CALCULATIONS OF FLOW OSCILLATIONS DURING REFLOOD USING RELAP4/MOD6

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ABSTRACT

RELAP4/MOD6 is an analytical computer code which can be used for best-estimate analysis of LWR reactor system blowdown and reflood response to a postulated LOCA. In this study, flow oscillations in the PKL reflood test K5A were investigated using RELAP4/MOD6. Both calculated and measured oscillations exhibited transient characteristics of density-wave and pressure drop-oscillations. The calculated average core mixture level rising rate agrees closely with the test data. Several mechanisms which appear to be responsible for initiation and continuation of calculated or experimental reflood flow oscillations are (a) the coupling between the vapor generation in the core channel and the U-tube geometrical arrangement of a downcomer and a heated core; (b) the inherent low core inlet resistance and high system outlet resistance; (c) the dependence of heat transfer rate on mass flow rate especially in the dispersed flow regime; (d) the amount of the liquid entrainment fraction of the heated core channel.

INTRODUCTION

In the event of a postulated loss-of-coolant accident (LOCA) in a pressurized water reactor (PWR), emergency core coolant (ECC) would be injected into the reactor system to reduce the fuel rod cladding temperature and prevent fuel rod rupture. After the blowdown phase of the LOCA transient, ECC water would begin to refill the downcomer and lower plenum and reflood the reactor core. During the core reflood phase experimental evidence suggests that flow oscillations occur with constant or damped amplitude. These oscillations could improve the core heat transfer and hence lower the predicted peak cladding surface temperature. Because of this potential effect on peak cladding surface temperature, the prediction of flow oscillations by LOCA codes is important. In order to demonstrate the ability of RELAP4 to predict flow oscillations during reflood relevant experimental data were examined. Recent experimental reflood tests, such as those conducted in Semiscale (EG&G Idaho, Inc.)[1] and FLECHT-SET (Westinghouse Electric Corporation[2,3] test facilities, exhibited flow oscillations between the downcomer and the reactor core. During RELAP4/MOD6 code simulations of these reflood experimental tests, similar flow oscillations were calculated to occur.

The purpose of the current investigation was to examine the primary mechanisms responsible for the initiation and continuation of reflood flow oscillations when subcooled ECC is injected into the reactor system during a LOCA. This investigation was accomplished by first assessing

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the capability of RELAP4/MOD6 to calculate simple U-tube manometer type oscillations. Second a flow oscillation study was conducted on the German three-loop Primary Kreislauf (PKL) Reflood Experimental System[4,5] which simulates a typical PWR plant.

U-TUBE MANOMETER FLOW OSCILLATION STUDY

An isothermal liquid oscillation in a U-tube (Figure 1) is a simple and well understood problem. The analytical solution of this problem can be obtained and the derivation can be found in most texts on fluid mechanics[6].

The capability of the RELAP4 code to calculate manometer type flow oscillations was examined by comparing code calculations with analytical results.

The U-tube manometer was simulated with two RELAP4 models which are identified as the three-volume and four-volume models as shown in Figure 2. The purpose of using two models was to investigate the effect of nodalization on the calculated results. In addition, the four-volume case was designed to simulate the typical RELAP4 nodalization used in modeling a PWR, which consists of a downcomer (Volume 1), lower plenum (Volume 4) and vessel core (Volume 2). Results from the RELAP4 calculation were compared with the exact solution for frictionless U-tube manometers (Tables I and II). For all of the cases studied, the RELAP4 calculations resulted in an oscillation frequency within 1% of that obtained from the analytical solution.

Results of the RELAP4 calculation for U-tubes with wall friction were also compared with the analytical results. Again RELAP4 accurately predicted the damping effect of wall friction on the flow oscillation. In addition, as was expected, the wall friction and form loss were found to have negligible effect on the frequency of flow oscillations.

RELAP4/MOD6 CALCULATION FOR THE GERMAN PKL TEST K5A

In a recent RELAP4/MOD6 reflood simulation of Semiscale reflood experiments, the calculated frequency of the flow oscillation was within 10% of the experimentally measured value[7]. However, since Semiscale is a highly scaled-down simulation system representation of a typical PWR, to improve confidence in the predictive ability of RELAP4, additional reflood studies on systems larger than Semiscale were conducted using RELAP4/MOD6. One of these large systems is the Kraftwerk Union (KWU) PKL experimental facility (Figure 3) in Erlangen, West Germany.

Facility Description and Test Conditions

The PKL facility is a three-loop simulation of a West German pressurized water reactor, fabricated in a reduced scale that maintains prototype volume-to-power ratio. It was designed specifically for system experiments simulating the reflood phase of hypothesized LOCA accidents.

The full length electrically heated 340-rod core is divided into hot, average, and cool zones and has an overall power capacity of 1.45 MW and a peak power of 1.5 kW/m. Test K5A was a 200% cold-leg break experiment with an initial system pressure of 0.42 MPa. The emergency core coolant was injected into the intact loop cold legs, and into the upper annulus. The coolant was subcooled 100 K. The average injection rate for the first 35 seconds was about 15.5 kg/s. Thereafter, the rate was suddenly reduced to between 10.5 and 6.8 kg/s. The initial cladding temperature at the 2-m elevation was 833 K.

RELAP4 Model of the System

To model the PKL facility for Test K5A, RELAP4/MOD6 standard modeling procedures and guidelines[a] for input parametric values were employed. The RELAP4 PKL model consists of 37 control volumes, 30 nodes, and 50 heat conductors as shown in Figure 4. Thirty-six heat conductors were used in the core volume to simulate the experimental electrical heater rods. Fourteen heat conductors were also used to model steam generators, the upper annulus, and downcomer walls. One volume, representing the containment system with its suppression tank and phase separators, was assigned pressure time dependency. One junction was assigned as a fill junction for injection of ECC water.

The system model has three loops, one broken and two intact (one of which is of double size), to represent a four-loop PWR. Three steam generators and three simulated pump volumes are used. The break was modeled in the cold leg, between the simulated pump and the upper annulus vessel. The downcomer and upper annulus were represented by a U-tube concept incorporating a steam bypass pipe between the lower plenum and the upper annulus. The RELAP4/MOD6 models for liquid entrainment, vapor superheating, reflood heat transfer, and the moving heat conduction mesh model for tracking the quench front (moving mesh) were implemented in the three core channels for calculating reflood phenomena.

Calculation of system behavior was initiated with the experimental system filled with saturated steam and with representative rods in each of the three electrically isolated core sections at prescribed surface temperatures. ECC injection was initiated in this environment at time equals zero seconds.

RESULTS OF THE PKL TEST K5A STUDY

The RELAP4 calculations of core-downcomer flow oscillations and core mixture level rising rate for the PKL Test K5A compared well with the experimental data. Figure 5 indicates that both calculated and measured oscillations exhibited transient characteristics of density-wave and

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[a] RELAP4/MOD6 User's Manual can be obtained from the National Energy Software Center, 9700 So. Cass Avenue, Argonne, Illinois 60439, U.S.A.

pressure-drop oscillations in the core channel. The dynamic features of density-wave oscillations in the PKL system are very similar to those observed in the Semiscale and FLECHT-SET reflood experiments.

The RELAP4 calculation of the onset of pressure-drop oscillations occurs about 50 seconds too early when compared with the test data. The calculated density-wave oscillation period is about 2.9 seconds, which is about 14% less than the experimental value of 3.3 seconds. The calculated maximum pressure-drop oscillation period is 7.1 seconds which is also 14% less than the experimental value of 8.3 seconds. This 14% discrepancy is insignificant when instrumentation error of more than 10% is taken into account. Figure 6 shows that the pressure fluctuations are 180 degrees out of phase with mass flow rate at the hot channel inlet, a key feature of density-wave oscillations[8,9]. Figure 7 shows that the pressure drop across the hot channel decreases whereas the channel flow rate increases, an instability criterion for Ledinegg pressure-drop oscillation[10,11,12]. The differential pressure spikes shown in Figure 7 also illustrate the superposition of the calculated density-wave oscillation on the pressure-drop oscillation. Figure 8 shows the relationship between the measured core mixture level and core inlet pressure fluctuations. However, the key feature of the density-wave oscillations (that is, core inlet flow oscillations and pressure fluctuations are 180 degrees out of phase) can still be discerned from Figure 8 by considering the maximum mixture level rising rate as the maximum mass flow rate. Figure 8 also shows that during the subcooled depressurization, the system pressure dropped from 0.42 MPa to as low as 0.26 MPa. Experiments which were carried out by Meyer[13] on water at low pressure (less than 0.42 MPa) indicated that flow oscillations would persist no matter how large the inlet pressure drop was, when the inlet flow is below a certain flow rate. Dr. A. S. Foust has also found, in experiments in the Chemical Engineering Department at Lehigh University, that low pressure water systems are highly unstable when generating vapor.

The relationship between the measured pressure drop across the upper annulus and the upper plenum and the liquid velocity in the downcomer volume is shown in Figure 9. Since the mass flow rate is directly proportional to liquid velocity, Figure 9 clearly satisfies the instability criterion for pressure-drop oscillations.

The effect of increasing core inlet resistance on flow oscillations is shown in Figure 10. Increasing the inlet resistance twentyfold did not completely dampen out oscillations, but the oscillation amplitude did decrease slightly. A similar damping effect on the flow oscillations could be achieved by decreasing the outlet orifice-resistance in each loop. Figure 11 shows that increasing the dependence of heat transfer rate on mass flow rate in the dispersed flow regime tends to decrease the oscillation amplitude and stabilize the system. Figure 12 shows that increasing the liquid entrainment fraction, thereby lowering the core channel exit void fraction and two-phase frictional pressure drops, tends to decrease the oscillation amplitude, eliminate pressure-drop oscillations, and stabilize the system.

CONCLUSIONS

RELAP4/MOD6 is a computer code developed specifically to calculate the transient thermal-hydraulic behavior of a PWR. In this study, flow oscillations during reflood were investigated using RELAP4/MOD6. In a simple U-tube oscillation study, RELAP4 was used successfully to calculate the oscillation frequency within 1% of that obtained from the analytical solution. In the PKL Reflood Test K5A study, both calculated and measured oscillations exhibited transient characteristics of density-wave and pressure-drop oscillations. The RELAP4 predicted average core mixture level rising rate agrees closely with the test data. Several mechanisms which appear to be responsible for initiation and continuation of reflood flow oscillations were identified as follows:

(1) The coupling between the vapor generation in the core channel and the U-tube geometrical arrangement of a downcomer and a heated core tends to initiate flow oscillations. When subcooled ECC water was injected into the cold legs and the upper annulus, a rapid system depressurization (Figures 6 and 8) occurred especially in the upper annulus and the downcomer. Consequently an excessive ECC water accumulation in the upper annulus and the downcomer established more than enough hydrostatic head to accelerate ECC water into the heated core channel. This liquid flow, in turn, provided sufficient two-phase liquid flow to the heated channel and the rest of the system to generate density-wave oscillations, resulting in flow oscillations.

(2) The PKL reflood test facility is a low pressure (0.42 MPa) system. Vapor generation in such low system tends to induce flow oscillations.

(3) The inherent low core inlet resistance and high system outlet resistance are also responsible for flow oscillations. The PKL Test K5A was conducted with three high resistance orifice-type measuring devices. They were installed downstream of three steam generator outlet pipe lines in order to measure the vapor flow in each loop.

(4) A superposition of the calculated density-wave oscillation on the pressure-drop oscillation was observed over a portion of the reflood transient.

(5) Other factors affecting flow oscillations in the calculation were also observed. These are (a) the dependence of heat transfer rate on mass flow rate especially in the dispersed flow regime, and (b) the amount of liquid entrainment fraction in the heated core channel.

The boiling two-phase flow oscillations are a complex problem because of the coupling effect with thermal-hydrodynamic interactions. Its existence in a experimental system during the reflood phase of a LOCA transient has been observed in the Semiscale, FLECHT-SET and PKL test facilities. During a postulated LOCA in a PWR, the calculation of peak rod cladding surface temperature for fuel rods is of primary interest for all LOCA related computer codes. However, in this study, flow oscillations were found to affect liquid-drop entrainment and heat transfer in the heated core channel and, hence, affected the peak rod cladding surface temperature of fuel rods. Therefore, additional work needs to be done to further understand two-phase flow oscillations and its effect on core heat transfer and fuel rod temperature. The current RELAP4 computer code has demonstrated that it may be a powerful thermal-hydraulic calculation tool for analyzing either LOCA or two-phase flow instability.

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TABLE I

U-TUBE FLOW OSCILLATION STUDIES WITH THREE VOLUME MODEL (FRICTIONLESS) SHOWN IN FIGURE 2.

Test conditions $(ML_1/ML_2) \times D$	Oscillation period (s)	
	Analytical solution	RELAP4 calculation
(8/5) × 1	2.82	2.8
(9/8) × 1	3.23	3.2
(30/20) × 1	5.54	5.5

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TABLE II

U-TUBE FLOW OSCILLATION STUDIES WITH FOUR VOLUME MODEL (FRICTIONLESS) SHOWN IN FIGURE 2.

Test conditions $ML_1/(ML_2+ML_4)$	Oscillation period (s)	
	Analytical solution	RELAP4 calculation
30/20	5.54	5.5
20/12	4.43	4.4
38/30	6.45	6.4
38/5	5.13	5.1

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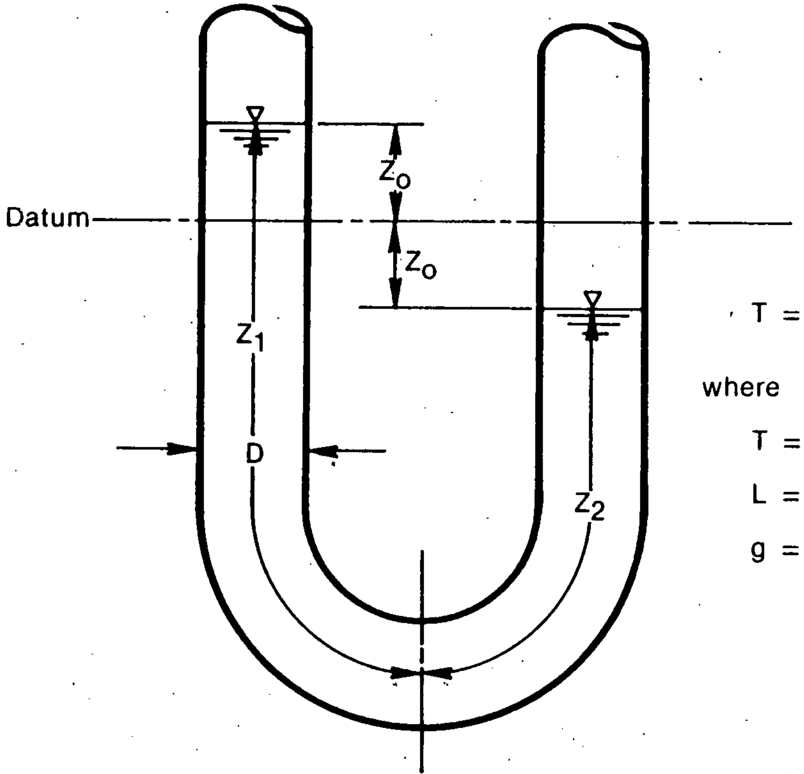

Frictionless

$$T = 2\pi\sqrt{L/2g}$$

where

T = period of oscillation
$L = Z_1 + Z_2$
g = gravitational constant

Fig. 1 U-tube Manometer

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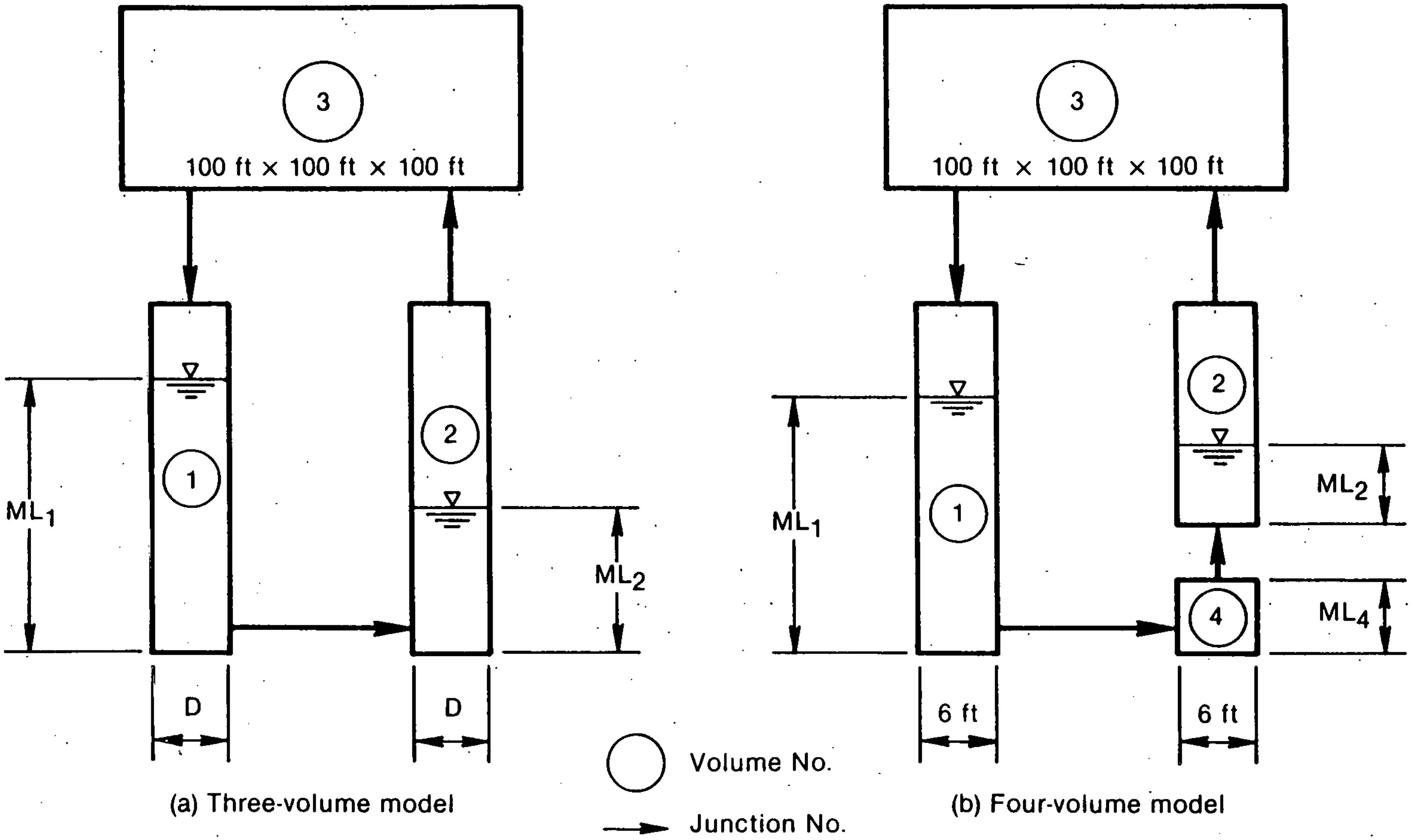

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Fig. 2 RELAP4 Manometer Models

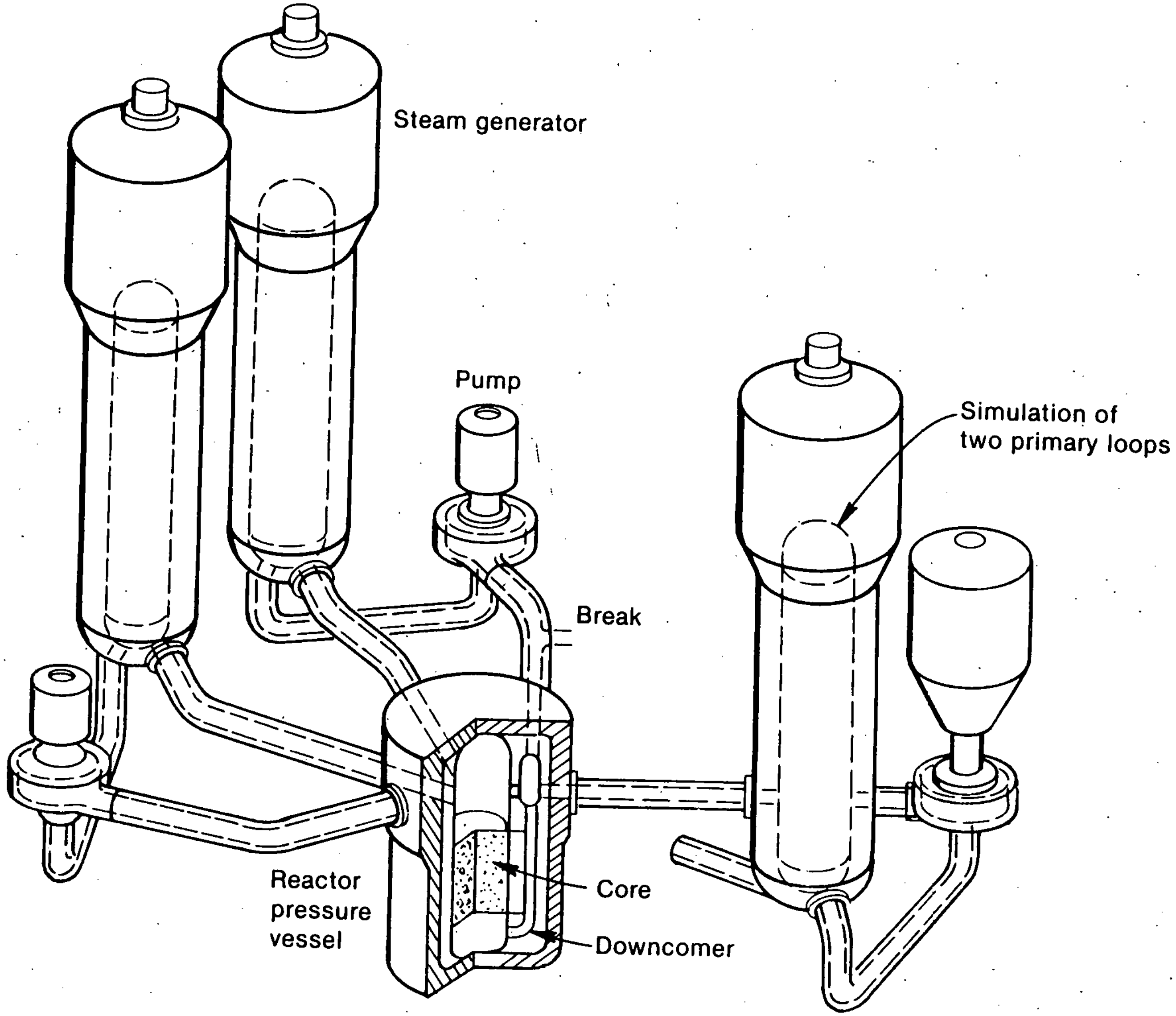

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Fig. 3 The West German PKL Reflood Test Facility

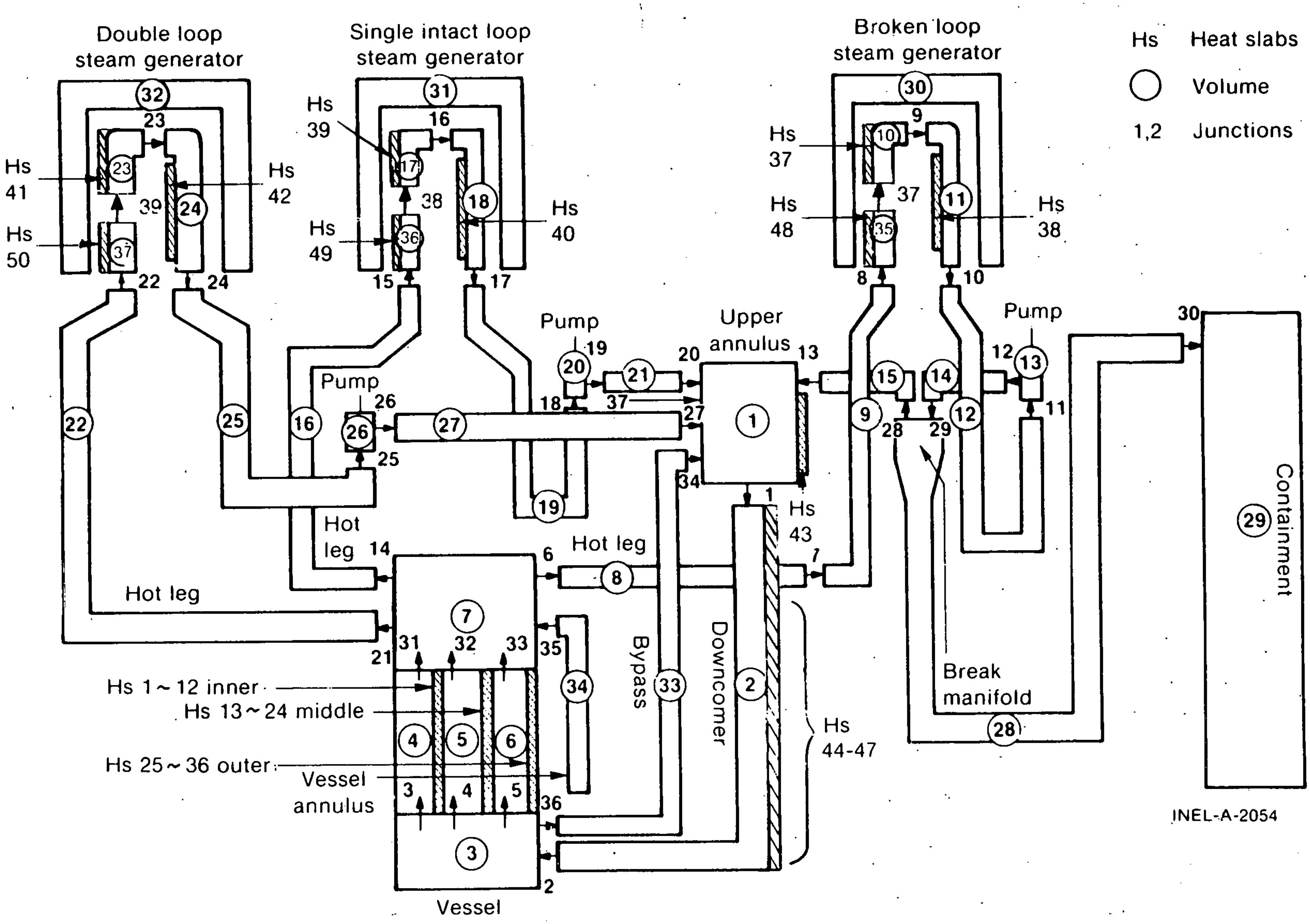

Fig. 4 PKL Three-loop RELAP4/MOD6 Nodalization

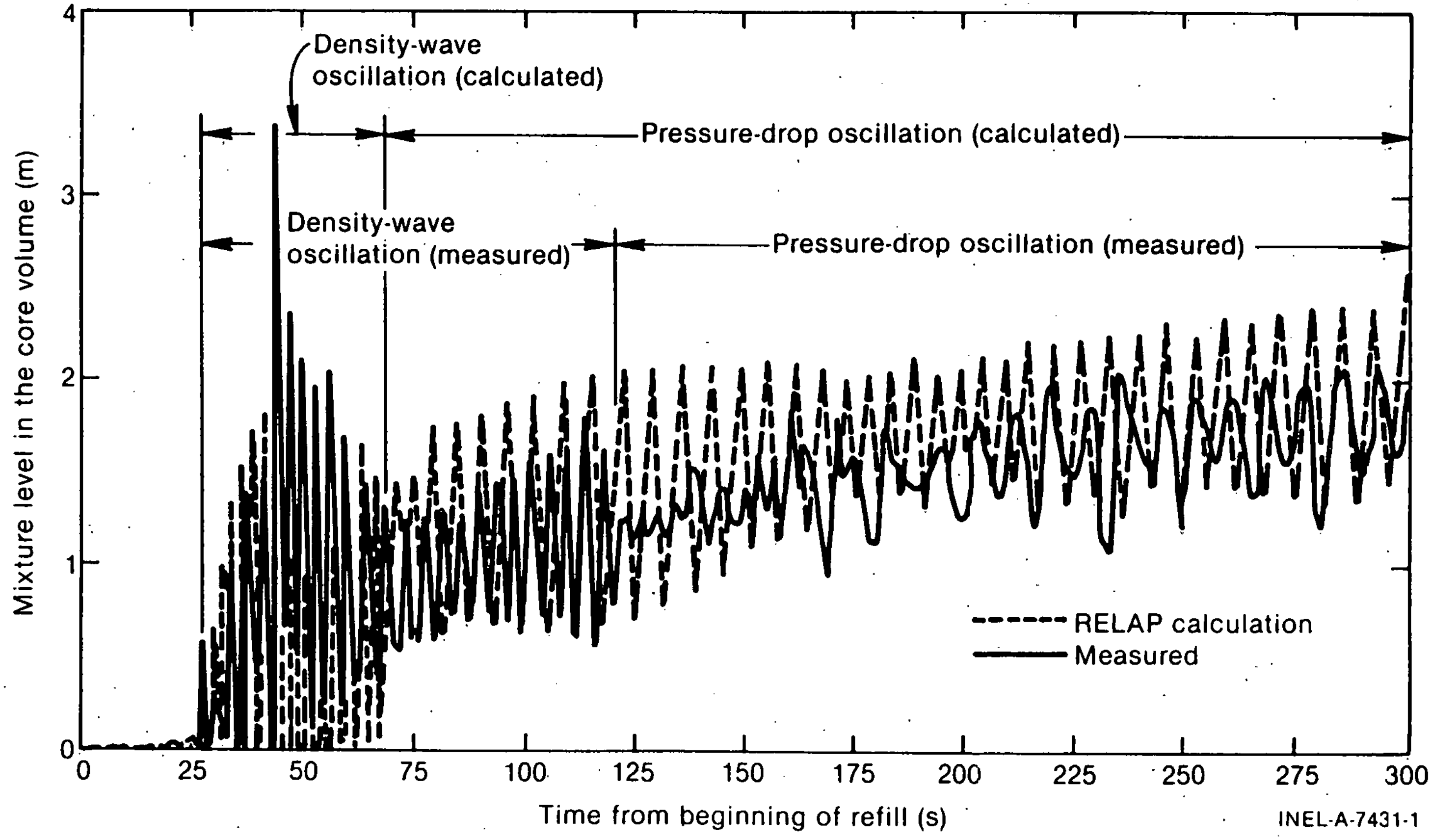

Fig. 5 Comparison of Calculated and Measured Flow Oscillations in the Core Volume for PKL Reflood Test K5A

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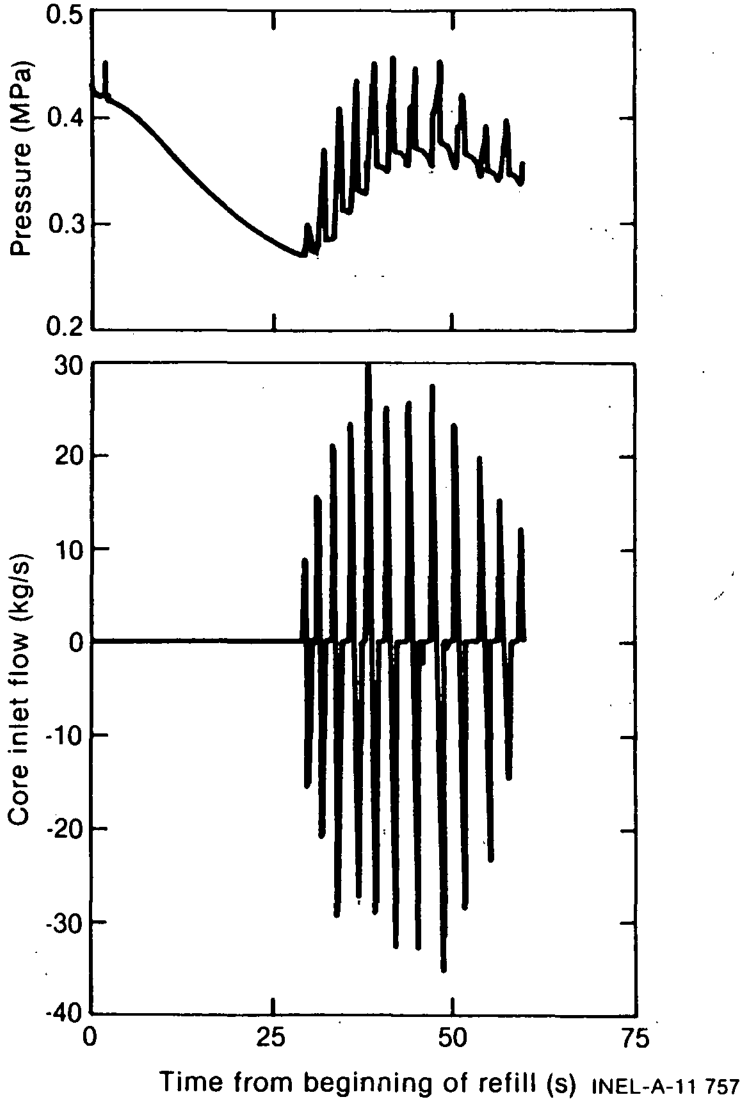

Fig. 6 Comparison of the Calculated Lower Plenum Pressure Fluctuations and Mass Flow Rate at the Core Hot Channel Inlet

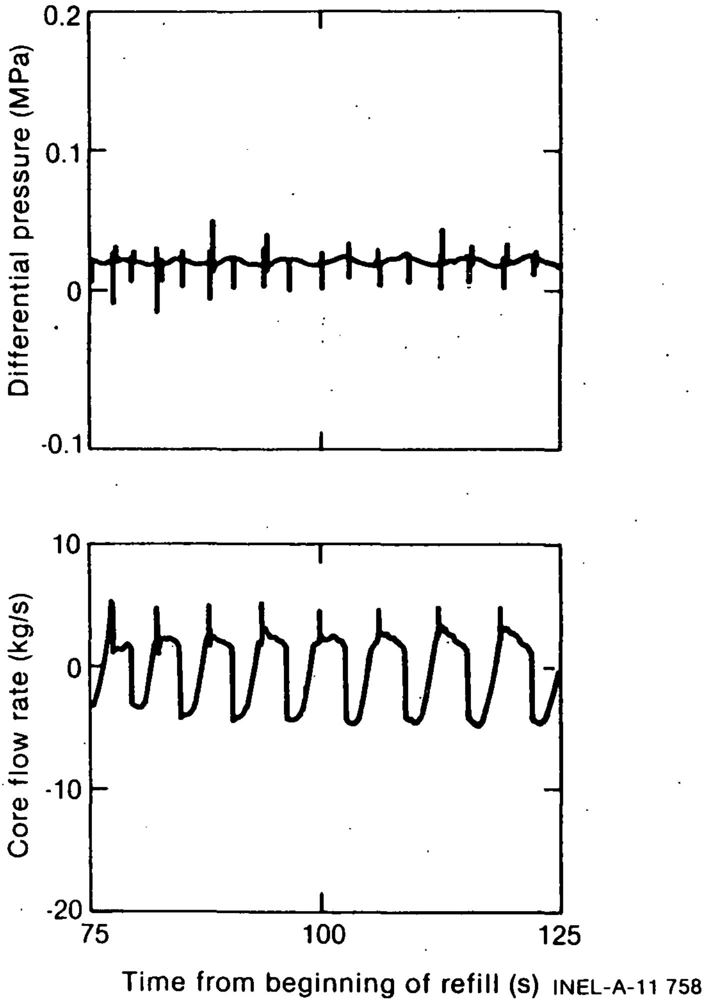

Fig. 7 Relationship Between the Calculated Pressure Drop Across the Core Hot Channel and the Net Core Mass Flow Rate

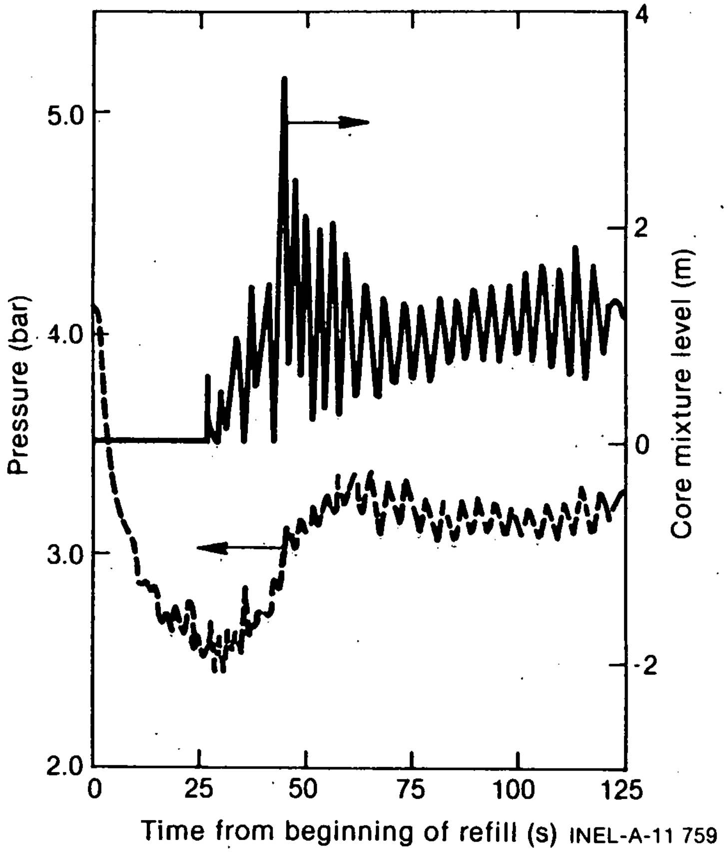

Fig. 8 Comparison of the Measured Core Mixture Level with Measured Core Inlet Pressure Fluctuations

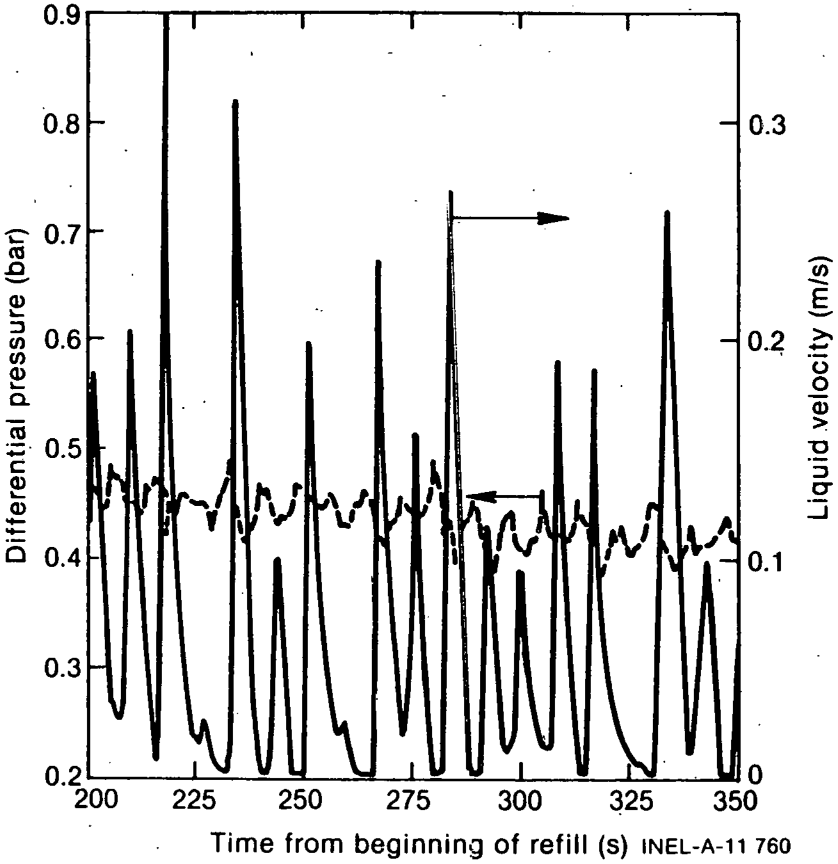

Fig. 9 Comparison of the Measured Pressure Drop Across the Upper Annulus and the Upper Plenum, and the Liquid Velocity in the Downcomer

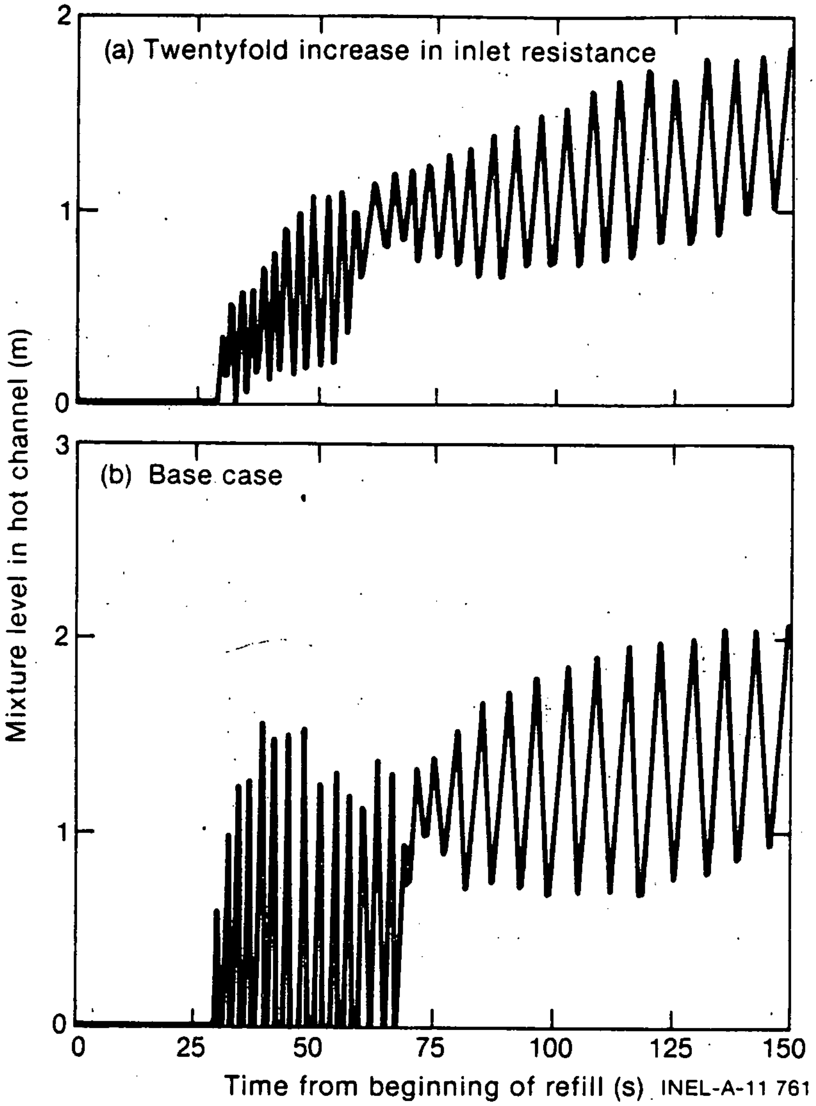

Fig. 10 The Effect of Increasing Core Channel Inlet Resistance on Calculated Mixture Level Oscillations

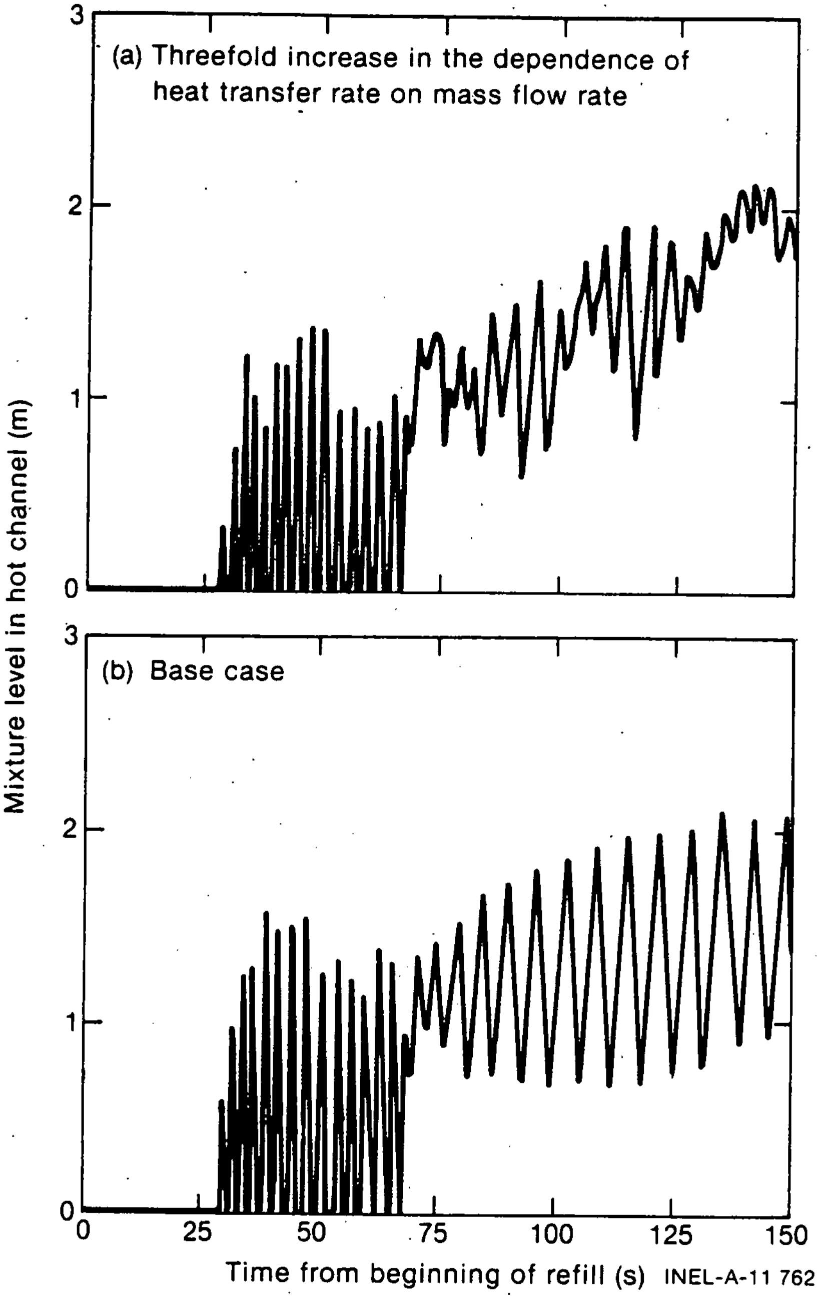

Fig. 11 The Effect of Increasing the Dependence of Heat Transfer Rate on Mass Flow Rate on Calculated Mixture Level Oscillations

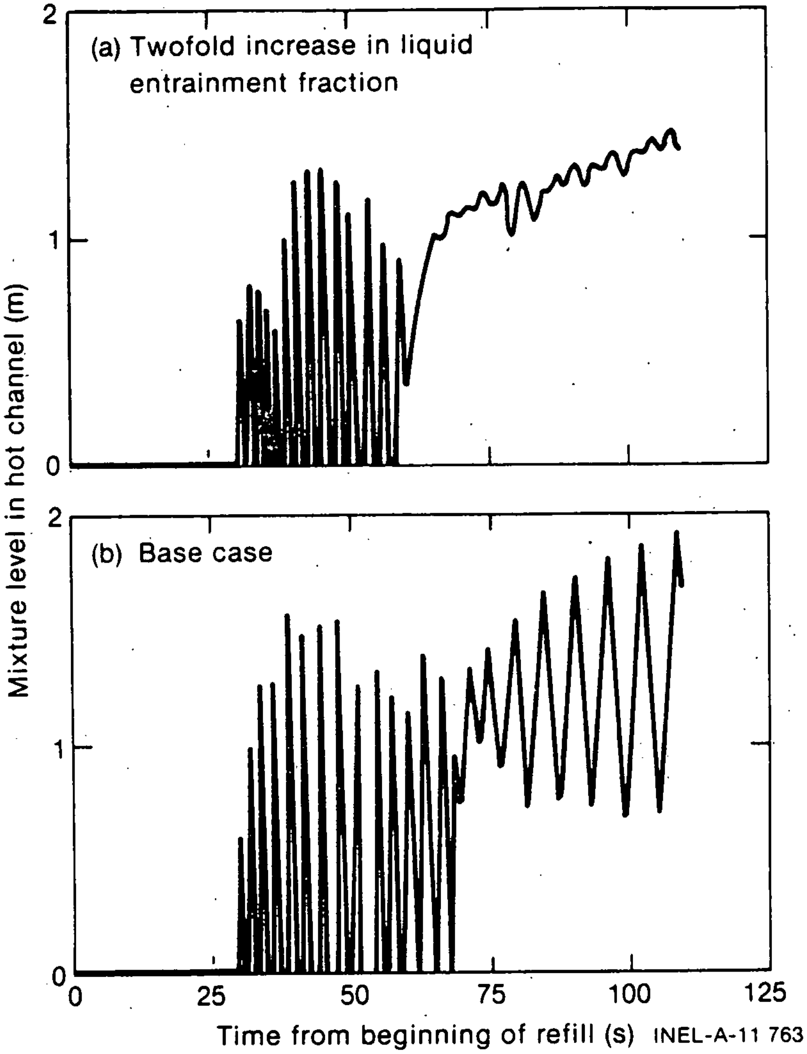

Fig. 12 The Effect of Increasing the Liquid Entrainment Fraction in the Core Channel on Calculated Mixture Level Oscillations.