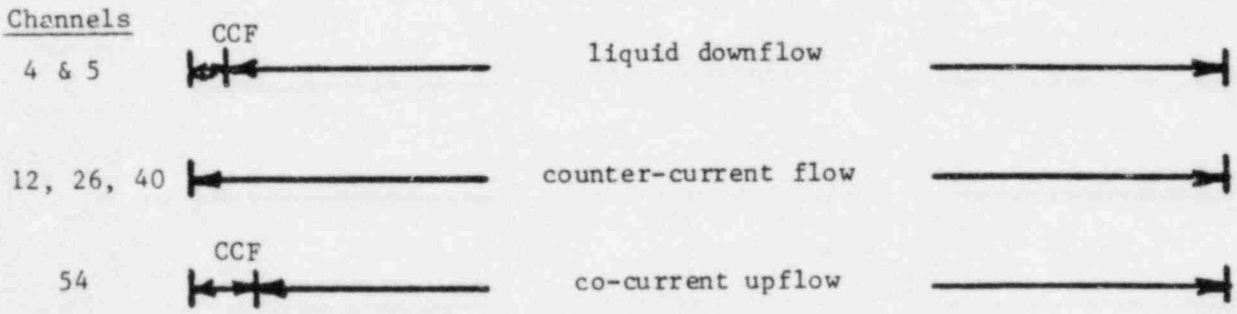
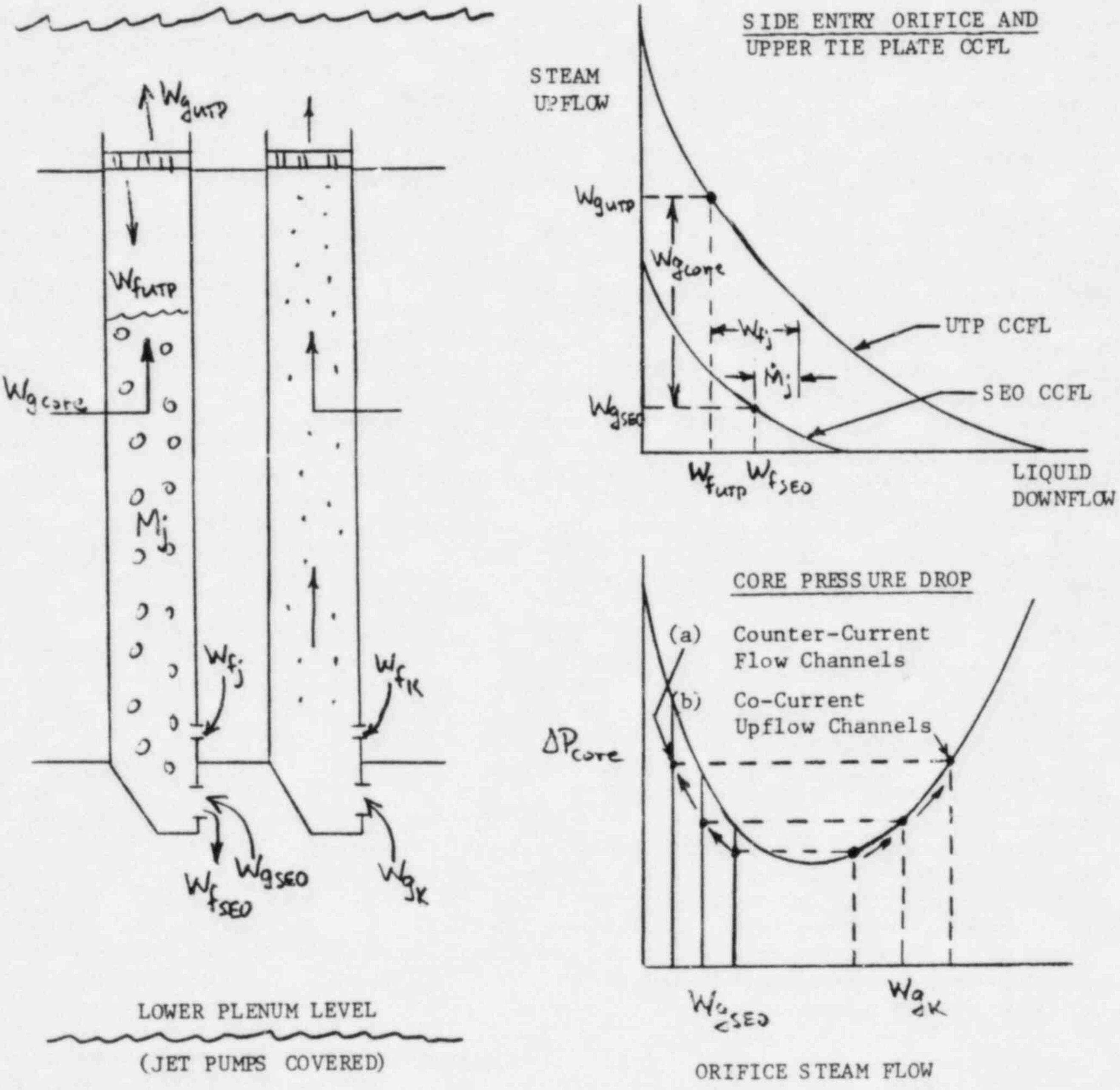


Figure 33

REFLOODING OF COUNTER-CURRENT FLOW CHANNELS

- REFLOOD RATE; $\dot{M}_j = W_{F_{UTP}} + W_{F_j} - W_{F_{SEO}}$
- DRAINAGE FROM BYPASS = W_{F_j}
- UTP STEAM: $W_{G_{UTP}} = W_{G_{SEO}} + W_{G_{CORE}}$
- LOWER PLENUM STEAM SPLIT: $W_{G_{LP}}{}' = W_{G_{SEO}} + W_{G_K}$



Between five and ten seconds into the blowdown transient, certain channels are observed to transition to either liquid downflow or co-current upflow.

Peripheral channels 4 and 5 experience subcooled CCFL breakdown at the UTP and transition to liquid downflow. The CCFL breakdown is confirmed by the UTP subcooled temperature measurements. The liquid downflow is evident by the SEO friction drop shown in Figure 32. This friction drop, which in 40 seconds peaks at 63" water, is a measure of the flow rate. This friction also supports a greater static head, and therefore mass inventory, in these channels as compared to the counter-current flow channels (Figure 32). Liquid downflow through the peripheral channels speeds drainage of the upper plenum and refilling of the lower plenum.

One of the multi-dimensional responses observed during the early part of this test is the development of a radial gradient in the bypass head, as summarized in Table 4. This is caused by the LPCI water, which is injected at the periphery, having to flow radially inward past the channel boxes and control blades. The result of this phenomena is that the center channel, number 54, initially does not receive as much liquid from the bypass as the other measured channels. It is, therefore, unable to fill as rapidly as these channels, and presents a lower resistance flow path for lower plenum steam to escape through. A transition to co-current upflow at approximately 8 seconds then occurs. The resulting SEO steam friction, shown in Figure 32, creates a relatively low pressure in the region of the lower tie plate holes. This pulls more liquid from the bypass into this channel than the counter-current flow channels receive. This liquid is swept through the bundle by the upflowing steam, thus filling the entire channel with a coolant mixture within 8 seconds.

Channel 54 remains in steam upflow through the SEO until the rising lower plenum level is high enough that an increasing amount of liquid is carried through the SEO. When the lower plenum fills completely, the parallel channel phenomena discussed here no longer exist. The level in the lower plenum then holds water in all the channels.

There is an additional parallel channel phenomena observed in this test that needs to be discussed. Subcooling was measured at some of the side-entry orifices but no sustained draining of these channels followed as has occurred in single channel facilities. This is explained by two facts. First there is a large quantity of lower plenum steam available to any channel with SEO subcooling and it cannot all be condensed by these few channels, as can occur in single channel facilities. Secondly, all channels are bounded by the same plenum-to-plenum core pressure drop. Individual channels, therefore, cannot drain independent of the remaining channels. If an individual channel starts to experience drainage due to subcooled SEO CCFL breakdown, more lower plenum steam will flow to this reduced resistance flow path and hold up the liquid. As previously discussed, this periodic subcooled breakdown of CCFL is confirmed by the SEO temperature cycles.

This system response test demonstrates that there is no delay in the core reflood. All channels reflood rapidly to a level that is supported by the jet pump head. The parallel channel phenomena that insure the presence of a coolant mass in every channel are understood and consistent with the explanations given in section 3.0.

TABLE 4

PRESSURE HEAD GRADIENT IN BYPASS

(TEST SRT-3 RUN 26)

(Inches of Water)

TIME (sec)	Peripheral Bypass Head	Center of Core Bypass Head	Bypass Head Gradient
1405	13.4	11.0	2.4
1410	21.9	19.3	2.6
1415	38.6	30.4	8.2

6.0 Conclusions

(1) Parallel channel flow occurs in multi-channel BWR- like cores. The required conditions are that a level in the lower plenum allows redistribution of steam to the channels, and liquid is held in the channels by CCFL at the SEO.

(2) There are three parallel channel flow regimes. These regimes can occur simultaneously. Most of the core is in the counter-current flow regime, controlled by CCFL at the SEO. The peripheral channels tend to be in liquid downflow. A few central channels are in co-current upflow.

(3) A coolant mixture is present in all channels. Equal pressure drops insures liquid hold-up in every channel either by CCFL at the SEO, SEO liquid downflow friction, or SEO steam upflow friction.

(4) Parallel channel flows rapidly drain the upper plenum. The result is that more mass is retained in the lower plenum, than in comparable one-dimensional facilities, with steam and water loss out the jet pumps minimized.

(5) Even without ECCS operation, the core drains very slowly. This is due to the minimal loss of steam out the jet pumps, and parallel channel effects that increase the fraction of lower plenum steam redistributed to the SEO's in CCFL as the core drains.

(6) The initiation of ECCS coolant injection refloods the core rapidly. There is no delay in channel reflood due to upper plenum mass hold-up, or liquid and steam lost out the jet pumps.

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NOMENCLATURE

A	Flow Area (ft^2)
CE	Conductivity Element
F	Function
F_{CCFL}	CCFL Correlation
F_{α}	Void Fraction Correlation
g	32.2 ft/sec^2
K	Flow Loss Factor (Dimensionless)
M	Mass (lb)
$\dot{M}$	Mass Accumulation Rate (lb/sec)
DP	Pressure Difference (in. H_2O)
ΔP	Pressure Difference (lb/ft^2)
W	Mass Flow Rate (lb/sec)
Z	Elevation (ft)

Greek

α	Void Fraction
ϕ^2_{lo}	Two Phase Multiplier
ρ	Density (lb/ft^3)

Subscripts

CCFL	Counter Current Flow Limiting (Flows)
ch	Channel
core	Core
f	Saturated Liquid
g	Saturated Steam
i	Peripheral Channels
j	Counter-Current Flow Channels
k	Co-Current Upflow Channels
LP	Lower Plenum
SEO	Side Entry Orifice
UTP	Upper Tie Plate

APPENDIX A

Application to SSTF Initial Conditions Scaling

1.0 Summary

The SSTF separate effects tests show parallel channel flow effects which are not included in single channel models that were used to estimate the target initial conditions for the SSTF system effects tests.

The parallel channel effects, which are evaluated in this report have been studied to determine the impact on the LOCA scenario and the target initial conditions. The resulting updated target initial conditions consist of a zero upper plenum mass (no ECCS injection and more rapid draining due to parallel channel flow), larger lower plenum mass (no jet pump uncovery due to a small upper plenum static head), and smaller bypass and channel masses (to give more bounding results).

The SSTF initial conditions tests, which are part of the separate effects test group, have set the conditions leading to the target values, confirming that they are physically representative.

2.0 Introduction

Initial conditions scaling for the SSTF is discussed in (Reference A-1). In that document it is pointed out that the methods used to estimate the initial conditions have some limitations, and the target conditions would be updated when as-built SSTF performance calibration data had been evaluated. The SSTF separate effects tests have been completed and the evaluation of this data used to update the target initial conditions.

The initial conditions are updated for two reasons: (1) to account for the parallel channel flow effects that had not been considered, (2) to simulate conditions prior to ECCS injection. The initial system masses are updated by estimating the impacts of the parallel channel effects and of not including the HPCS injection. The single channel mass predictions are then modified accordingly.

3.0 Effects of No HPCS Injection (Single Channel Model)

The LOCA transient simulating a single ECCS failure leaving the HPCS, LPCS, and one LPCI active, includes HPCS injection and added mass to the upper plenum early in the transient. The added upper plenum mass is predicted to depress the lower plenum level more quickly than in the non-HPCS case, which results in jet pump uncovery and consequent increased steam leakage out the jet pumps. This event is not predicted to occur in the non-HPCS case (1 LP CS + 3 LPCI), thus giving a larger lower plenum mass and smaller upper plenum mass for this case.

The non-HPCS LOCA transient is a more conservative accident to simulate because of the larger refill system mass required at ECCS initiation, and the delayed subcooled injection which delays CCFL breakdown.

4.0 Impact of Parallel Channel Effects

Parallel channel effects are not expected to have any significant impact on the LOCA transient until a level forms in the lower plenum. This event, which allows steam communication between the channel side-entry orifices, is estimated to occur at about 33 seconds.

After 33 seconds the single channel estimates must be modified to include the effects of parallel channel flow. As this calculation has not been made using the BWR TRAC code, the modifications are made qualitatively based on SSTF separate effects test results.

A conservative estimate of the time required to drain the upper plenum can be made by neglecting the lower tie plate (LTP) hole leakage to the channels and considering only the upper tie plate (UTP) CCFL drainage. This drainage, for the saturated case, is a function of the core steam rate and the SEO CCFL steam flow, as shown in Figure 28. This method estimates the time to drain the upper plenum mass (1072 lb. at 33 sec.) to be between 13 and 28 seconds. Since the time from lower plenum level formation (33 sec.) to test initiation at 150 psia (63.5 sec.) is 30.5 sec., the LOCA test initial upper plenum mass should be zero.

The lower plenum mass will be greater than the 1945 lb. estimated from the single channel model (level at jet pump): however, it should be less than the mass when full of two-phase mixture (6786 lb.). The SSTF LOCA test variation of initial mass covers the expected range.

The guide tube mass is not affected by the parallel channel response. Therefore, the initial mass of 1675 lb. predicted by the single channel method is appropriate.

The annulus level is at the recirculation line at test initiation, with a liquid mass of 600 lb. There is no change in this initial mass due to parallel channel effects.

The bypass and channels will be partially drained at test initiation and the masses in these two regions should be less than 1000 lb. and 1383 lb. respectively, which are the masses when full. This mass will drain into the lower plenum. The modified initial mass estimates are summarized in Table A.1. The partially drained masses were obtained from test SRT-3 Run 26 initialization (see Figure 31). The original masses from the single channel model estimates are included for comparison. The actual reference case initial masses are also included showing the partial draining of the channels and bypass. Table A.2 compares the multi-channel and single channel conditions at the beginning of the blowdown.

TABLE A-1

SSTF INITIAL MASSES

REGION	SINGLE CHANNEL	MULTI-CHANNEL	REFERENCE CASE (#26)
Upper Plenum	2360	0 (1)	0
Lower Plenum	1945	4305 (2)	5430 (4)
Guide Tubes	1675	1675	1530
Annulus	600	600	696
Bypass	1000	1000 (3)	688 (4)
Core	1383	1383 (3)	840 (4)
TOTAL	8963	8963	9184

(1) Upper Plenum drains

(2) Jet pumps covered

(3) Regions full

(4) Core and bypass partially drained to lower plenum

TABLE A-2

COMPARISON OF SINGLE AND MULTI-CHANNEL INITIAL CONDITIONS

REGION	MULTI-CHANNEL	SINGLE CHANNEL
Upper Plenum Mass	No	Yes
Lower Plenum Level	Above Jet Pump	Below Jet Pumps
Core Flow Regimes	Parallel Channel Flow Regimes	Counter-Current Flow
Channels	Draining	Draining
Bypass	Draining	Draining

References:

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This report interprets the results from SSTF separate effects tests and system response tests and evaluates the parallel channel flow phenomena.

Parallel channel flow of interest occurs when there is a level in the lower plenum which allows redistribution of steam to the channel inlet orifices. Parallel channel effects are evidenced by three different flow regimes that may occur simultaneously. These regimes, identified from SSTF tests, are: (1) counter-current flow, (2) co-current upflow, and (3) liquid downflow.

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