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STEAM CONDENSATION AND LIQUID HOLDUP IN STEAM GENERATOR U-TUBES DURING OSCILLATORY NATURAL CIRCULATION

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Flow oscillations during two-phase natural-circulation experiments for pressurized water reactors (PWRs) with inverted U-tube steam generators occur at high pressure and at a primary inventory range between two-phase circulation and reflux heat removal. These oscillations, originating in the steam generator U-tubes, consist of alternating phases of (1) interrupted (or stalled) flow and (2) rapid two-phase circulation. Using integral system data from LOBI-MOD2 experiments, it is demonstrated that the predominant mechanism that governs the duration of the interrupted flow phase is steam condensation at the top of the U-tubes. The frequency is not governed by mechanisms related to limitation of countercurrent flow (CCFL). The article also discusses the possible mechanisms of liquid holdup in the vertical U-tube region, necessary to have a closed condensation space. This may be CCFL but could also be simply related to the water inventory in the circuit. Furthermore, the influence of pressure is discussed, showing that the phenomenon can truly be observed only in a high-pressure facility.

In many accident scenarios, natural circulation is an important heat transport mechanism for long-term cooling of light water reactors. In the event of a small pipe break, with subsequent loss of primary cooling fluid (LOCA), or under abnormal operating conditions, early tripping of the main coolant pumps can be actuated. Primary fluid flow will then progress from forced to natural convection. Understanding of the flow regimes and heat removal mechanisms in the steam generators during the entire transient is of primary importance to safety analysis.

This article deals with the oscillatory flow behavior that was observed during the transition period between two-phase natural circulation and reflux condensation. These oscillations consist of alternating phases of stalled flow and rapid two-phase circulation in the inverted steam generator U-tubes. When the flow in parallel U-tubes oscillates in phase, the oscillations can eventually extend to the entire cooling circuit and have implications for the coolant distribution inside the primary system and for the core coolability. Flow oscillations during natural circulation have been observed in integral system facilities in the high-pressure range, Semiscale [1], LPTF [2], and in ad-hoc test apparatus in the low-pressure

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NOMENCLATURE

A	cross-sectional area
D	mean diameter
g	gravity acceleration
h	heat transfer coefficient
L	length of heat transfer area in the U-tube
L_0	length for arrested wedge
$\dot{m}$	mass flow
N_t	number of U-tubes
$\dot{Q}$	energy transfer rate
r	evaporization heat
T	time duration of a phase
v	fluid velocity
$\dot{V}$	volumetric flow
x	vapor quality
α	void fraction
δ	thickness of U-tube wall
η	kinematic viscosity
λ_w	heat conduction coefficient in U-tube wall
ρ	fluid density

Subscripts

bottom	bottom of U-tubes
c	condensation
c.o.	carryover phase
ex	exchanged
HL	hot leg
s	steam
st	stalled phase
t	single U-tube
top	top of U-tubes
w	water, wall
x	position in U-tube
i	inner surface
o	outer surface

range [3, 4]. De Santi [5] identified these oscillations as occurring in the transition region between two-phase circulation and reflux condensation during the LOBI experiments. The knowledge of basic mechanisms governing heat removal and liquid holdup in complex multitube steam generators still needs further development.

Based on results from low-pressure experiments, the onset of flow oscillation during reflux condensation was related to the occurrence of flooding in the vertical pipes [6, 7]. CCFL would allow only part of the condensate to flow backward from the U-tubes to the core and the remainder to be dragged upward and held up by the steam. A liquid column developed in the U-tubes above the two-phase condensation region, establishing an increasing gravitational pressure drop that reduced the water inventory, i.e., depressed the water level, in the core.

This article demonstrates that the mechanism that forms the liquid column may not necessarily be CCFL; it may also be simply a "loop full" condition. During the stalled phase, liquid accumulates in the vertical steam generator tubes by condensation of primary vapor at the top of U-tubes. As the liquid column reaches the top elevation, it can flow over the U-bend and reestablish a rapid two-phase circulation (carryover phase). This cycle does not require CCFL. The liquid column in the rising leg, necessary for formation of a closed steam condensation volume, may be formed simply at a relatively high primary inventory.

The article is divided into three parts. The first part gives a description and physical interpretation of the oscillations measured in the LOBI experiment [8]. Then the frequency of flow oscillations is calculated by the speed of steam condensation. Finally, mechanisms of liquid holdup are discussed and results are compared to measurements from low-pressure experiments.

EXPERIMENTAL APPARATUS

The LOBI-MOD2 Experimental Facility, see Figure 1, is a scaled model of a nuclear pressurized water reactor cooling system. The reference reactor is of the electric 1300-MW Siemens KWU type. It is similar to plants built by Westinghouse, Framatome, etc. The facility is scaled 1:712 in volume and 1:1 for elevations, to conserve gravity influence during natural circulation. The nuclear fuel of the reference plant is simulated by 64 directly heated electrical heater rods with a fixed

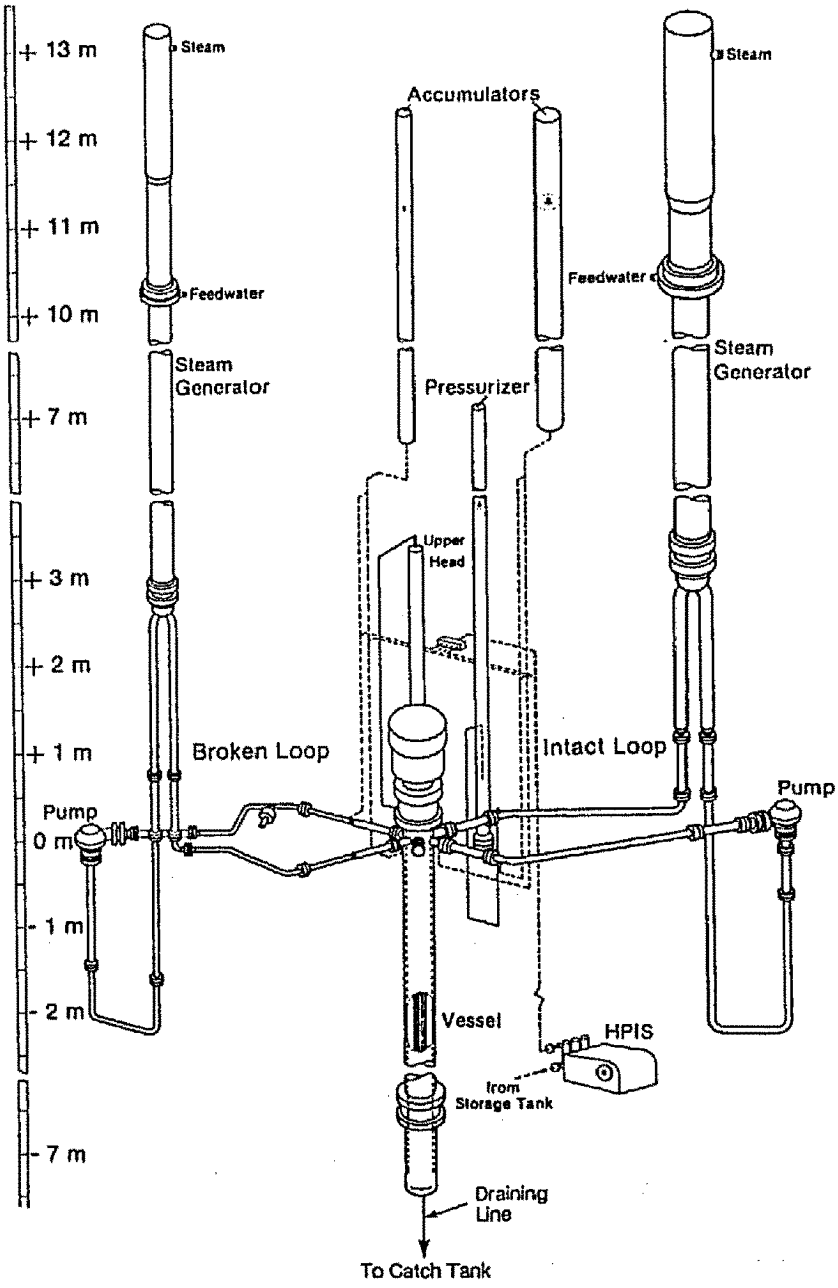


Figure 1. Primary cooling system in the LOBI-MOD2 facility. The LOBI test facility is operated at the Joint Research Centre (JRC), Ispra, of the Commission of the European Communities (CEC). A description of the LOBI facility and the test program is given in [9] and [10].

axial heating profile similar to the nuclear profile. Heating power can be continuously controlled up to 5.3 MW (1:1 power-to-volume scaling).

The LOBI facility incorporates the major components of a PWR, including steam generators, vessel, pumps, pressurizer, accumulators, HPIS, etc. The test facility has two loops. The "triple loop" represents three of the four reactor loops and has three times the volume of the "single loop." Both loops have active components as steam generators and centrifugal pumps. The two steam generators have 8 and 24 U-tubes, respectively, of about the same shape as in the reactor plant. The main coolant pumps were not used for the natural-circulation test. Pump rotors were in locked condition, and no seal water was injected into the circuit. The pressurizer was connected only at test initiation to establish subcooled natural circulation. The upper head remained valved out during the entire experiment.

Test Outline and Objectives

LOBI-MOD2 Test A2-77A simulates natural circulation at typical PWR system pressures and temperatures and at a decay heat power level. It was designed to provide representative data of the integral system response during single-phase, two-phase natural circulation and reflux condensation. The experimental data and a description of the test boundary conditions are given in [11]. The test profile is outlined in [12].

Test A2-77A consists of a sequence of steady states of decreasing primary fluid mass inventories. These steady states cover the range of single-phase and two-phase natural circulation, reflux heat removal, and intermediate situations. During the test performance, each steady state was followed by draining of a finite amount of primary water and a stabilization period prior to the measurement of the following steady state. The secondary conditions were set constant: (1) by the relief valve pressure at 8.65 MPa, leading to a secondary loop temperature of about 300°C; and (2) feedwater level control by maintaining the U-tubes covered. Core power was maintained constant at about 183 kW (3.5% of nominal power) throughout the test. Before initiation of the test, the primary loop was filled with dimeralized water and vented to ensure a liquid-full system.

The experiment started with a completely filled system in stationary conditions at 14 MPa, with subcooled single-phase natural circulation. In the single-loop steam generator, nonuniform mass flow distribution among the inverted U-tubes was measured. A mathematical model developed by Sanders [13] shows that stable parallel flow in the U-tubes can be attained when the water flows backward in some of the U-tubes.

The test continued through a sequence of steady-state conditions at decreasing primary system mass inventories, leading to two-phase natural circulation and the reflux condensation mode. As the first amount of primary coolant was drained from the vessel lower plenum, the primary pressure reduced to the saturation pressure corresponding to the coolant temperature and stabilized out at about 9 MPa for the remainder of the test. The relationship between primary system mass flow and inventory, as obtained by Test A2-77A, is shown in Figure 2. The interpretation of the integral system response during the experiments, including the most significant phenomena, is given in [8].

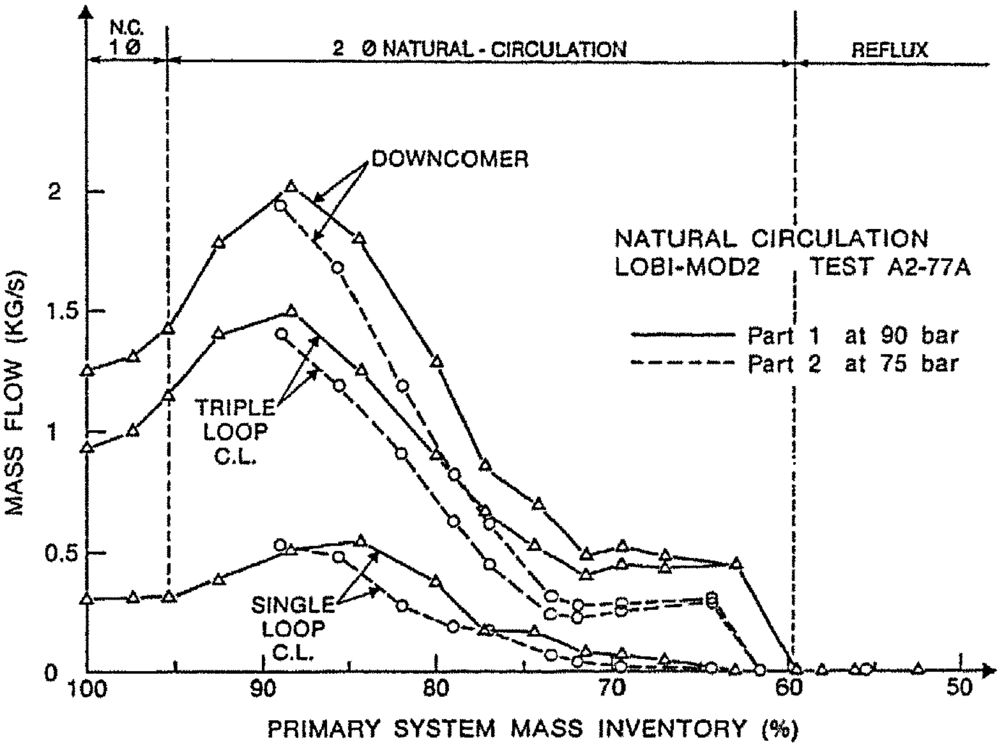


Figure 2. Primary mass flow (steady-state values).

Interpretation of Two-Phase Mass Flow Oscillations

The two-phase natural-circulation oscillations studied here started at a primary inventory below 83% of the initial value. These flow oscillations occurred in both the triple and the single loop over a wide range of mass inventories, between 83% and 52%; see Figure 3. In the single-loop steam generator, the 8 U-tubes oscillated in phase. The periodic stalling of the loops can be related to synchronized temporary cessation of flow in the individual U-tubes of the steam generators. Figure 4 shows the single-loop flow for a period during which the primary inventory was constant at approximately 74%. These flow oscillations are representative of all the flow oscillations observed in the experiment. Figure 5 shows one fluid velocity oscillation period in the hot and cold legs of the single loop together with the collapsed-level behavior in the steam generator U-tubes. Starting from a condition of "stalled" flow, at about 12,920 s in Figure 5, each single steam generator U-tube can be ideally subdivided into three distinct zones, characterized by different flow regimes, as depicted in Figure 6.1: a zone at the inlet of the tube of two-phase mixture (zone A) in which the incoming vapor bubbles condense; a zone at the top of the tube with stagnant pure vapor (zone B); and two other zones of liquid (zone C).

In the following it is explained how the flow oscillations are caused by an instability of the two-phase circulation, leading to alternating periods of two-phase circulation and stalled flow with condensation. To describe the flow oscillations we first look at the condensation of primary vapor. The flow oscillations were originated by primary vapor condensation at the top of the U-tubes (zone B). Due to water properties in the high-pressure range ($p_{\text{prim}} = 9$ MPa), the primary vapor saturation temperature above the liquid column, which reflects the pressure at the

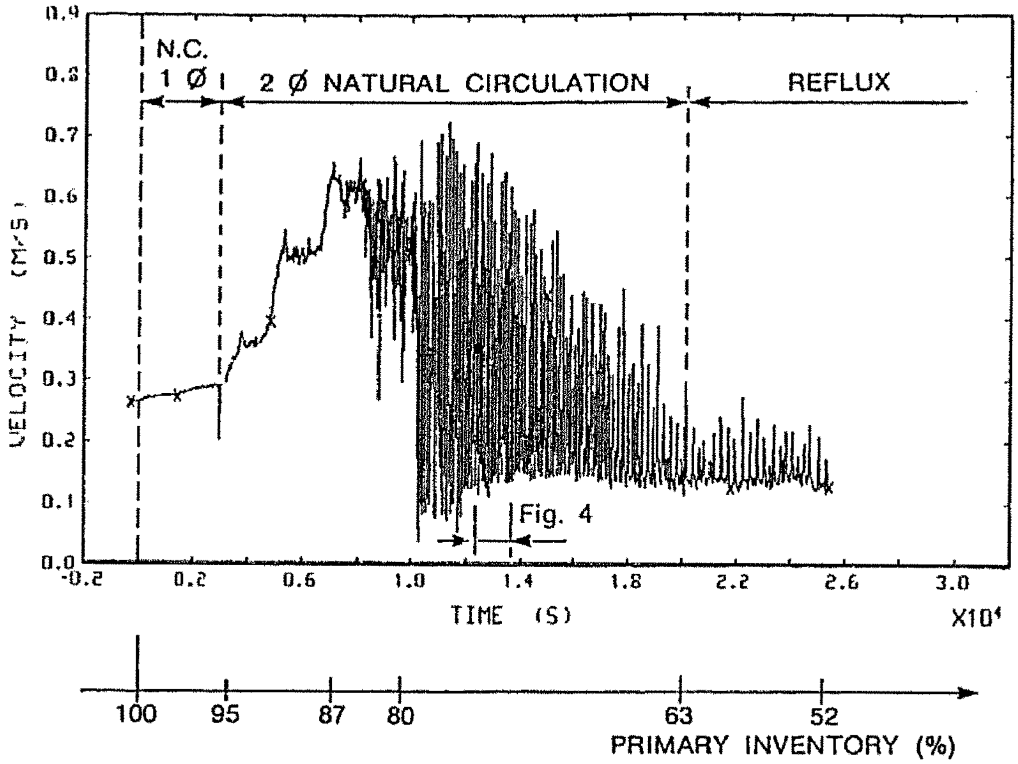


Figure 3. Hot-leg fluid velocity.

top of the U-tubes, is only about 0.5 K lower than the primary fluid saturation temperature at the tube inlet. The positive temperature difference between the primary and secondary systems condenses vapor at the top of the tubes, causing the liquid column in the ascending and descending side of the tubes (zones C) to rise. Growth of the liquid column creates an increasing gravitation pressure drop, which

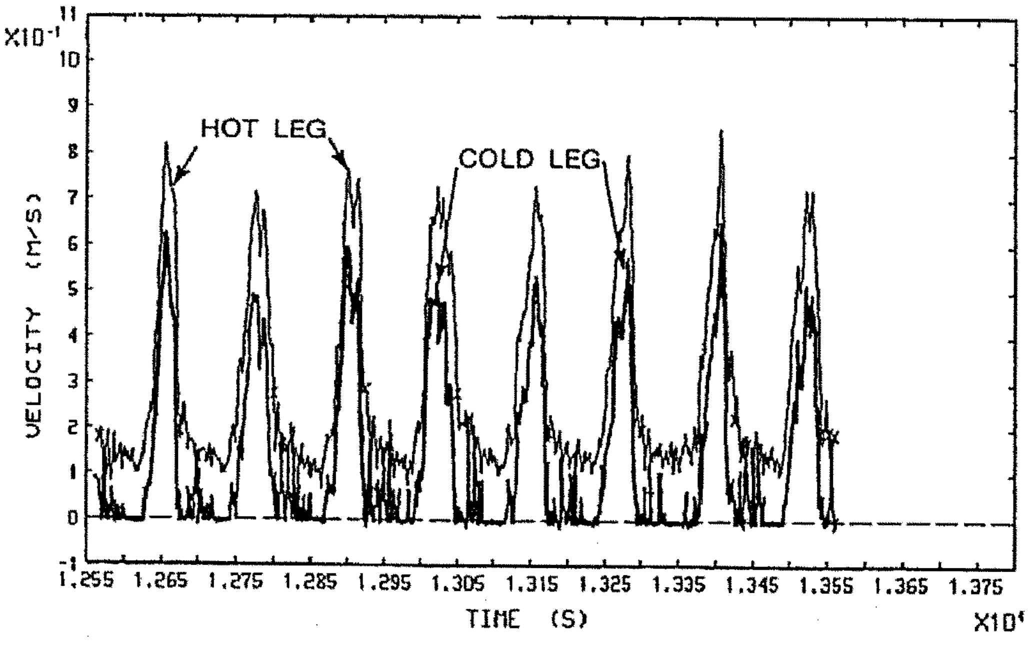


Figure 4. Oscillations of fluid velocity in hot and cold legs at 74% coolant inventory (expanded time scale).

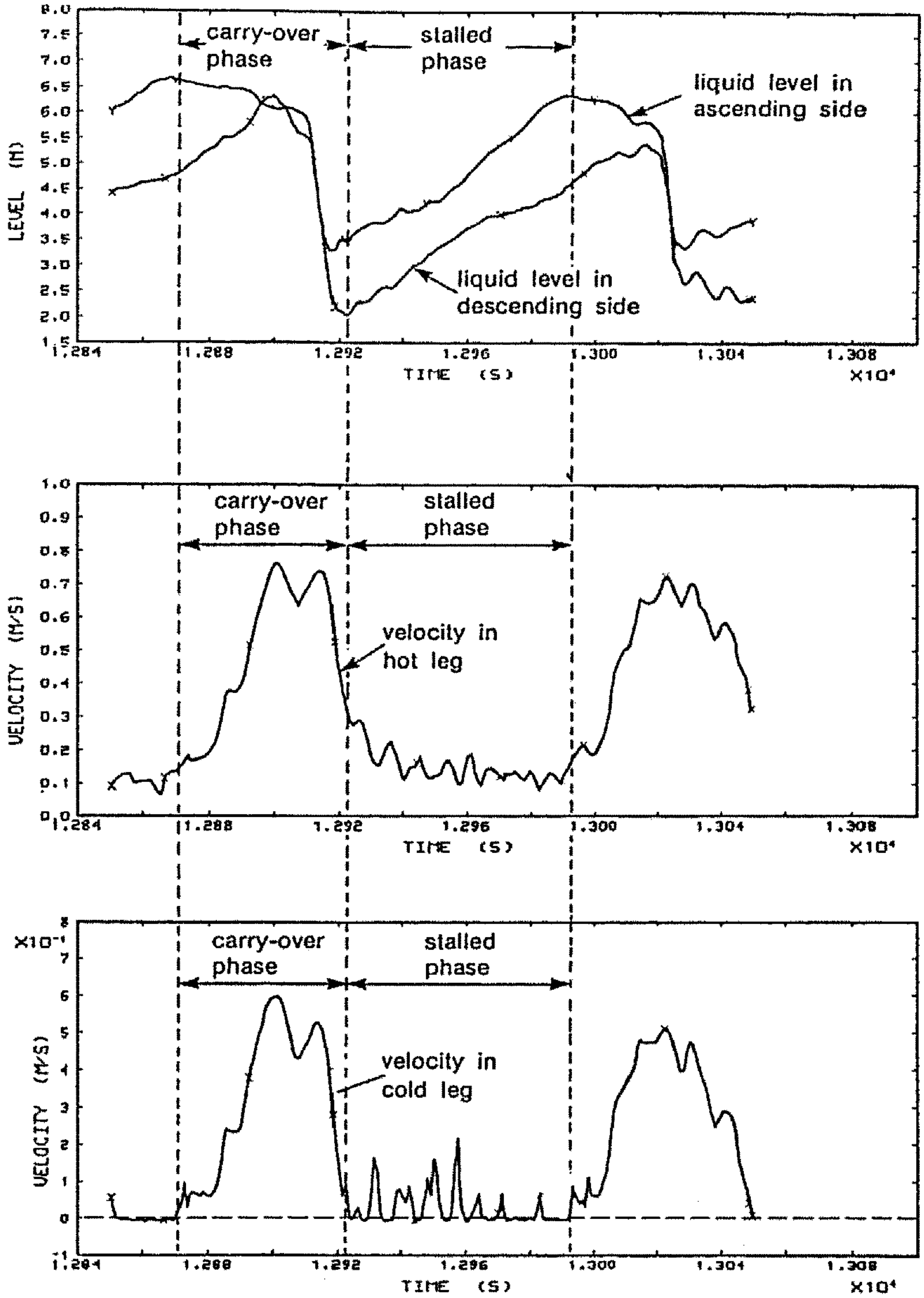


Figure 5. An oscillation cycle of fluid velocity and liquid level in U-tubes at 74% coolant inventory.

reflects the amount of condensate collected there, between 12,920 s and 12,990 s in Figure 5. During water column formation a hydrostatic balance exists between the ascending and descending sides of the tube so that the full flow turbines measure almost zero fluid velocity in the cold leg and very low velocity in the hot leg. This measurement supports a temporary two-phase natural-circulation interruption.

When the liquid column on the ascending side reaches the top of the U-tubes (at about 12,990 s in Figure 5), some water is allowed to flow over the tube U-bend,

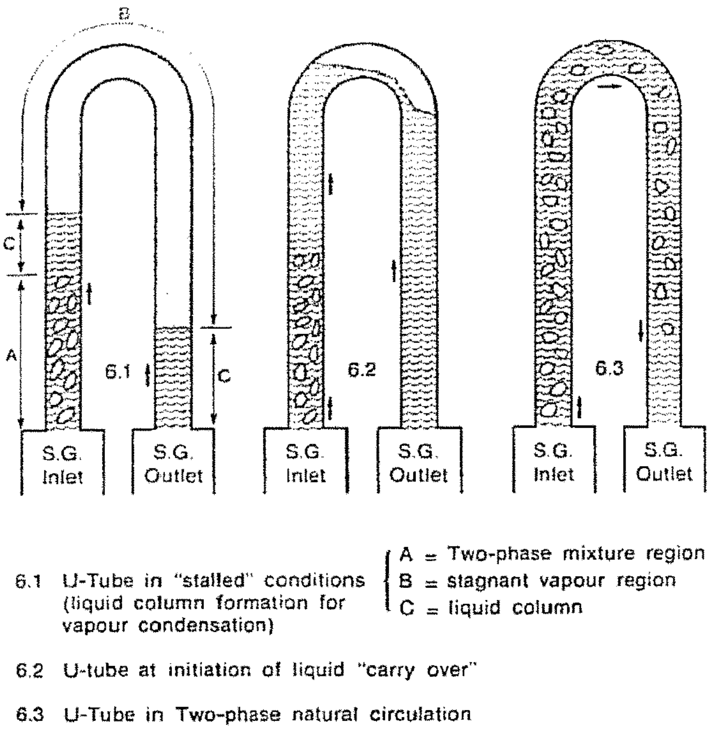


Figure 6. Oscillation mechanism in vertical S.G. U-tubes. 6.1. U-tube in "stalled" conditions (liquid column formation for vapor condensation): A = two-phase mixture region; B = stagnant vapor region; C = liquid column. 6.2. U-tube at initiation of liquid "carryover." 6.3. U-tube in two-phase natural circulation.

as depicted in Figure 6.2. This liquid carryover further raises the water column (between 12,990 s and 13,010 s as shown in Figure 5) in the descending side at a faster rate. At this moment there is an initial flow increase of the two-phase mixture in the hot leg which is sucked up into the steam generator ascending tubes (which also diminishes the collapsed level in the ascending side, see Figure 5). The additional steam entering the tubes eventually reestablishes a two-phase natural circulation at 13,010 s in Figure 5. The whole loop flow is definitely sharply increased, with a two-phase acceleration (low-density fluid) in the hot leg and a flow peak of high-density fluid in the cold leg, as shown in Figure 7.

The two-phase natural circulation, see Figure 6.3, persists for a short period and eventually stalls with a large accumulation of steam at the top of the tubes. This is again the start of the condensation phase. The flow oscillations inside the U-tubes have a time period of about 120 s. The measured frequency and amplitude of the flow oscillations have been adequately calculated in a RELAP5-MOD2 code calculation [14]. The circulation phase and the mechanism leading to sudden stalling of the flow will be studied in a following article.

CALCULATION OF THE STALLED-PHASE DURATION

The duration of the stalled phase can be calculated from the primary vapor condensation rate in the single-loop steam generator. During stalled conditions the single loop is characterized by no flow in the cold leg and increasing water columns in the ascending and descending sides of the steam generator tubes; see Figure 5.

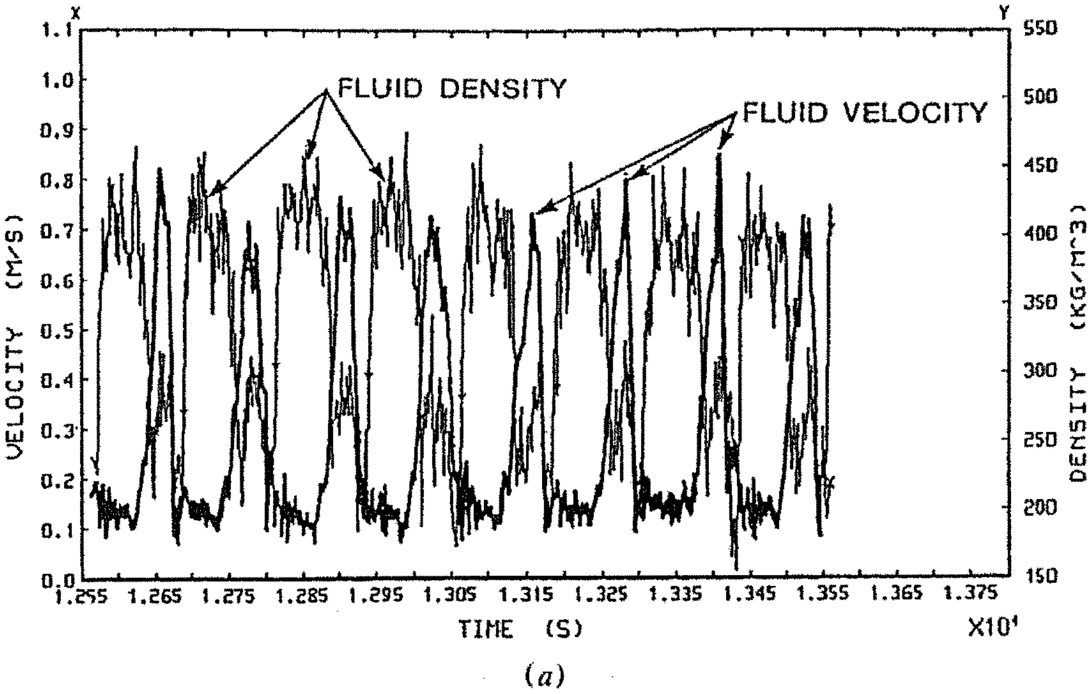
The heat transfer rate from primary to secondary in the vapor zone at the top of the U-tubes (zone B of Figure 6) can be calculated as

$$\dot{Q}_{\text{top}} = \int^{L_{\text{st}}} \pi h(x) D_t N_t \, \Delta T(x) \, dx \tag{1}$$

where

$h(x)$ = overall heat transfer coefficient at position x

$$= \frac{1}{1/[h_o(x)] + 1/[h_i(x)] + \delta/\lambda_w} \tag{2}$$



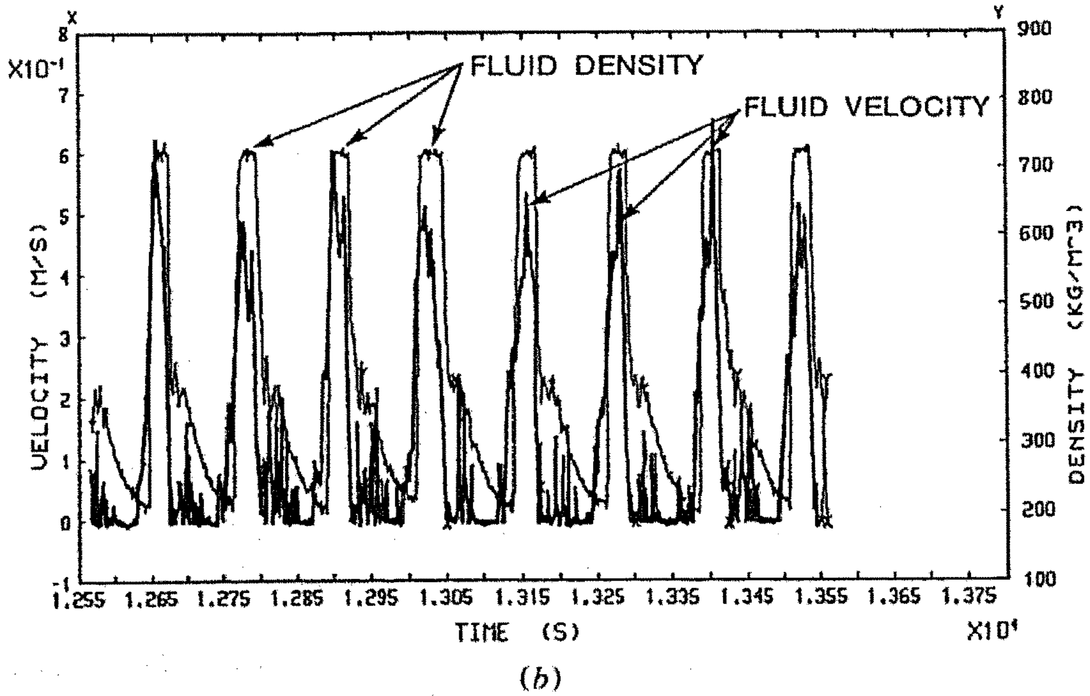


Figure 7. Oscillations of fluid velocity and density in: (*a*) hot leg; (*b*) cold leg.

h_o = heat transfer coefficient on the outer tube wall
h_i = heat transfer coefficient on the inner tube wall
λ_w = thermal conductivity in the tube wall
δ = thickness of the tube wall (Incoloy 800)
L_{st} = length of vapor zone for condensation at beginning of stalled phase in each tube
D_t = mean tube diameter (= 0.0208 m)
$\Delta T(x)$ = temperature difference between primary and secondary fluid at distance x
N_t = number of U-tubes (= 8).

As an approximation of Eq. (1) we consider an average overall heat transfer rate:

$$\bar{\dot{Q}}_{\text{top}} = N_t \cdot \pi D_t \cdot L_{\text{st}} \cdot \Delta \bar{T}_{\text{st}} \cdot \bar{h}_{\text{st}} \tag{3}$$

where

$\bar{h}_{\text{st}} = 2700\ \text{W/m}^2\,\text{K}$ = average overall heat transfer coefficient with vapor condensation [16] at the inner wall and saturated nucleate boiling [16] at the outer wall, during the staled phase [15]
$\Delta\bar{T}_{\text{st}} = 2.65\ \text{K}$ = measured mean difference between primary and secondary fluid saturation temperature at the U-tubes top elevation during the stalled phase
$L_{\text{st}} = 3.5\ \text{m}$ = measured mean length of vapor zone (zone B) during the stalled phase in each tube

Hence

$$\bar{\dot{Q}}_{\text{top}} = 13.1\ \text{kW} \qquad \text{(heat transfer rate at the top of U-tubes)} \tag{4}$$

The corresponding primary vapor condensation rate is (mean value)

$$\overline{\dot{m}_c} = \frac{\bar{\dot{Q}}_{\text{top}}}{r} = 9.5\ \text{gr/s} \tag{5}$$

(r is the evaporation heat at 9 MPa).

Having assumed identical vapor condensation rates on the ascending and descending sides of the tubes, we can now calculate the speed of the height increase for the water column:

$$\frac{dH}{dt} = \frac{\overline{\dot{m}_c}}{(\rho_s) \cdot A_t \cdot 2N_t} = 0.040\ \text{m/s} \tag{6}$$

($\rho_s = 49\ \text{kg/m}^3$ = vapor density at 9 MPa, $A_t = 0.0003\ \text{m}^2$ = cross-sectional area of a U-tube).

Finally, we get the time needed to raise the collapsed water level in the U-tubes from the initial to the final elevation, which represents the duration of the

Table 1. Results During Stalled Phase

Thermohydraulic parameter	Calculated	Measured
Duration of "stalled" phase (T_{st})	80 s	70 s
Water column increasing rate (dH/dt)	0.04 m/s	0.046 m/s
Vapor condensation rate ($\dot{m}_c$)	9.5 gr/s	10.9 gr/s
Energy transfer rate at the top of U-tubes ($\dot{Q}_{top}$)	13.1 kW	15 kW

loop stalled conditions:

$$\text{Initial measured collapsed level} = H_i = 3200 \text{ mm (see Figure 5)}$$

$$\text{Final measured collapsed level} = H_f = 6400 \text{ mm (see Figure 5)}$$

$$T_{st} = \frac{H_i - H_f}{dH/dt} = 80 \text{ s} \qquad (7)$$

Table 1 shows the comparison of the calculated to the measured values of the most significant parameters.

Similar calculations have been performed to predict the duration of the flow interruption periods measured during other natural-circulation experiments performed at different core powers and primary pressures in the LOBI facility. Figure 8 shows the comparison of the measured heat transfer at the top of the U-tubes during the stalled phase to the calculated value by considering the condensation mechanism. The good agreement of measured to calculated quantities supports the theory that the liquid column formation speed is controlled by the condensation mechanism.

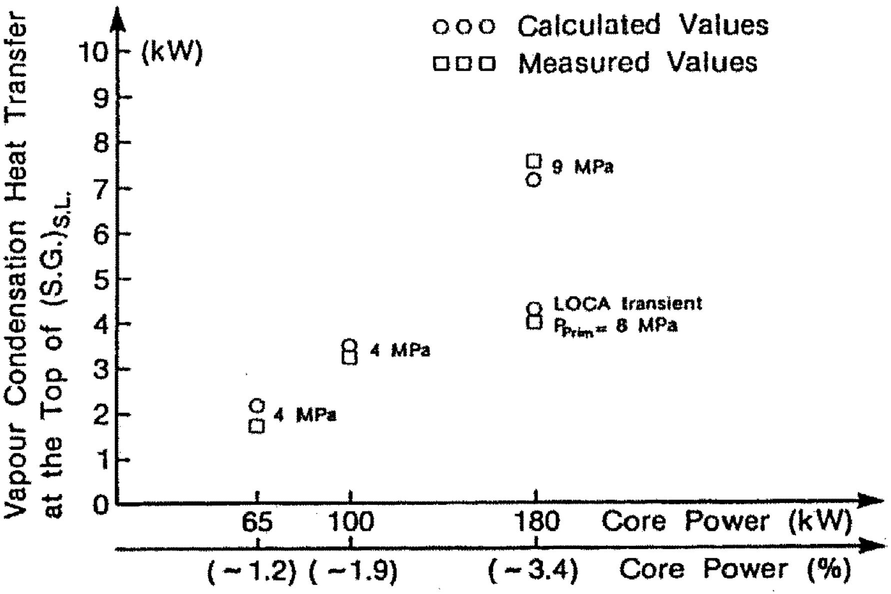


Figure 8. Comparison of measured to calculated heat transfer at the top of U-tubes during stalled phase.

FREQUENCY OF FLOW OSCILLATION

The measured flow oscillation frequencies must be related to the overall energy balance on the primary system during an entire oscillation cycle. In the following we calculate the heat transfer during an entire oscillation cycle, for comparison to the average power input into the primary system. For this calculation the oscillation cycle is divided into the "stalled" phase (condensation heat transfer) and the "carryover" phase (two-phase convection heat transfer).

In the stalled phase, the contribution to heat transfer comes both from the condensation at the top of the U-tubes, calculated in Eq. (4), and from the condensation at the inlet of the ascending leg (respectively, zones B and A of Figure 6.1). The single-phase water regions in the ascending and descending legs (zones C in Figure 6.1) are assumed to be in thermal equilibrium with the secondary side. To calculate the vapor flow at the inlet of the ascending leg, it is assumed that a two-phase mixture is drawn into the tubes via the hot leg at the speed of the water column rise. Assuming for the top of the U-tube an equal vapor condensation rate in the ascending and descending legs, the volumetric flow of water entering the tubes is

$$\bar{\dot{V}}_w = \frac{1}{\rho_s} \cdot \frac{1}{2} \cdot \bar{\dot{m}}_c \tag{8}$$

The liquid flow into the tubes is then

$$\bar{\dot{m}}_w = \bar{\dot{V}}_w \rho_w = 0.068 \text{ kg/s} \tag{9}$$

($\rho_w = 705 \text{ kg/m}^3$ is saturated water density).

The corresponding fluid velocity in the hot leg at the inlet of the steam generator is

$$\bar{v}_{\mathrm{HL}} = \frac{\bar{\dot{m}}_w}{\rho_{\mathrm{HL}} \cdot A_{\mathrm{HL}}} = 0.10 \text{ m/s} \tag{10}$$

where

$\bar{\rho}_{\mathrm{HL}} = 400 \text{ kg/m}^3$ = mean fluid density measured in the vertical section of the hot leg

$A_{\mathrm{HL}} = 0.00166 \text{ m}^2$ = hot-leg cross-sectional area

This calculated velocity is also confirmed by the full flow turbine indication in the vertical section of the hot leg during the stalled phase; see Figure 5 between 12,920 and 12,990 s.

From the density measurement in the hot-leg vertical section, the average void fraction can be deduced:

$$\begin{aligned} \bar{\rho}_{\mathrm{HL}} &= \alpha_{\mathrm{HL}} \rho_s + (1 - \alpha_{\mathrm{HL}}) \rho_w \\ \alpha_{\mathrm{HL}} &= 0.46 \end{aligned} \tag{11}$$

Using the Zivi correlation [17] for an estimation of the steam/water slip velocity in the vertical pipe,

$$S = \left(\frac{\rho_w}{\rho_s} \right)^{1/3} = 2.5 \tag{12}$$

the average steam quality in the hot leg can now be calculated from

$$S = \frac{1-\alpha}{\alpha} \frac{x}{1-x} \frac{\rho_w}{\rho_s} \tag{13}$$

We get $x = 0.13$.

Hence the steam mass flow at the inlet of the steam generator is

$$\overline{\dot{m}}_s = x\overline{\dot{m}}_w = 0.0088 \text{ kg/s} \tag{14}$$

Notwithstanding the flow stagnation, some vapor enters the steam generator U-tubes during the loop-stalled period. The primary-to-secondary energy transfer at the bottom of the U-tubes, by vapor condensation, is

$$\overline{\dot{Q}}_{\text{bottom}} = \overline{\dot{m}}_s r = 12.2 \text{ kW} \tag{15}$$

Together with the heat transfer at the top of the U-tubes from Eq. (5), the total calculated heat transfer during loop-stalled conditions is

$$\begin{aligned} \overline{\dot{Q}}_{\text{st}} &= \overline{\dot{Q}}_{\text{top}} + \overline{\dot{Q}}_{\text{bottom}} \\ &= 12.2 \text{ kW} + 13.1 \text{ kW} = 25.3 \text{ kW} \end{aligned} \tag{16}$$

The heat transfer during the carryover phase will be higher than during the stalled phase due to the larger heat transfer area, which extends to the full length of the tubes. The energy exchanged under these conditions can then be calculated:

$$\overline{\dot{Q}}_{\text{c.o.}} = \overline{h}_{\text{c.o.}} \overline{\Delta T}_{\text{c.o.}} N_t \pi D_t L_{\text{c.o.}} \tag{17}$$

where

$L_{\text{c.o.}} = 14.21$ m = length of U-tube for heat transfer (= total length)

$\overline{\Delta T}_{\text{c.o.}} = 30.$K = difference between primary and secondary fluid temperatures; average value calculated from the differential temperatures measured at the various instrumented locations in the U-tubes during carryover phase

$\overline{h}_{\text{c.o.}} = 2100$ W/m^2 K = overall heat transfer coefficient; average value over the tubes length during carryover phase [15]

Hence we get, during the carryover period,

$$\overline{\dot{Q}}_{\text{c.o.}} = 47.5 \text{ kW} \tag{18}$$

Finally, the average energy transfer from primary to secondary over the single-loop steam generator during an entire flow oscillation period is

$$\bar{\dot{Q}}_{SG} = \frac{\bar{\dot{Q}}_{st} T_{st} + \bar{\dot{Q}}_{c.o.} T_{c.o.}}{T_{st} + T_{c.o.}} = 34 \text{ kW} \tag{19}$$

where

T_{st} = calculated time duration of stalled phase [Eq. (7)]
$T_{c.o.}$ = measured time duration of carryover phase

Assuming that the single-loop steam generator exchanges one-fourth of the supplied energy, the total heat exchanged between the primary and secondary systems amounts to

$$\bar{\dot{Q}}_{ex} = 4 \times \bar{\dot{Q}}_{SG} = 136 \text{ kW}$$

This compares well to the total heat supplied to the system of 183 kW, considering the measured primary system heat loss of 35 kW [18].

The above calculation was performed to check the overall balance of energy for the system during an oscillation cycle under the assumptions made.

The calculation could also be performed in a different way. If the core power is known and the time duration of the "loop-stalled" phase calculated by assuming that vapor condensation is the governing mechanism, it is possible to estimate the flow oscillation frequency. The theory, however, does not yet predict the length of the vapor zone (L_{st}), which forms after interruption of the circulation flow. At the moment this value, as well as the primary loop pressure, have to be taken from the measured data. The mechanism that controls L_{st} will be studied in the future.

In other LOBI experiments carried out at different core power levels and primary pressures, as in Test A2-77A, similar oscillations have been measured at equivalent primary coolant inventories during the transition period between two-phase natural-circulation and reflux condenser modes. Figure 9 shows the compari-

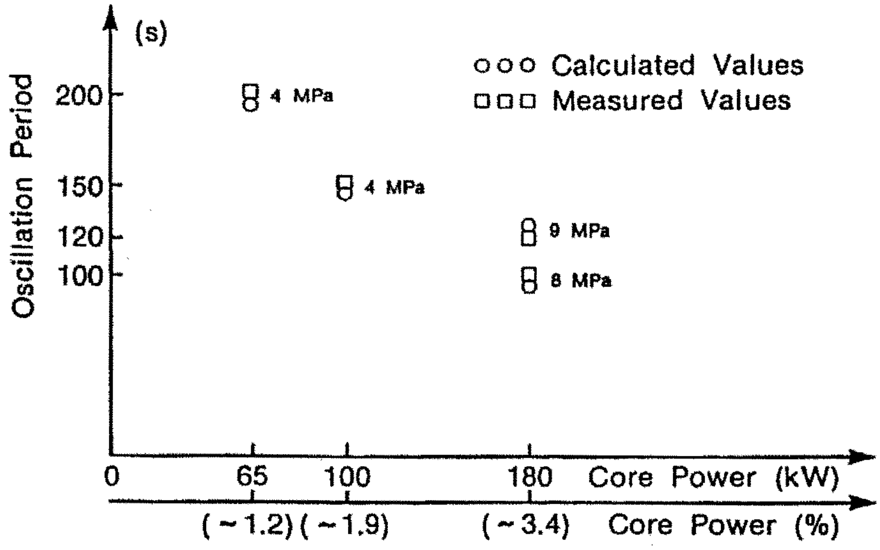


Figure 9. Comparison of measured to calculated flow oscillation frequencies.

son of the measured to calculated flow oscillation frequencies. By increasing the core power the oscillation cycle becomes shorter (higher frequency), and the amplitude reduces. At a high core power the process of vapor condensation is restricted to the very high sections of the U-tubes. In each single tube a reduced amount of condensate rapidly accumulates and then flows over the U-bend, almost independently of the other tubes. The vapor condensation in the U-tubes has, therefore, a weak influence on the overall loop flow, which is no longer stopped and remains almost constant. This is different than at very low core power levels, where the vapor condensation length is much longer and involves a considerable part of the tubes. Stall and carryover phases clearly alternate in the loop, with flow oscillations of relatively high amplitude and low frequency.

MECHANISM OF LIQUID HOLDUP

As discussed in the previous section, the flow oscillations observed during natural circulation in the LOBI facility were caused by vapor collection and condensation at the top of the steam generator U-tubes. This flow oscillation occurs over a large range of primary coolant inventories, from 85% down to 52% of the initial value, as shown in Figure 3. The mechanisms that hold up the condensate columns in the vertical steam generator U-tubes are, however, different for flow oscillations at high or low primary mass inventories.

Flow Oscillations at High Primary Mass Inventory

The flow oscillations observed at high primary mass inventory between 83% and about 63% of the initial value can occur because of a "primary loop full" condition. In Figure 10 the coolant distribution inside the primary loop at 74% mass inventory is depicted. The lower, intermediate, and upper regions of the primary system, up to about half of the steam generator U-tube height, are full of liquid. Under these inventory conditions, as steam condenses at the top of the U-tubes, the condensate is accumulating in the U-tubes above the lower parts already full of liquid, as indicated by the increasing pressure difference over the U-tubes length. This fact implies that loop flow oscillations, caused by periodic interruptions of steam generator tube flow, can be expected during natural circulation in the high inventory range even when the core power level is very low. Countercurrent flow limitation (CCFL) at the bottom of the U-tubes and/or liquid entrainment between the upflow of steam at the tube center and the annular downflow of liquid around the wall is not necessary. The occurrence of oscillations at reduced decay-heat levels has been experimentally confirmed by additional LOBI tests. Strong flow oscillations in both the triple and the single loop were measured at relatively high inventory and reduced steam velocity, at which CCFL in the loop can be excluded.

Flow Oscillations at Low Primary Mass Inventory

At an inventory below 63%, the behavior in the two steam generators was different. The triple-loop steam generator was almost void, showing steady reflux condensation. The single-loop steam generator could not void due to CCFL in the hot leg (smaller tube diameter); see Figure 11. This shows that the previous "loop

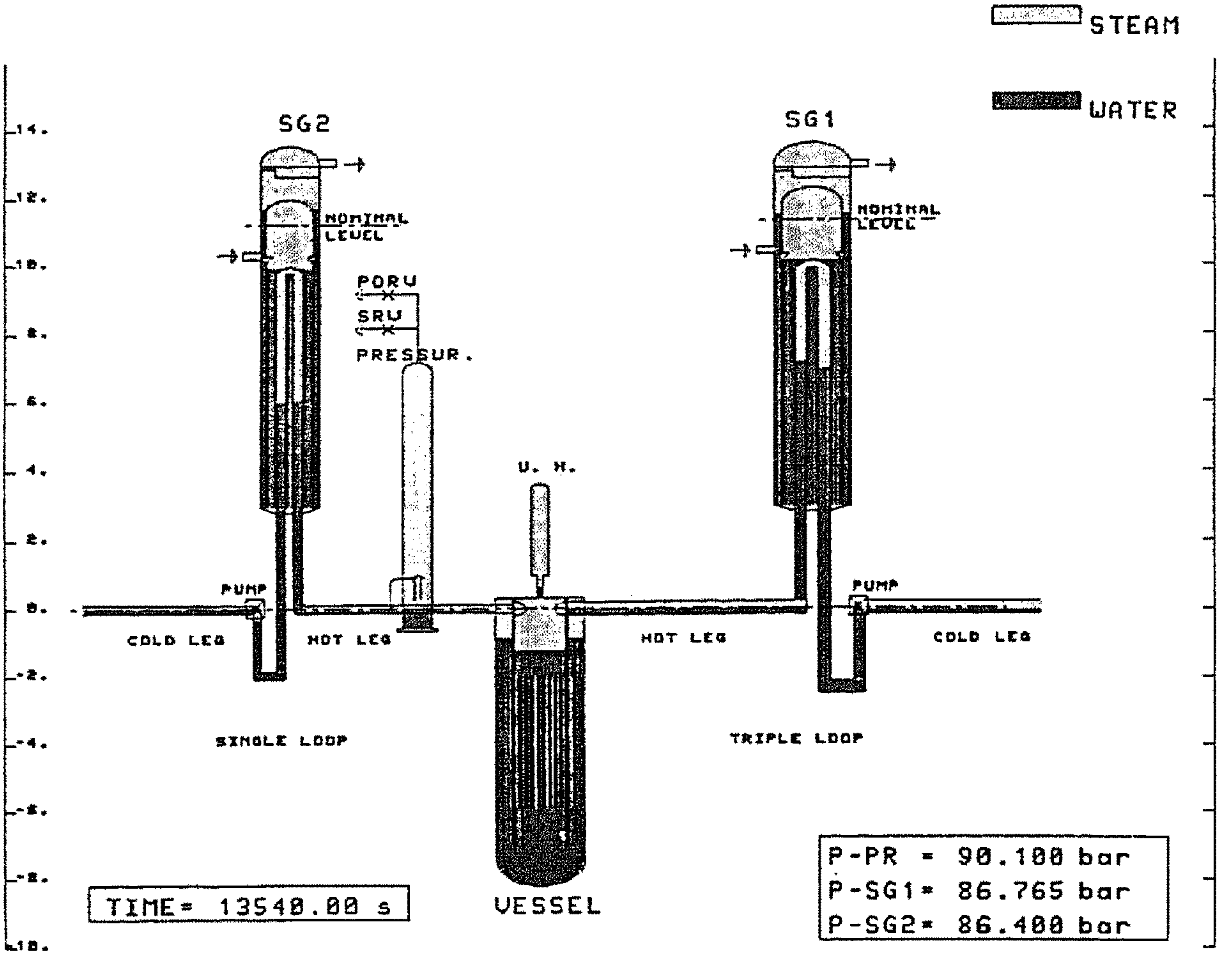


Figure 10. Fluid distribution at 74% coolant inventory.

full" condition does not exist any more. The liquid holdup is now caused by the CCFL mechanism, which due to the geometry occurs only in the single loop. CCFL for stratified flows in a horizontal pipe is considered in the literature by Keulegan [19] as a high-density fluid wave that moves in a lighter fluid. He presented a correlation for calculating the length of an arrested wedge:

$$\frac{L_0}{D} = \frac{1}{30}\left(\frac{D}{\eta_s}\,\frac{g\,\Delta\rho\,D}{\rho_w}\right)^{0.5}\left(\frac{v_s\sqrt{\rho_w}}{\sqrt{g\,\Delta\rho\,D}}\right)^{-2.5} \tag{20}$$

where D = hot-leg pipe diameter
v_s = vapor velocity
ρ_w = fluid density
η_s = vapor kinematic viscosity
L_0 = required length for arrested wedge

Figures 12 and 13 show the results obtained applying Eq. (20) to the LOBI hot legs during test A2-77A. It can be seen that in the single-loop hot leg, conditions for

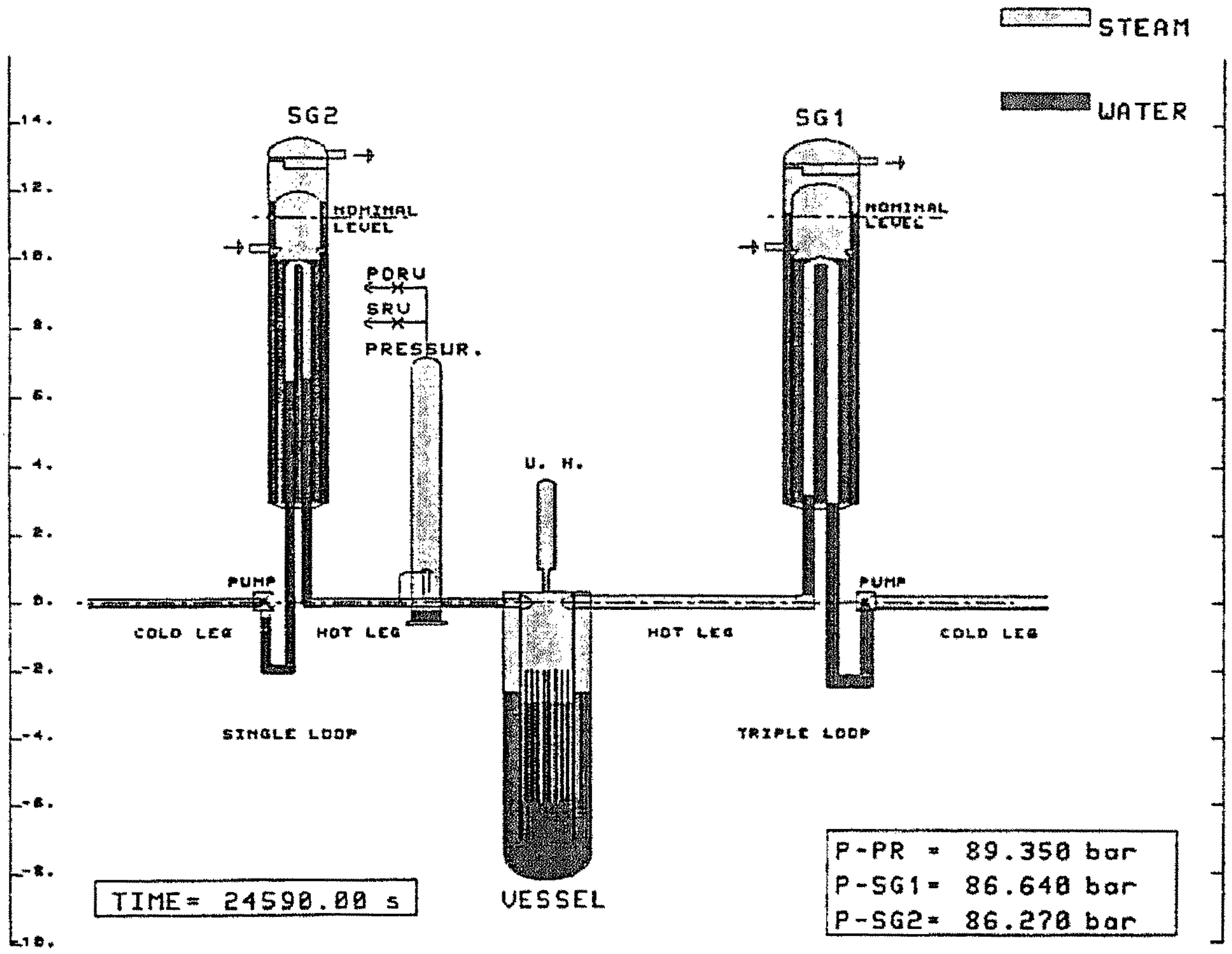


Figure 11. Fluid distribution at 56% coolant inventory.

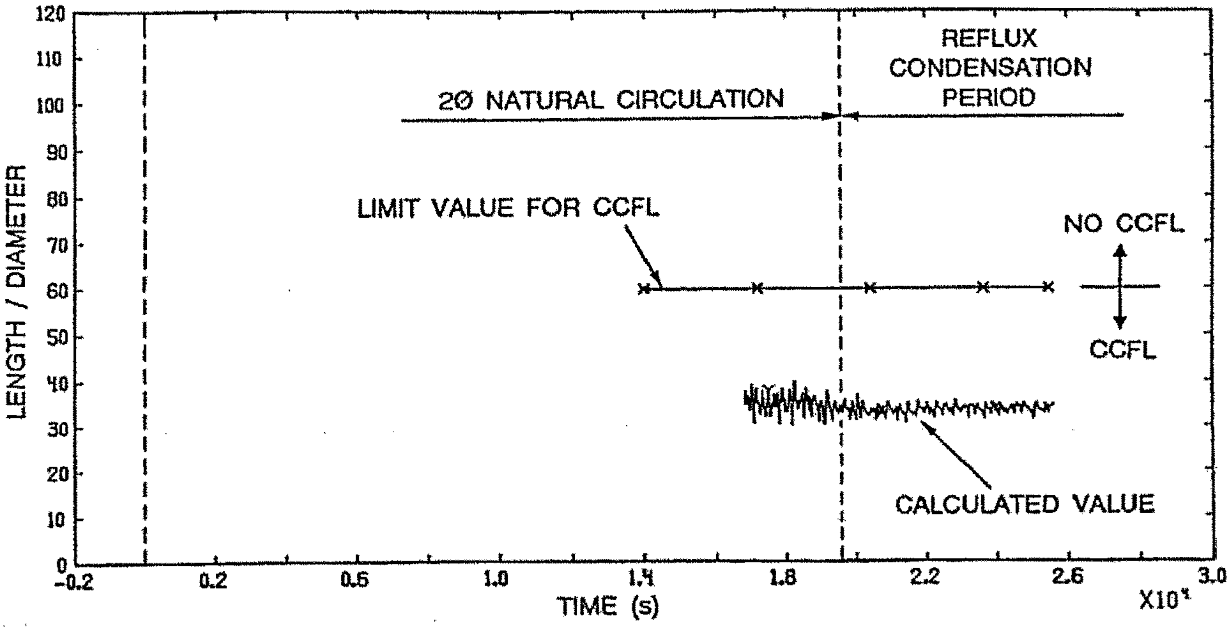


Figure 12. Calculated length for arrested wedge in single-loop hot leg during reflux condensation.

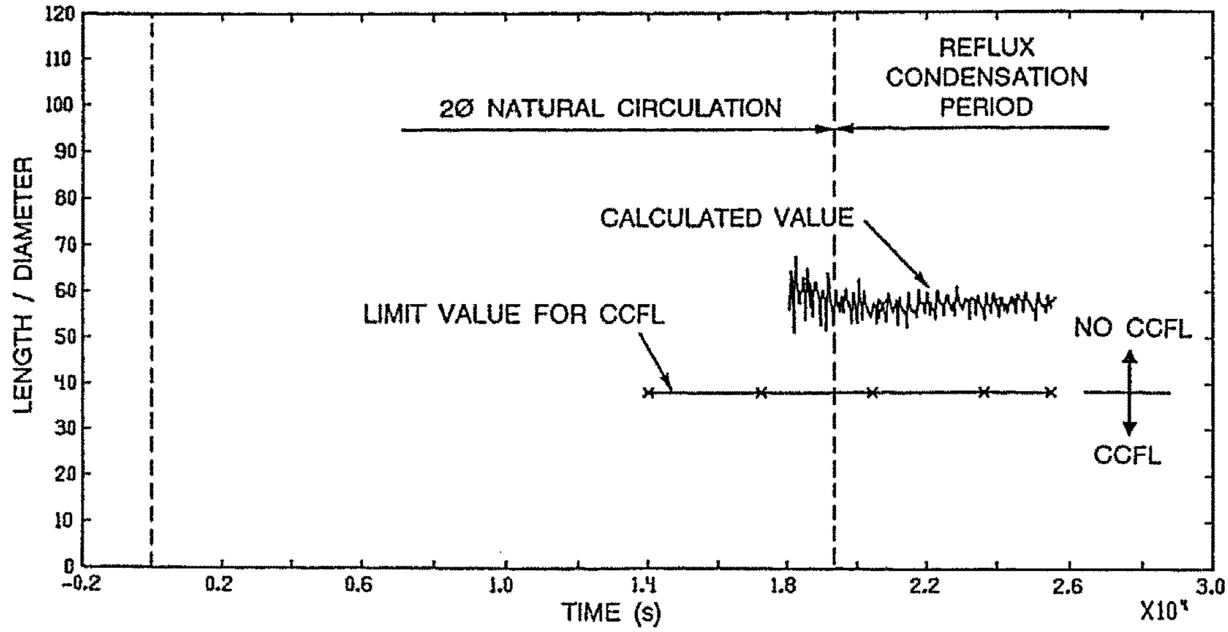


Figure 13. Calculated length for arrested wedge in triple-loop hot leg during reflux condensation.

occurrence of CCFL were calculated. The actual length in the hot leg is longer than the length required for stopping the liquid flow by the countercurrent steam flux. In the triple-loop hot leg, CCFL was not anticipated. As a consequence, flow oscillations persist also during the reflux condenser mode period, similar to those measured in the high inventory range, but with longer time periods (about 250 s, see Figures 14 and 15).

In conclusion, the flow oscillations can occur independently of the mechanism of liquid holdup, which for high inventory is a "loop full" condition and for low inventory is CCFL.

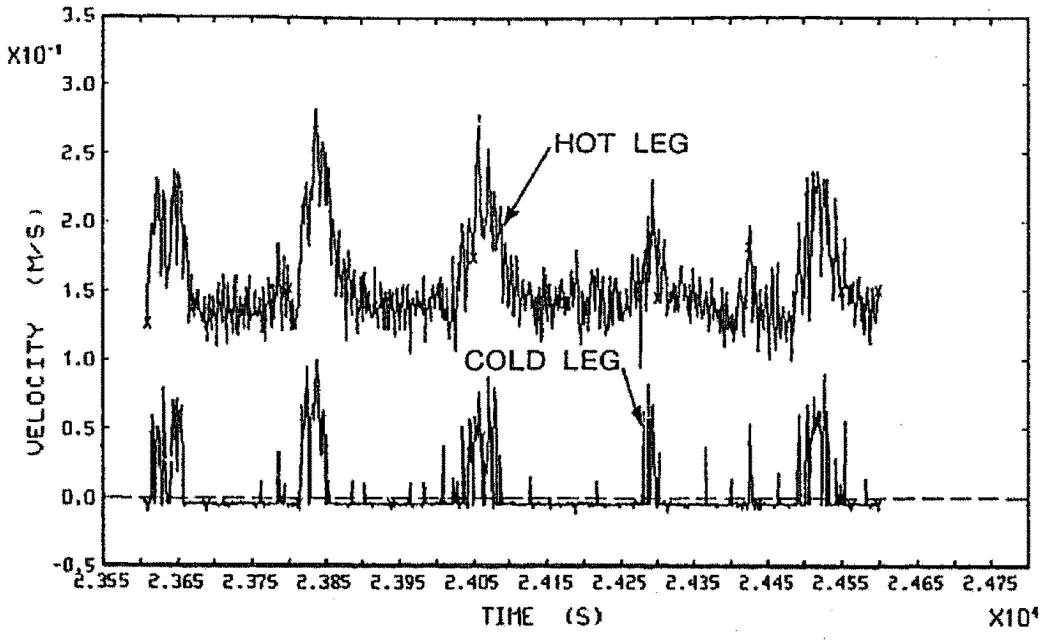


Figure 14. Oscillations of fluid velocity in hot and cold legs at 56% coolant inventory.

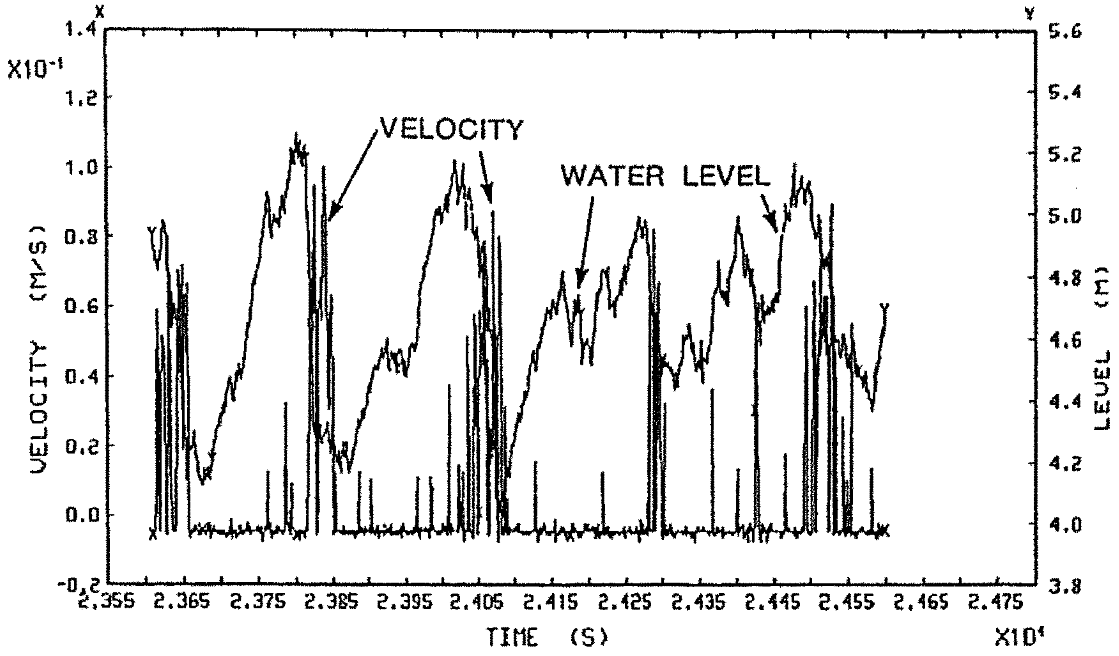


Figure 15. Oscillations of flow velocity and U-tube collapsed level at 56% coolant inventory.

FLOW OSCILLATION DURING LOCA TRANSIENT

Small break LOCA transients in a PWR are characterized by a slow primary system depressurization following core scram and main coolant pump trip. Long periods of "quasi"-thermal equilibrium between the primary and secondary systems can exist in which the primary pressure settles out slightly above the secondary relief-valve set pressure. Removal of core decay heat is usually accomplished by a natural-circulation cooling mechanism, with the core as the heat source and the steam generator (and system heat losses) as the heat sink. When the high-pressure injection system (HPIS) is not used, the thermohydraulic conditions and the coolant distribution in the primary system do not differ much from a steady-state experiment. LOBI Test BL-21 simulates a 0.4% steam generator U-tube rupture with no active emergency cooling system available [20]. Oscillations were clearly observed during the natural-circulation phase in the single loop at about 8.0 MPa primary pressure. Flow-rate oscillation frequency and magnitude were typical of those found previously in the LOBI natural-circulation steady-state experiments; see Figure 9. The primary-to-secondary heat transfer during the stalled phase, due to vapor condensation at the top of the steam generator U-tubes, is also in accordance with the steady-state data, as shown in Figure 8.

The above comparison leads to the conclusion that the flow regimes and heat removal mechanisms studied in the stationary experiments can also be expected during slow depressurization LOCA transients.

LOW-PRESSURE EXPERIMENTS

Recalling the situation of the ascending leg of the U-tube during the "stalled" phase (Figure 6.1), in high-pressure experiments, condensation takes place at both the top (zone B) and the bottom (zone A) of the tube, because the temperature within the U-tubes is fairly uniform, resulting in an almost constant T. This situation is different at near-atmospheric pressures, at which geostatic heads of liquid columns affect the pressure significantly. With a primary-to-secondary ΔT of 4 K at the tube inlet, a stagnant water column of only 50 cm would result in saturation vapor temperature at the top of the U-tubes in thermal equilibrium with the secondary fluid. Condensation and consequential rise of the liquid column would not take place. However, oscillations could still take place at sufficiently large differential temperatures at the tube inlet, i.e, higher core heating power.

Low-pressure experiments have been reported in the past by Griffith [4] and Benerjee [5]. In these experiments, flow oscillations were clearly visualized in the Pyrex U-tube array. The initiation of the formation of liquid columns above the two-phase region was related to the rising steam velocity at the inlet of the tubes. At the onset of flooding some portions of the condensate are dragged upward and held up by the steam to form a stable water column. This conclusion is consistent with the explanation given in the article for the oscillations' onset during reflux condensation at high pressure. The mentioned low-pressure experiments were affected by noncondensable gas content in the tubes, which heavily reduced the saturated vapor condensation rate during liquid column formation. Notwithstanding the high temperature difference between the primary and secondary fluids (more than 60 K in [5], the frequency of these oscillations was much lower (less than 15 times) than for the LOBI tests.

CONCLUSIONS

The two-phase natural-circulation oscillations are caused by synchronized periodic interruptions of steam generator U-tubes flow, due to vapor trapped at the top. As steam condenses, liquid columns develop in the ascending and descending legs of the U-tubes; as they reach the top, flow starts again.

The duration of the "stalled" phase of the flow oscillations in the LOBI natural-circulation experiments is controlled by the speed of steam condensation at the top of the U-tubes. By increasing the core power, the oscillation cycle becomes shorter (higher frequency), with smaller amplitude. The mechanism that forms the liquid column may not necessarily be CCFL; it may also be a simple "loop full" condition. Similar flow instabilities can occur during small break LOCA depressurization transients.

An overall energy balance, including the "stalled" condensation phase and the carryover phase, shows that the models are in a good agreement with experimental data. Future work will concentrate on the mechanisms driving the carryover flow and leading to the interruption of flow. The aim is to predict the amount of accumulated steam in the U-tubes at the initiation of stalling.

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