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Fifteenth Water Reactor Safety Information Meeting

Volume 4

- Separate Effects/Experiments and Analyses
- Source Term Uncertainty Analysis
- Integral Systems Testing
- 2D/3D Research

Held at
National Bureau of Standards
Gaithersburg, Maryland
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Reflooding Phenomena of German PWR
Estimated from CCTF, SCTF and UPTF Results

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Abstract

The reflooding behavior in a PWR with a combined injection type ECCS was studied by comparing the test results from Cylindrical Core Test Facility (CCTF), Slab Core Test Facility (SCTF) and Upper Plenum Test Facility (UPTF).

Core thermal-hydraulics is discussed mainly based on SCTF test data.

In addition, the water accumulation behavior in hot legs and the break-through characteristics at tie plate are discussed.

1. Introduction

Under the 2D/3D program, Japan Atomic Energy Research Institute (JAERI) is investigating reflood behavior in a German PWR with a hot leg and cold leg injection (combined injection) type emergency core cooling system (ECCS) by using test data from the Cylindrical

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The work was performed under contract with the Atomic Energy Bureau of Science and Technology Agency of Japan.

Core Test Facility (CCTF)[1] and Slab Core Test Facility (SCTF)[1] in JAERI and Upper Plenum Test Facility (UPTF) [2] in FRG.

Several CCTF tests were performed to study the over-all system characteristics of the reflood behavior for a PWR with a combined injection type ECCS. However, there is a possibility that the observed phenomena might be different from those in a PWR, since the volumetric scaling of CCTF is one twenty-fourth of a 1000 MWe class PWR. As shown in Fig 1, cross sectional area of CCTF core is almost equal to the one zone of steam/water injector in UPTF which simulates a full size PWR. On the other hand, SCTF has the heated core with the same radius as UPTF or PWR, but no realistic primary loop. UPTF is a full scale facility, however it substitutes a heated core and steam generators in PWR by a core simulator with steam/water injectors and steam/water separators with steam/water injector. The characteristics of each facility are summarized in Table 1.

In this presentation, JAERI's plan for the investigation of the reflooding behavior in a PWR with combined injection type ECCS is outlined and the most probable picture on the reflooding behavior is drawn based on the comparison of the test results from CCTF, SCTF and UPTF.

Some special phenomena are selected and discussed in this presentation as seen in Sections 3-6, since these phenomena are considered to be important. The data are mainly referred CCTF[3] Run 79, SCTF Run 717, and UPTF Test 3. They are performed under evaluation model condition.

2. Outline of JAERI's plan

As shown in Fig.2, JAERI is planning to make physical understanding of the reflooding behavior in a PWR with combined injection type ECCS by analysing the CCTF, SCTF and UPTF test results.

Based on the physical understanding, JAERI is planning to establish a quantitative prediction method on the reflooding behavior.

3. Hot leg water accumulation

Figure 3 shows CCTF test results on the fluid density and vertical differential pressure in a hot leg. Some amount of water accumulated in the hot leg as shown in the figure. The water accumulation in the hot leg was found to be close to slug flow from 92 to 103 s and after 135 s of the transient, when the water accumulation in the upper plenum was as high or higher than the hot leg nozzle. The flow from 105 to 135 s, on the other hand, was close to stratified as indicated by the 3-beam γ density measurement.

Figure 4 shows CCTF test results on the differential pressures across riser and steam generator plenum, and across steam generator tubes. The osillatory differential pressure across riser and steam generator plenum in loop 4 (broken loop) coincides with the oscillatory differential pressure across steam generator tubes. This indicates that the water penetrated into the steam generator tube is quickly vaporized. The generated steam then pushes the water in the steam generator plenum buck to vessel side resulting in the flow oscillation in the beoken loop. In the intact loops (loop 1 and 3), on the other hand, the differential pressure and hence the flow across steam generator tubes are almost zero. This is because that the loop seal part is quickly filled with ECC water injected into cold legs, which prevented the flow in the intact loops.

Figure 5 shows UPTF test results on fluid density in a hot leg. The water accumulation in the hot leg is oscillatory and close to slug flow in the intact loops, even if the water level in the upper plenum is comparatively low. This is supposed to be related to the continuous steam injection from the steam generator simulator used in UPTF test operation. On the other hand, a relatively continuous water accumulation in the hot leg was observed in CCTF. Either intermittent or continuous water accumulation in the hot legs can occur in GPWR's depending on transient conditions. To investigate this phenomena, a more sophisticated test in UPTF is necessary, simulating natural feedback from the steam generator. It should also be noted that the large flow oscillatinon observed in CCTF broken loop is carefully considered for the future test planning.

4. Core thermal-hydraulics

Figure 6 shows the illustration[4] on the core thermal-hydraulics, which has been derived from SCTF and CCTF test results. In the core, two regions are formed during reflood phase, i.e. water downflow region and non-downflow region (two-phase upflow region). A flow circulation is observed in the core.

Figure 7 shows the clad temperatere in water downflow region. The clad temperature indicates a quick quenching and good cooling before the reflood initiation due to downflowing water (not staying water). Figure 8 shows the clad temperature in two-phase upflow region. The clad temperature gradient after ECC water injection till reflood initiation in SCTF is nearly identical to that before ECC water injection indicating poor core cooling in this region and time period in the SCTF test.

In actual PWR, core cooling due to downward two-phase flow during end-of-blowdown and refill periods can be expected. However, this effect cannot be included in this test results because of initiation of the test from steady conditon at 6 bars.

Figure 9 shows a flow circulation in the core observed in SCTF. This flow circulation is induced by the region separation (water downflow region and two-phase upflow region). The numbers in the figure were obtained from various measurement, so that each value is not quantitatively consistent with each other due to the measurement error. However, the existence of a strong flow circulation is considered to be certain.

In a PWR, the fluid temperature from the upper plenum to the core depends on the heat exchange between the upflowing steam and the injected ECC water in the upper plenum. The heat exchange is governed by the mixing and the condensation behaviors in the upper plenum. The supposed subcooling of the downflowing water in a PWR is considered to be 20-40K in average based on the UPTF result[3]. Referring to this value, high subcooling test (△Tsub=40K) and low subcooling test (△Tsub=15K) have been performed. The comparison of core boundary conditions is shown in Table 2.

Figure 10 shows the core thermal-hydraulics of high and low subcooling tests. High subcooling gives a low water temperature at the core inlet, a stronger flow circulation and then a higher core flooding rate, and more water accumulation in the core. The resultant clad temperature transient shows that the high subcooling gives good core cooling, as noticed from Fig.11.

The heat transfer coefficient in the two-phase upflow region is higher than the predicted with Murao-Sugimoto correlation[5] which is developed for a PWR with cold leg injection type ECCS, under rather low core flooding rate (a few cm/s) as shown in Fig. 12. However, by modifying the correlation by newly including the effect of the high core flooding rate[6], the heat transfer can be predicted well for both high and low subcooling tests, except for early reflood phase (0-50 s).

Figure 13 shows the comparison of void fraction and core differential pressure (differential pressure across bottom and top of the core) between the measured in SCTF and the predicted with REFLA code[7]. In REFLA code, we assumed that the core was fully filled with two-phase flow along the entire elevation. (This means no pure steam existence.) The predicted result nearly agrees with the data. Therefore, we consider that the core is fully filled with two-phase flow after the reflood initiation. In UPTF, the water can be accumulated in the lower part of the core and the steam region can be formed in the core.

As shown in Fig.14, the differential pressures of various sections are related. We assume for simplicity that the downcomer is filled with solid water and $\Delta P_{B/SG}$ is negligible in comparison with ΔP_{DC}, then

$$\Delta P_{CORE} + \Delta P_{UP} + \Delta P_{B/SG} = \Delta P_{DC}$$

Therefore, if ΔP_{CORE} is larger, ΔP_{UP} and/or $\Delta P_{B/SG}$ becomes smaller. This means that water accumulation in the upper plenum and the loop differential pressure can be simulated well only when both two-phase flow from core to upper plenum (steam flow and net water flow excluded de-entrainment below the tie-plate) and core differential presuure are typical. Accordingly, it is necessary to pay special attention to boundary conditions.

5. Tie plate counter-current flow limitation (CCFL)

(Scale effect)

Figure 15 shows the region where the break-through occurred in CCTF. The break-thrugh occurs in one wide region (~ 35% of core area) before the reflood initiation. It terminates once after the reflood initiation.

Other characteristics are obesrved in UPTF, as shown in Figs. 16 and 17. The break through occurs in two (or one) regions. The break-through continues during the entire test period. The break-through location moves with time. The difference in the number and the location of the break-through region is thought to be caused by the difference in multi-dimensionality of the behavior due to different scaling. In CCTF, the break-through tends to concentrate in one region due to a small scale.

The moving of the break-through location in UPTF is attributed to the intermittent delivery of water from the hot legs to the upper plenum almost in opposite phase between loops 2 and 3.

6. Tie plate CCFL (Heated core)

No break-through occurred near the hot leg in CCTF where intermittent water delivery was observed (the broken hot leg), whereas break-through occurred even near the hot legs in UPTF where intermittent water delivery was observed.

In order to investigate whether the intermittent tie plate CCFL break found near such hot legs in UPTF Test 3 occurs also in the case of heated core, a SCTF test was performed as a UPTF/SCTF coupling test. In this SCTF test the intermittent ECC water injection was made just above the upper core support plate to simulate the intermittent water delivery. The injection flow rate is shown in Fig.18. Just after the initiation of the injection, the differential pressure across the end box tie plate below the injection location shows the negative value, indicating an immediate break-through occurrence. Hence, it is confirmed that the break-through occurs also with the heated core near the hot leg where intermittent water delivery occurs as observed in UPTF Test 3.

7. Conclusions

CCTF, SCTF and UPTF test data were compared concerning to reflooding behavior in a PWR with combined injection type ECCS's.

Usefulness of those tests were clarified. Especially, SCTF test with full radius active core is valuable for studying core thermal-hydraulics. Upper plenum and loop behavior can be studied with full size UPTF but special attention should be paid to the boundary conditions. For broken loop behavior, CCTF test with active steam generator should be referred.

The remarkable findings through this study are:

(1) existence of region with little core cooling before reflood initiation under initial conditions based on licensing assumption.

(2) flow circulation on occurrence in core after reflood initiation, and

(3) good core cooling due to the flow circulation

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[1] K.Hirano and Y.Murao; J. At. Energy Soc, Japan, Vol.22, 10,681-686 (1980).

[2] K.R. Hofmann; 2nd Int. topical Mtg. on Nucl. Power plant Thermal Hydraulics and Operations, 2-113 (1986).

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[4] T.Iguchi; 14th Water Reactor Safety Information Mtg. (1986).

[5] Y.Murao and J.Sugimoto; J. Nucl. Sci. Technol., 18(4), 275-284 (1981).

[6] A.Onuki; Private communication.

[7] Y.Murao, et al.; JAERI-M 84-243 (1984)

Table 1 Characteristics of experimental facilities

CCTF :	· integral system simulation · 1/21 volumetric scaling
SCTF :	· wide heated core simulating actual radius · imperfect system simulation (e.g. simulated steam generator by steam/water separator with steam injection system) · 1/21 volumetric scaling
UPTF :	· actual size · simulated non-heated core with steam and water injection system · simulated steam generator by steam/water separator with steam injection system

Table 2 Comparison of core boundary conditions

	SCTF Run 717	CCTF Run 79		SCTF Run 722
Heat transfer coefficient (W/m^2K)	170	130	Difference between SCTF and CCTF +40 W/m^2K	110
			Estimation of parameter effect contribution	
Pressure (MPa)	0.35	0.25	~ 10 W/m^2K	0.35
Local power (kW/m) (Power ratio)	1.4 (1.08)	1.55 (1.36)	~ − 30 W/m^2K	1.25 (1.08)
Cladding temperature at reflood initiation (K)	1010	930	~ 0 W/m^2K	1080
Total power (kW)	6000	5500	~ 0 W/m^2K	6000
Hot leg ECC water temperature (K)	310	305	————	390
Subcooling of falling water (K)	41	19	————	16

SCTF Run 717 } Under boundary conditions estimated in safety analysis (EM conditions)
CCTF Run 79 } and referring other test results partly

SCTF Run 722 Higher ECC water temperature than in Run 717

Falling water temperature in PWR : UPTF results (Test 3)
Falling water subcooling 20 ~ 40 K

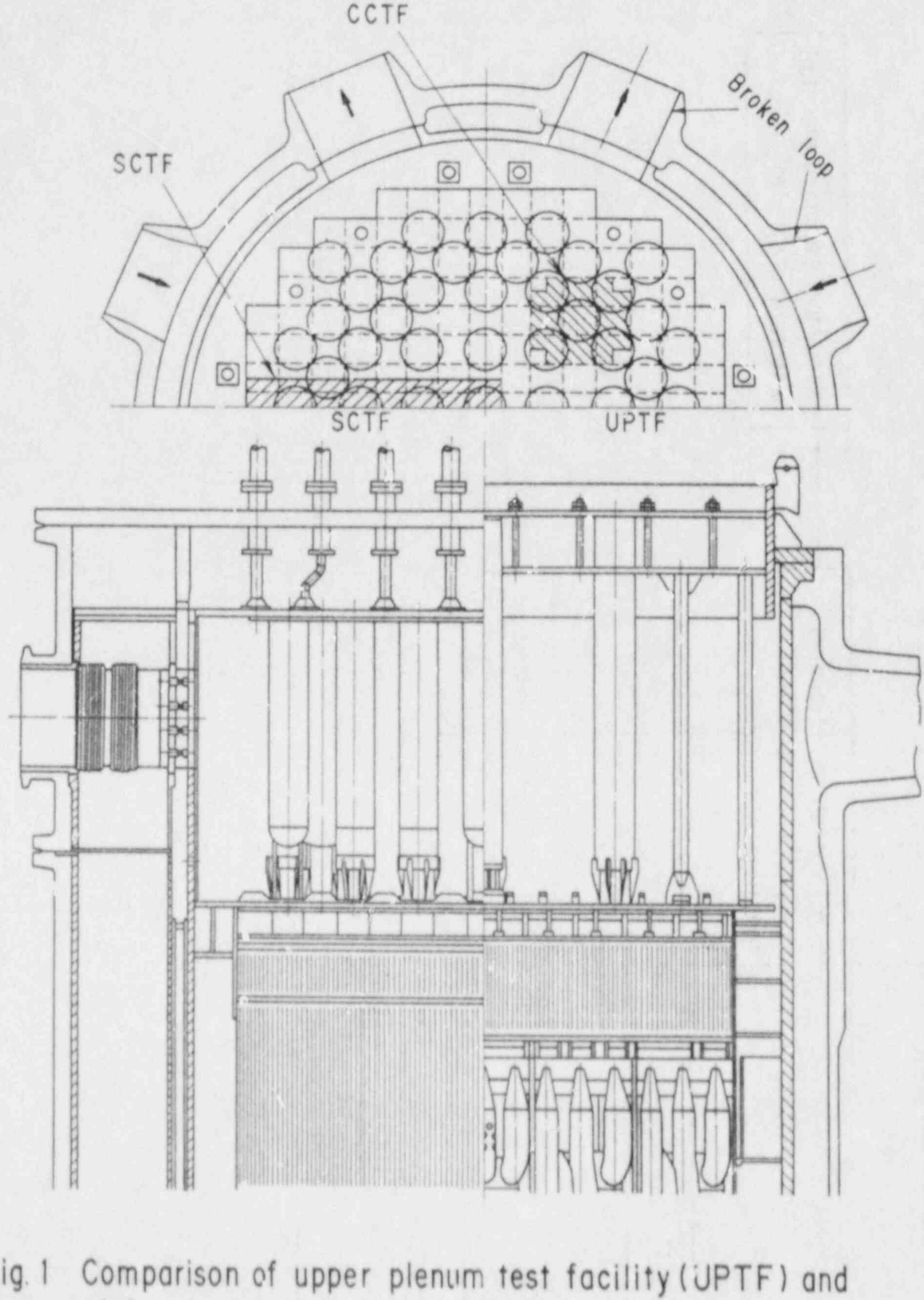


Fig. 1 Comparison of upper plenum test facility (UPTF) and slab core test facility (SCTF)

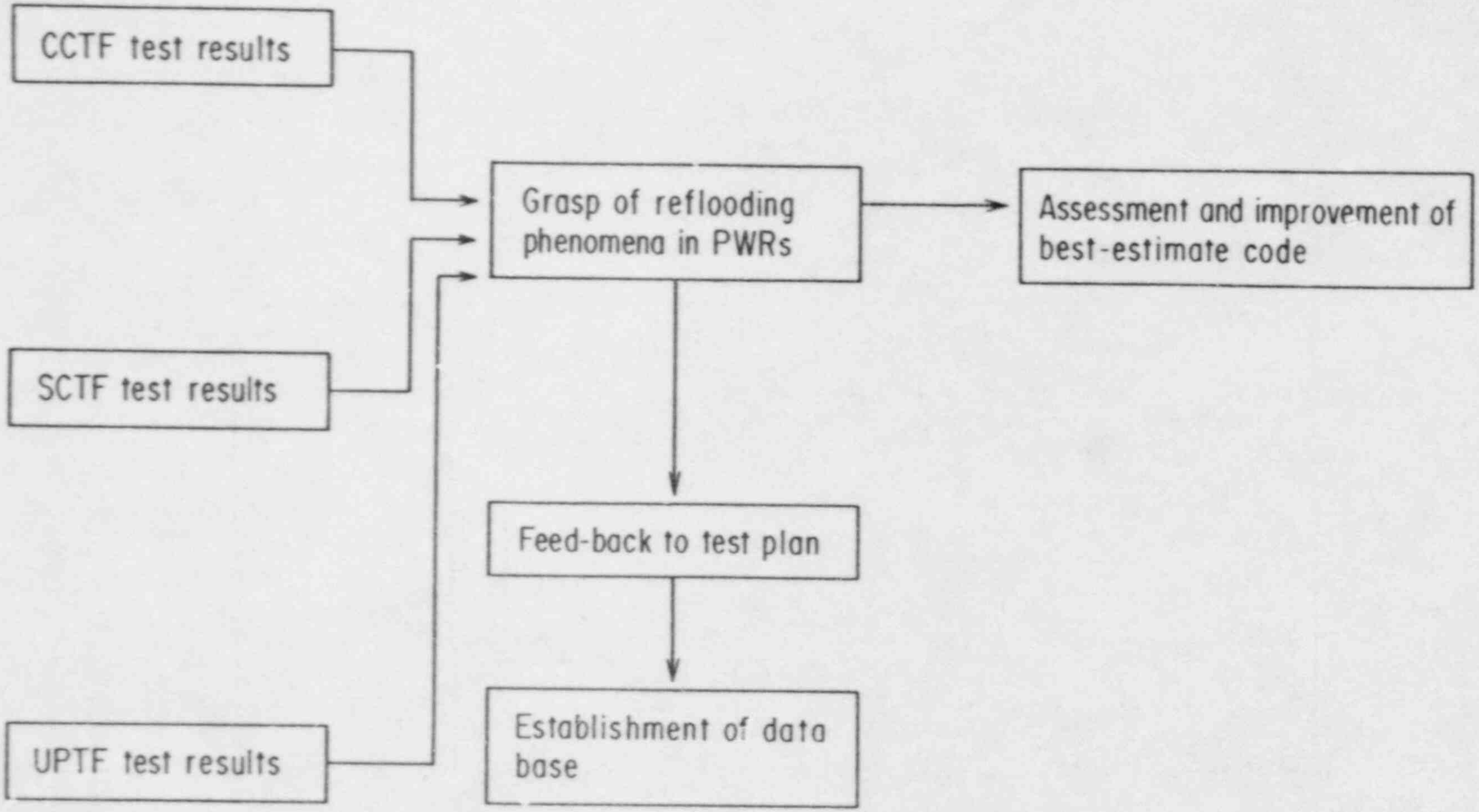


Fig. 2 JAERI's plan

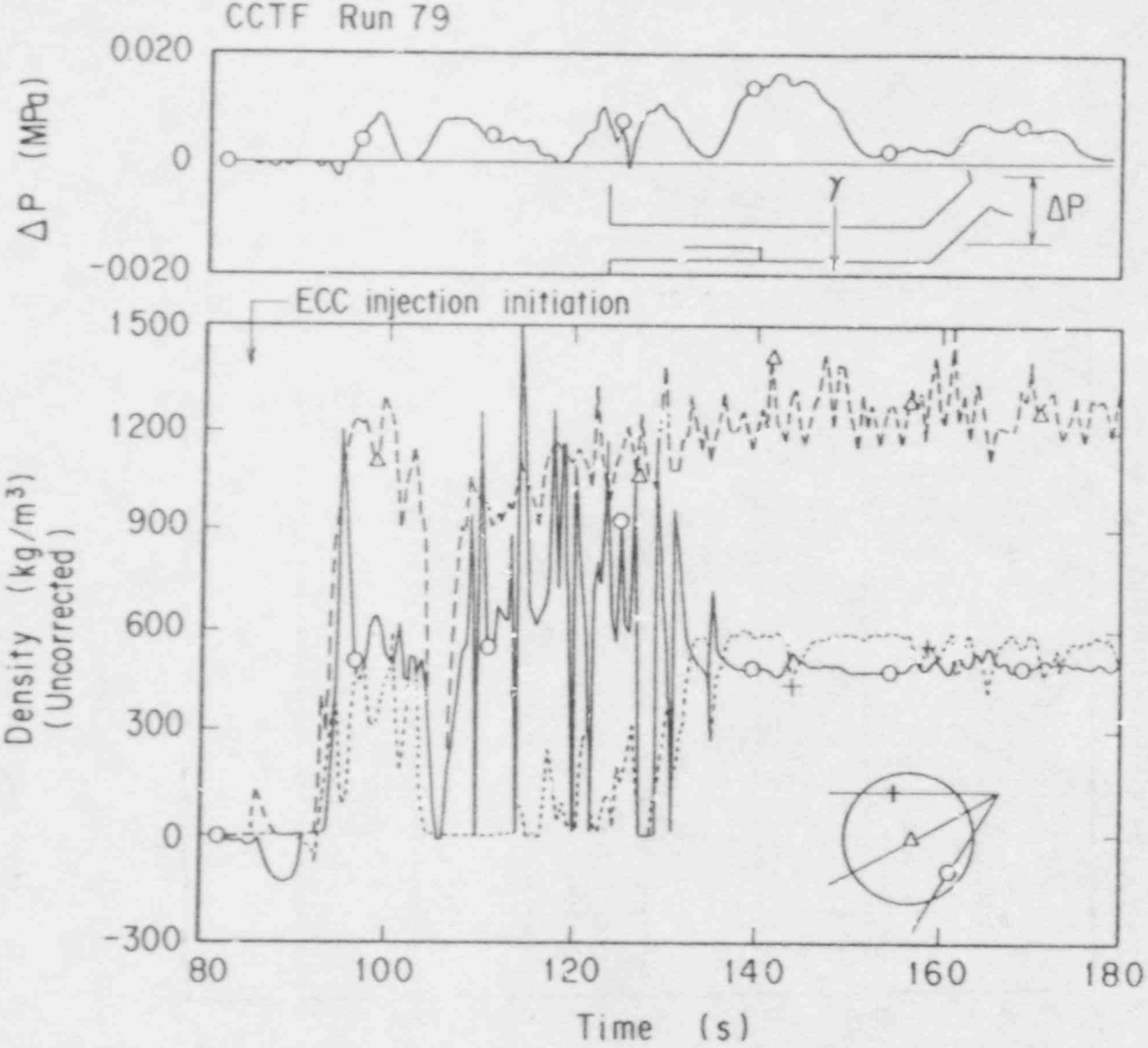


Fig. 3 Hot leg water accumulation in CCTF

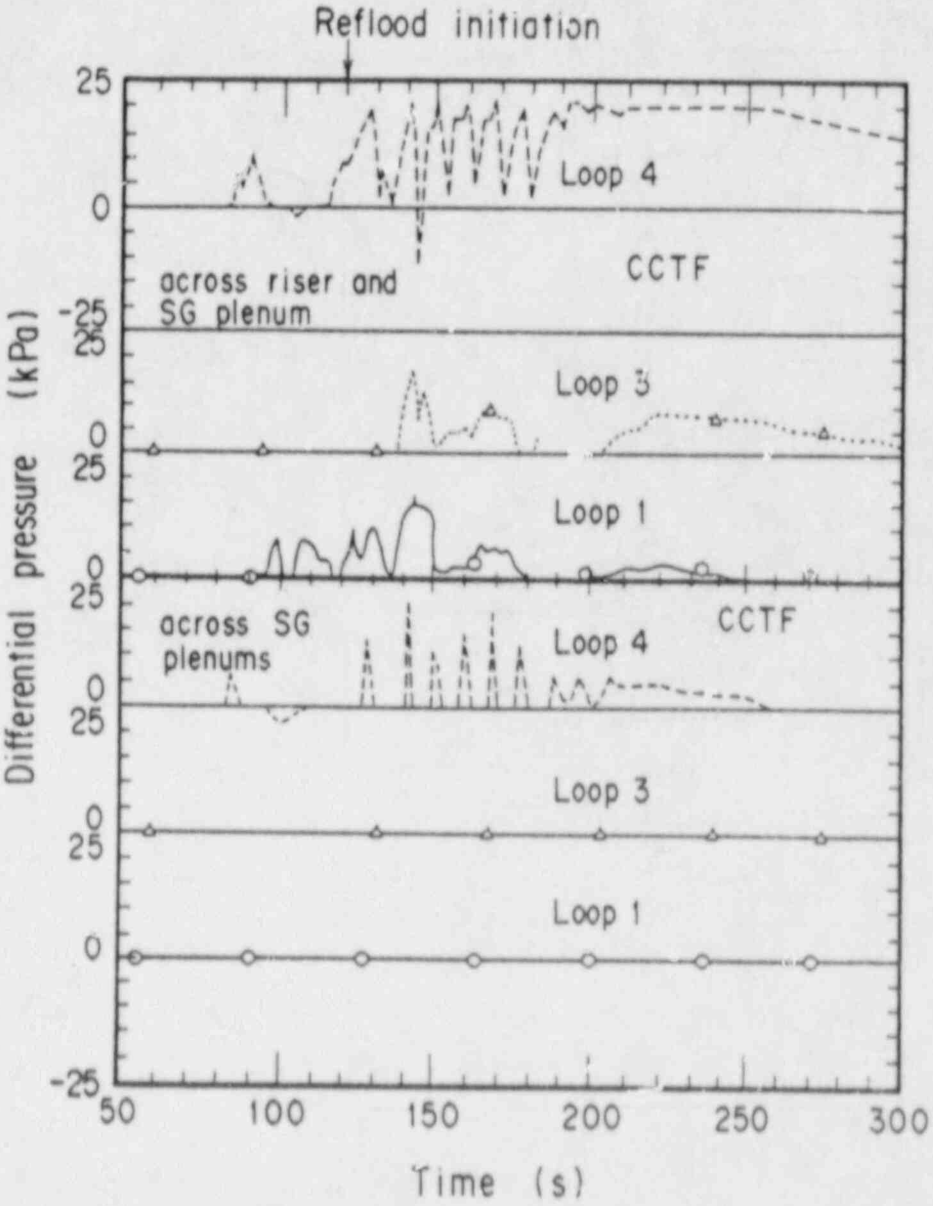


Fig. 4 Hot leg differential pressures in CCTF

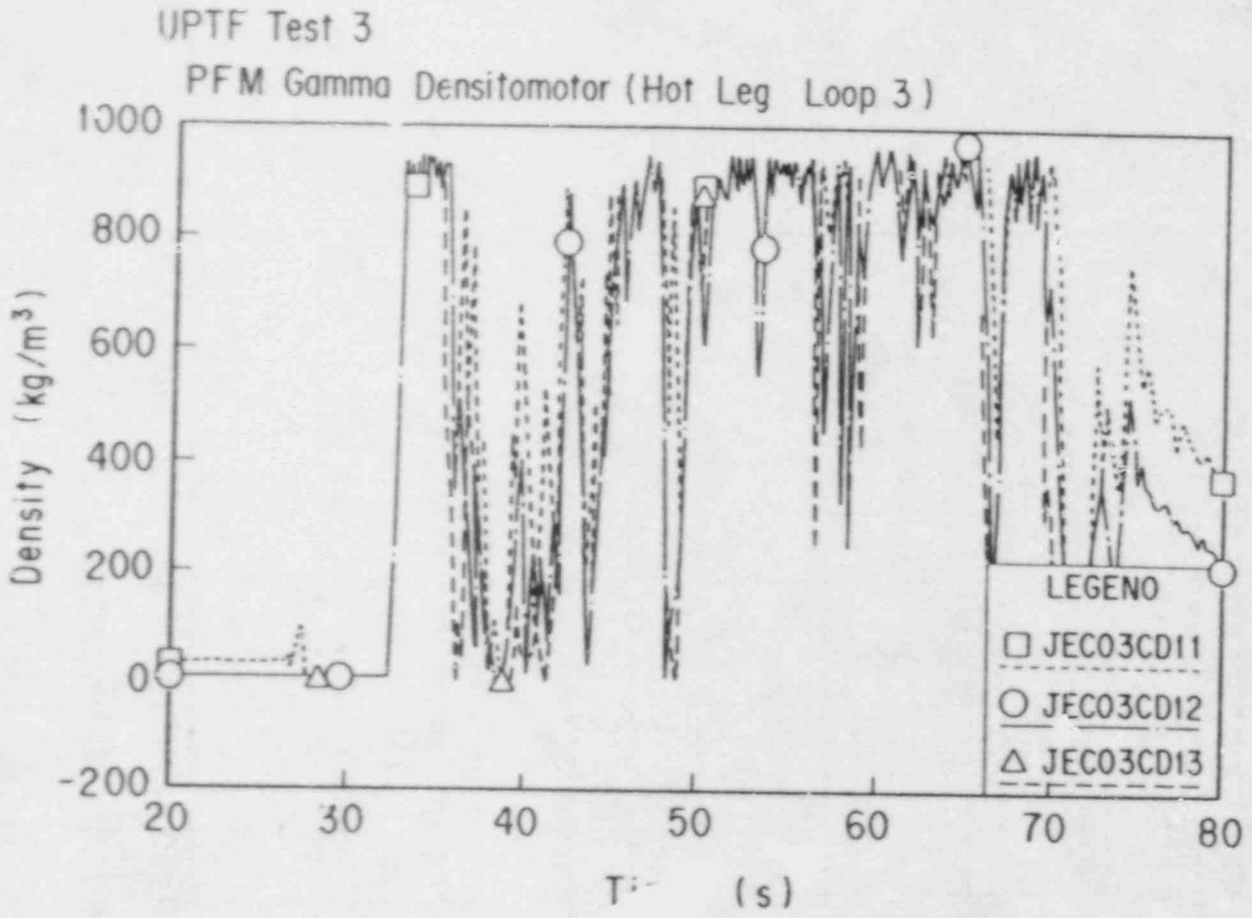
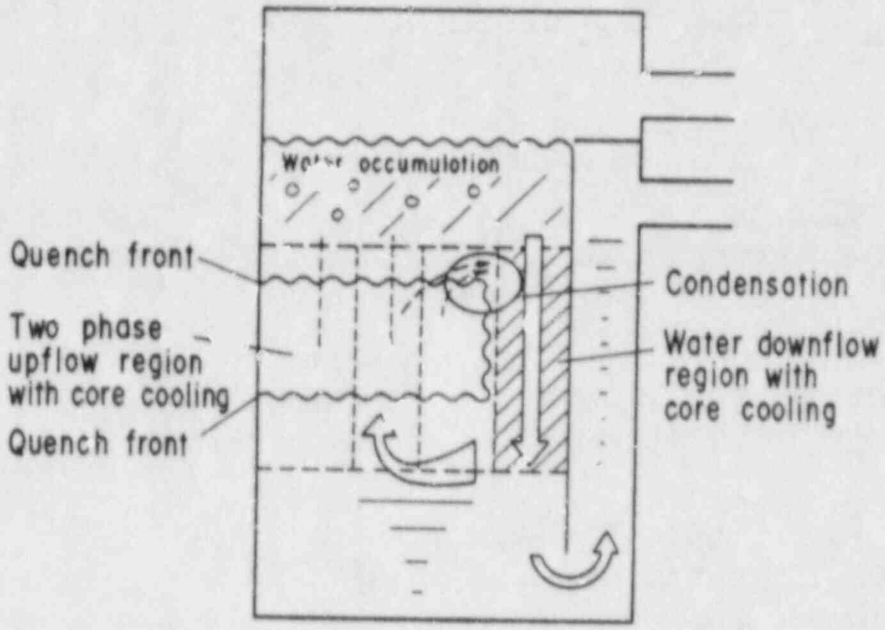


Fig. 5 Hot leg water accumulation in UPTF



- Formation of water downflow region and two-phase upflow region
- Formation of circulation flow going down in water downflow region and going up in two-phase upflow region
- Enhanced core cooling in two-phase upflow region

Fig. 6 Thermo-hydraulics in pressure vessel observed in SCTF test

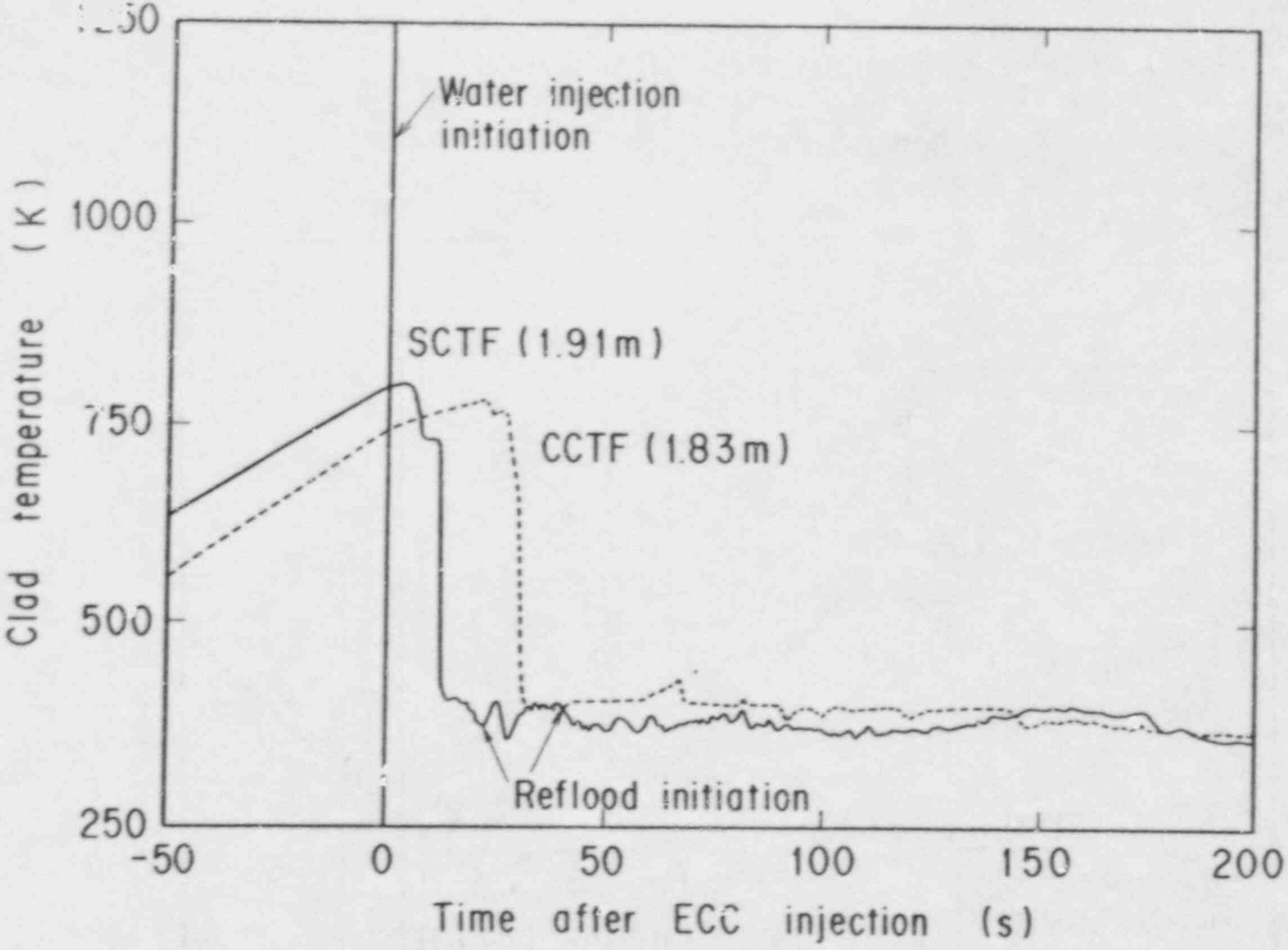


Fig. 7 Core cooling in water downflow region before reflood initiation

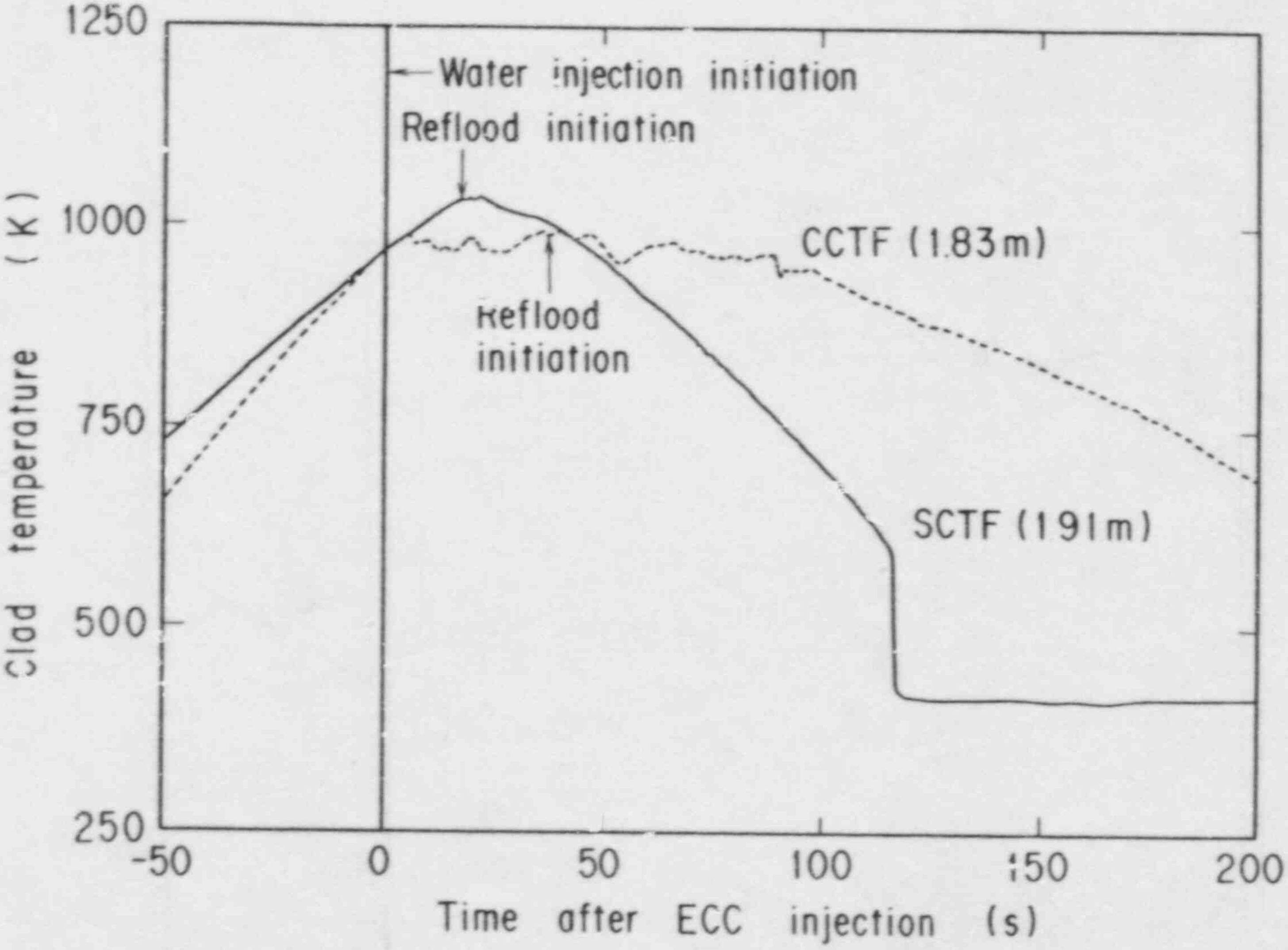


Fig. 9 Cladding temperatures in two-phase upflow region

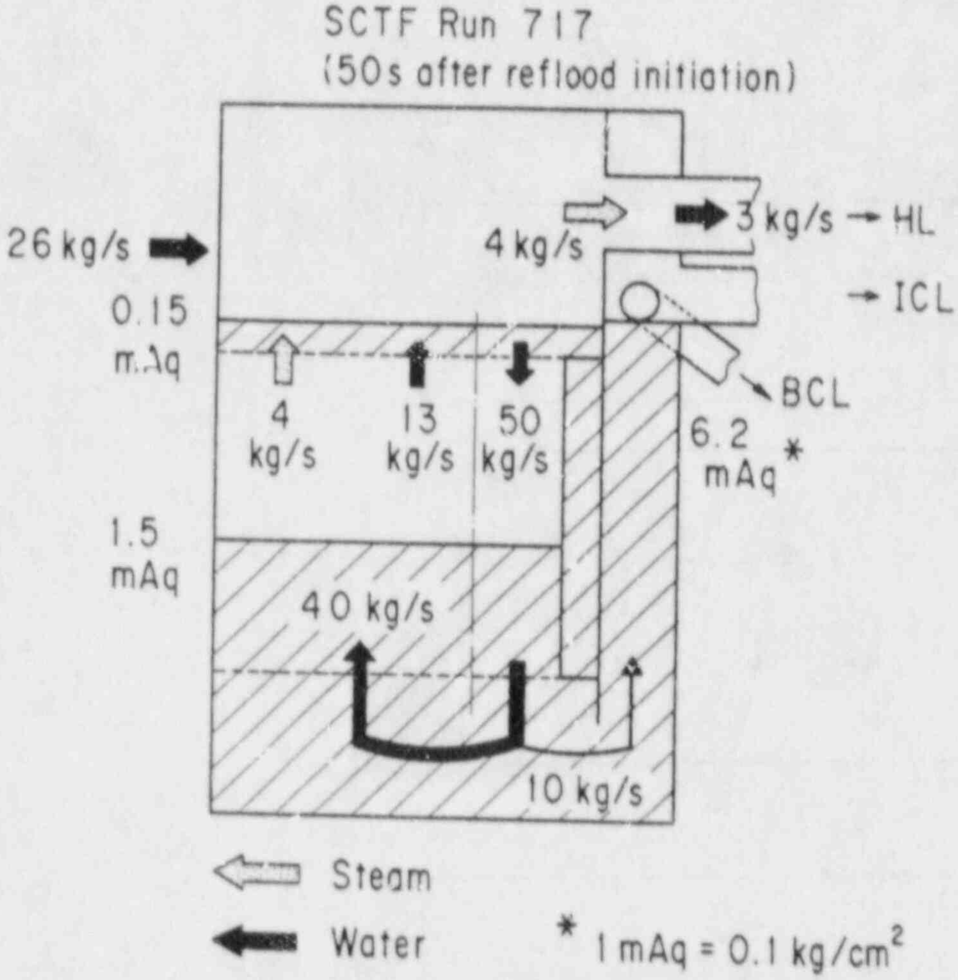


Fig. 9 Circulation flow in core caused by water falling down

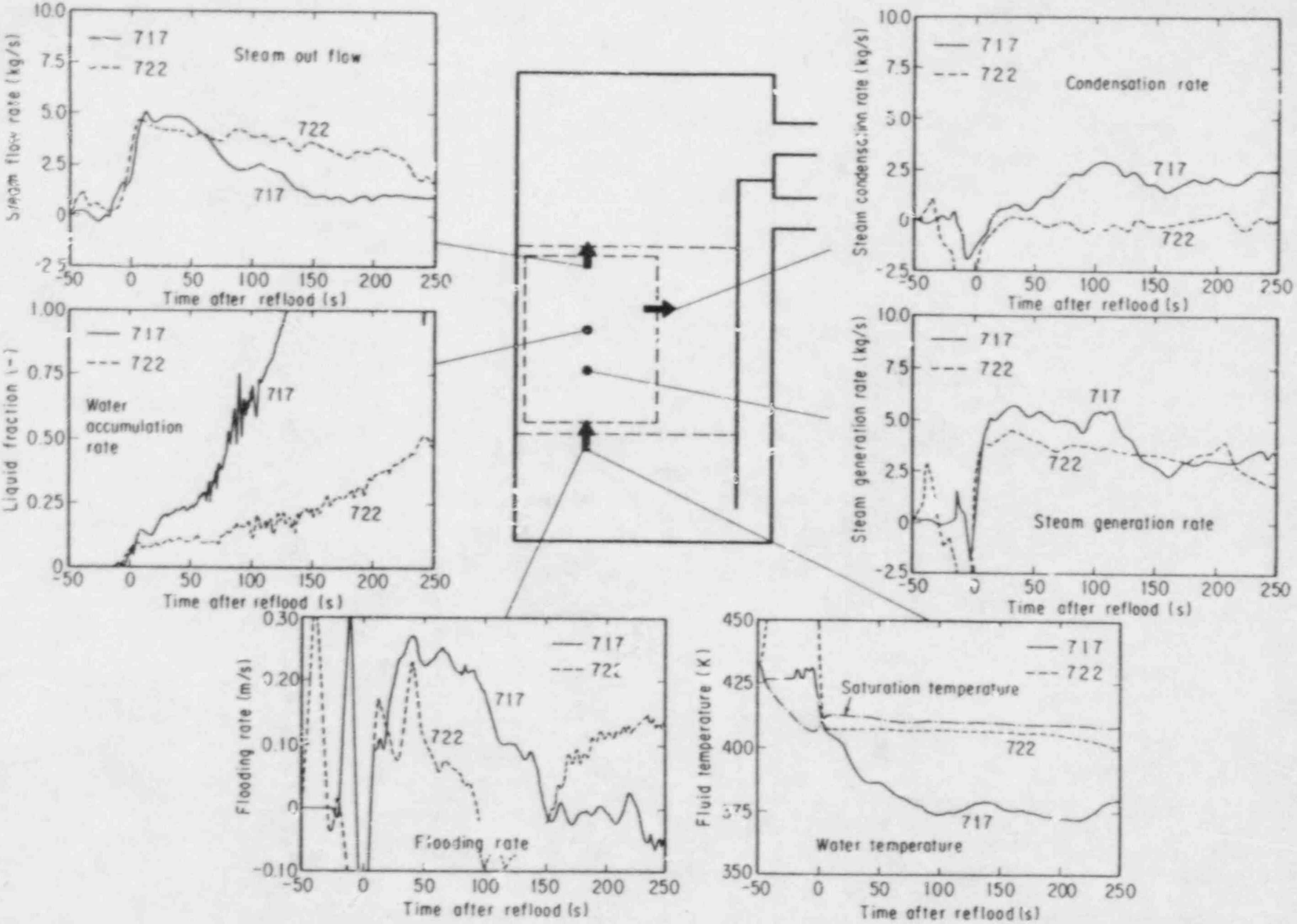


Fig. 10 Difference of core behavior due to difference of break-through water temperature

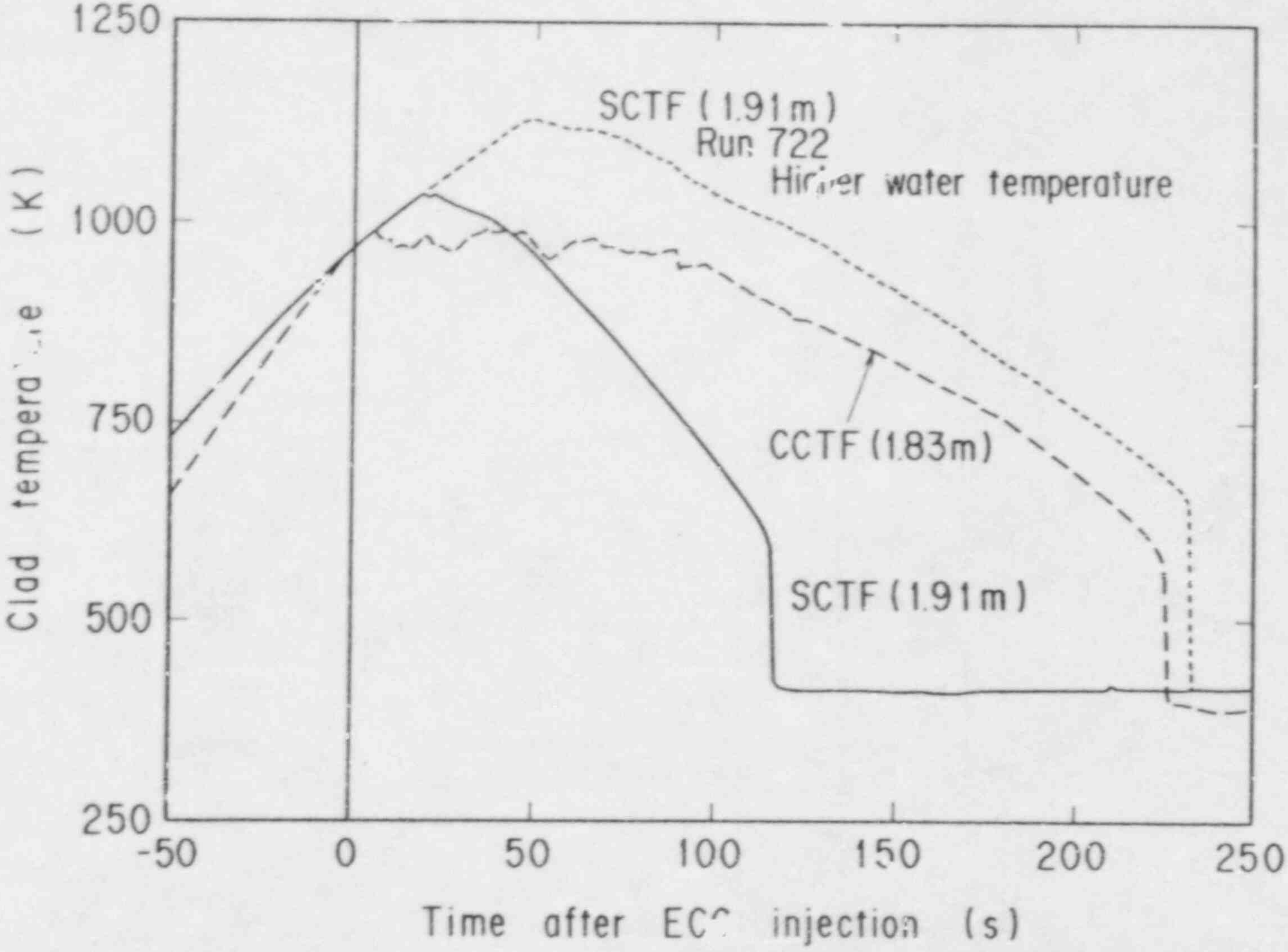


Fig. 1. Cladding temperature under higher break-through water temperature

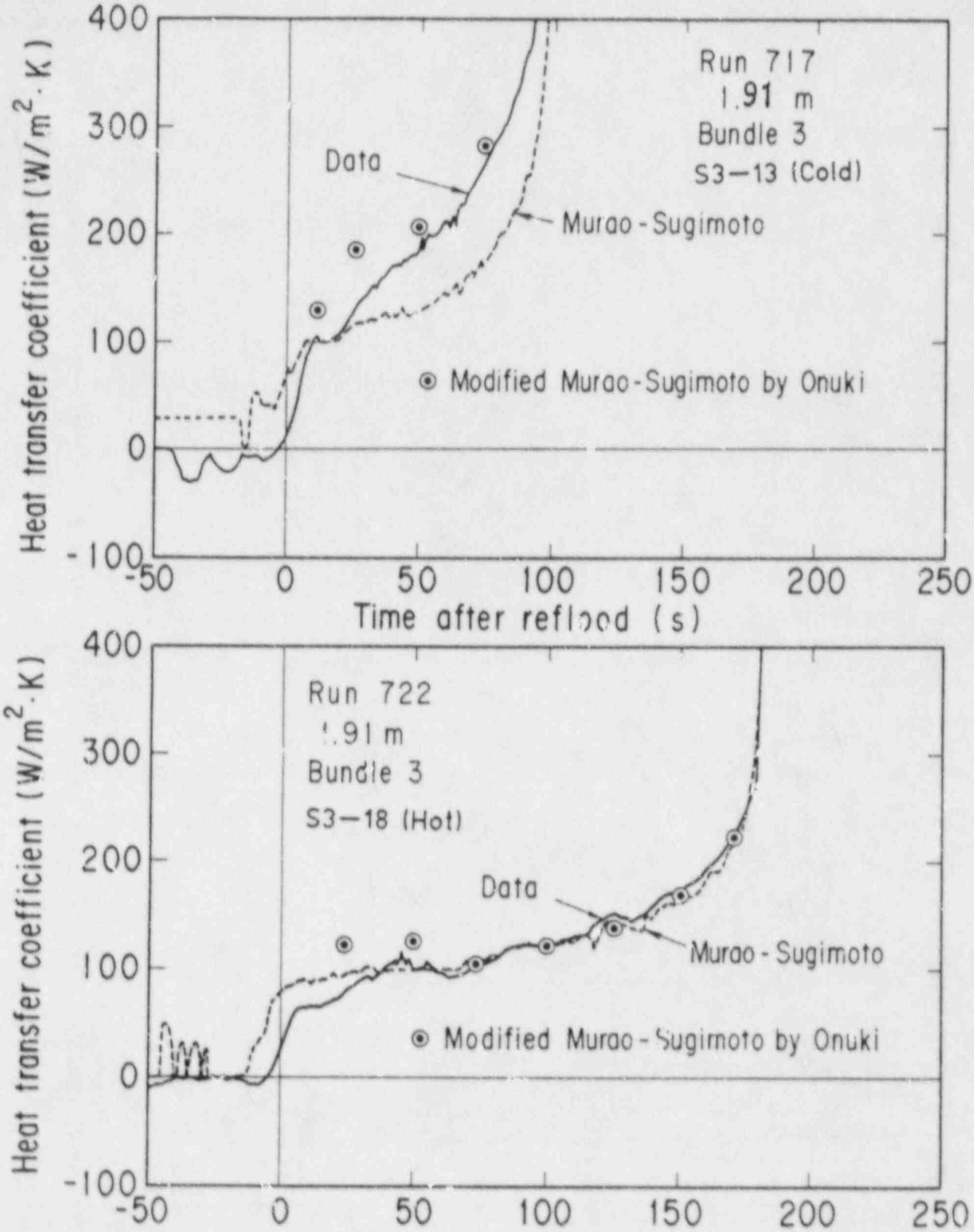


Fig.12 Prediction of heat transfer coefficient

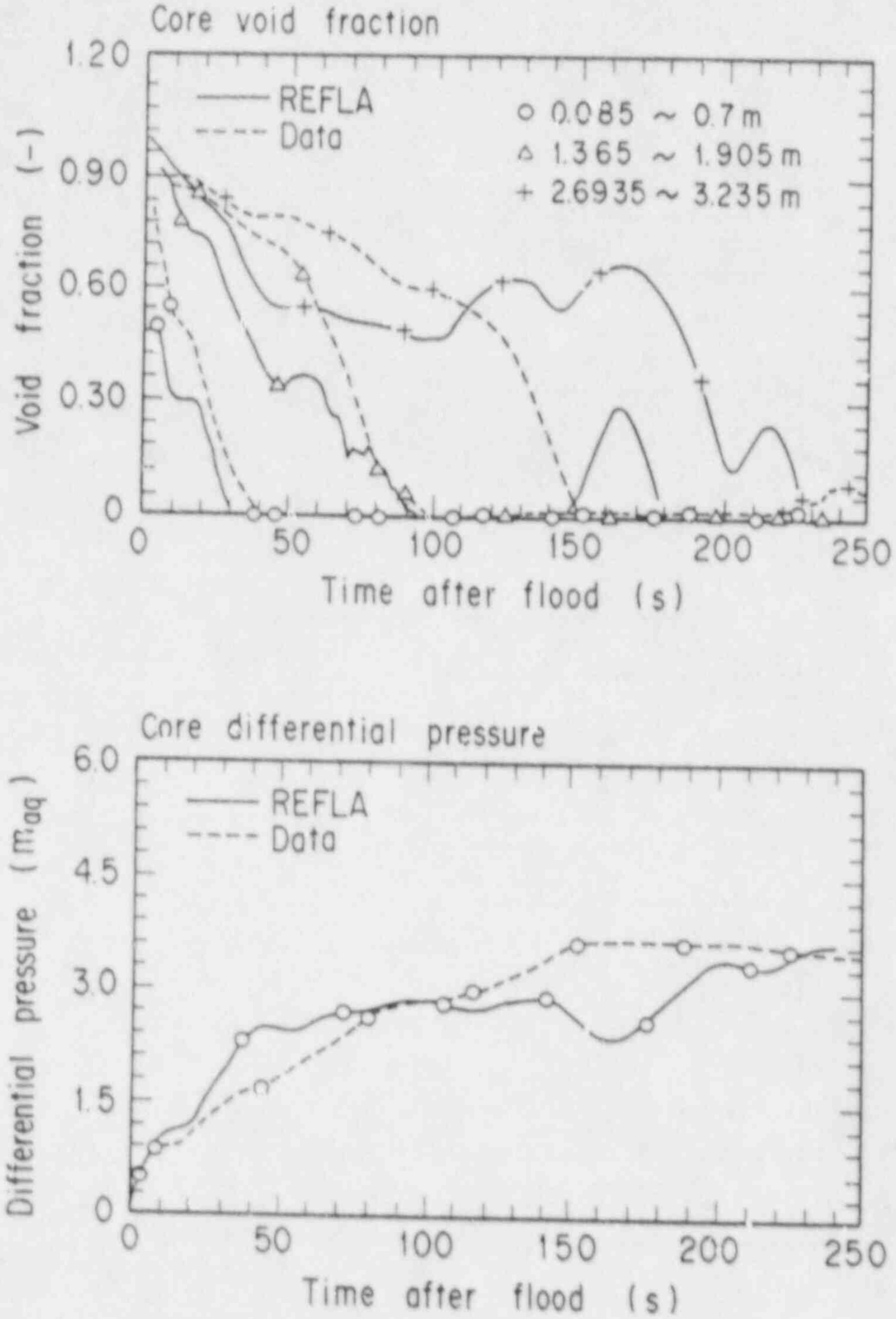
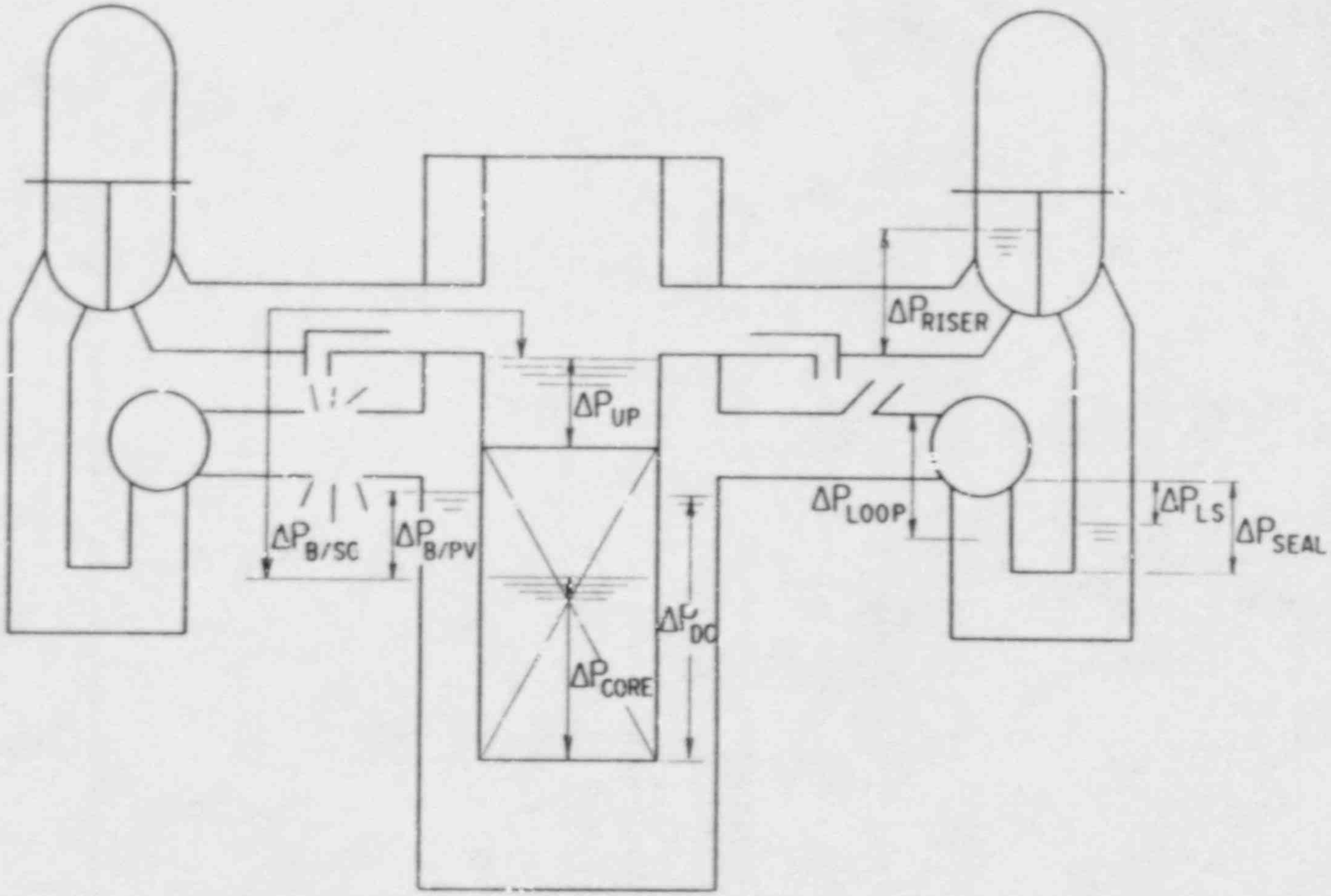


Fig. 13 Prediction of core void fraction and differential pressure by REFLA code for SCTF Run 717

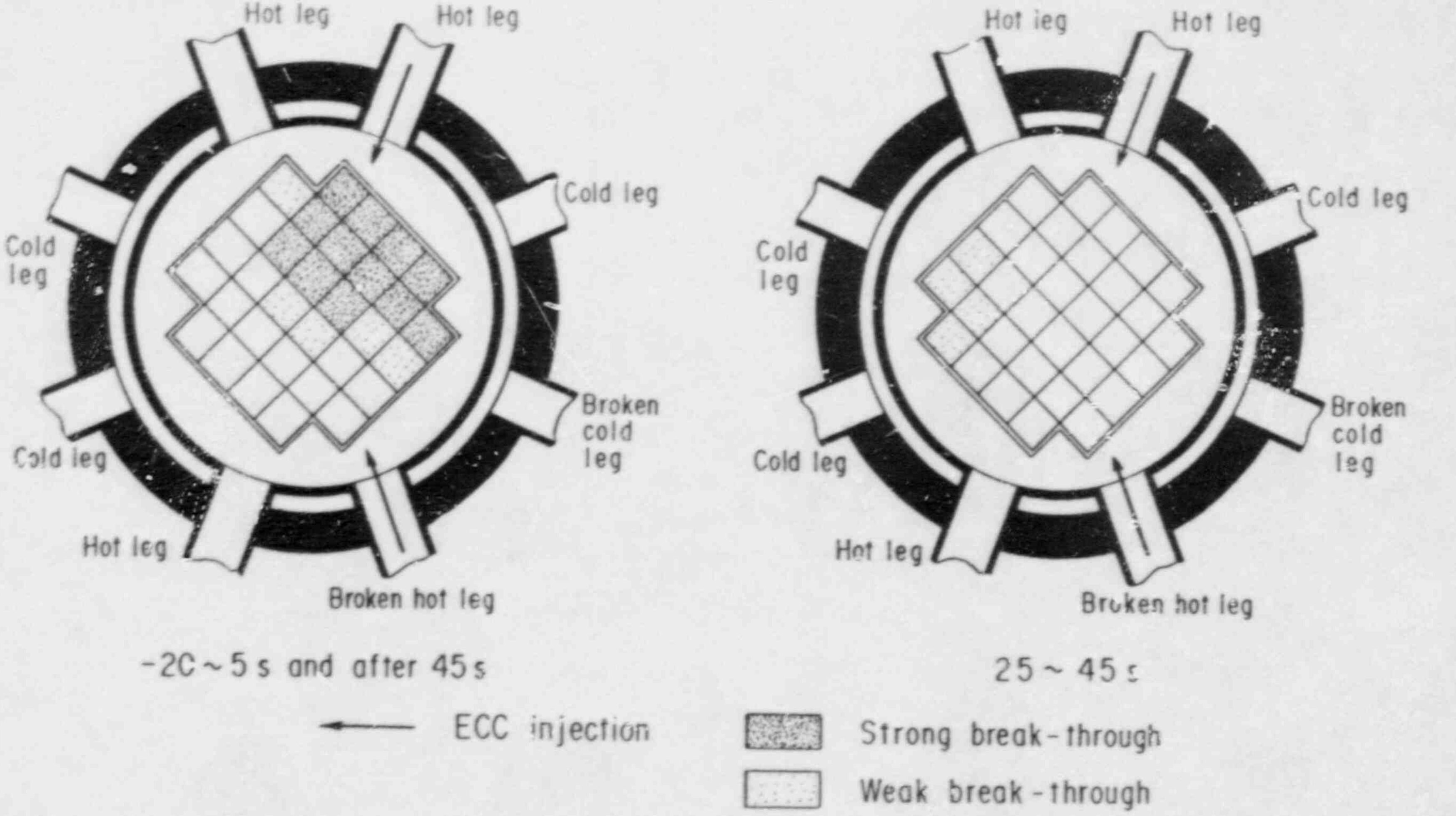


$$\Delta P_{DC} + \Delta P_{B/PV} = \Delta P_{CORE} + \Delta P_{UP} + \Delta P_{B/SG}$$

$$\Delta P_{DC} = \Delta P_{CORE} + \Delta P_{UP} + \Delta P_{RISER} + \Delta P_{LOOP} + \Delta P_{LS}$$

$\Delta P_{LS} \geqq \Delta P_{SEAL}$: Loop seal clearing

Fig. 14 Momentum balance in system



-20 ~ 5 s and after 45 s

25 ~ 45 s

Fig. 15 Break-through area (CCTF)

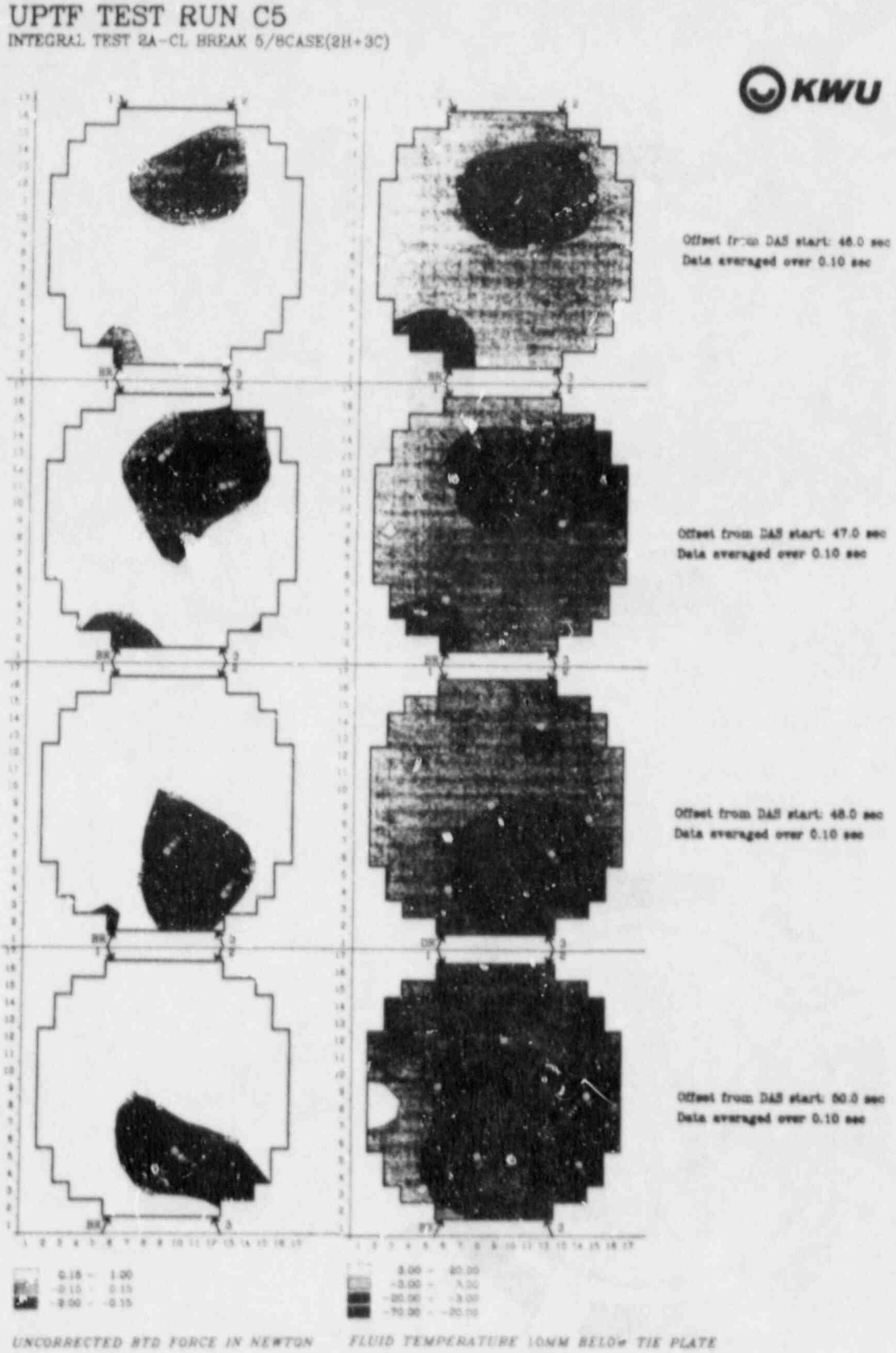


Fig. 16 Break-through area (UPTF)

UPTF TEST NO. 3

↑ 1,0 ÷ 0,15 N
± 0,15 ÷ -0,15 N
↓ -0,15 ÷ -2,0 N

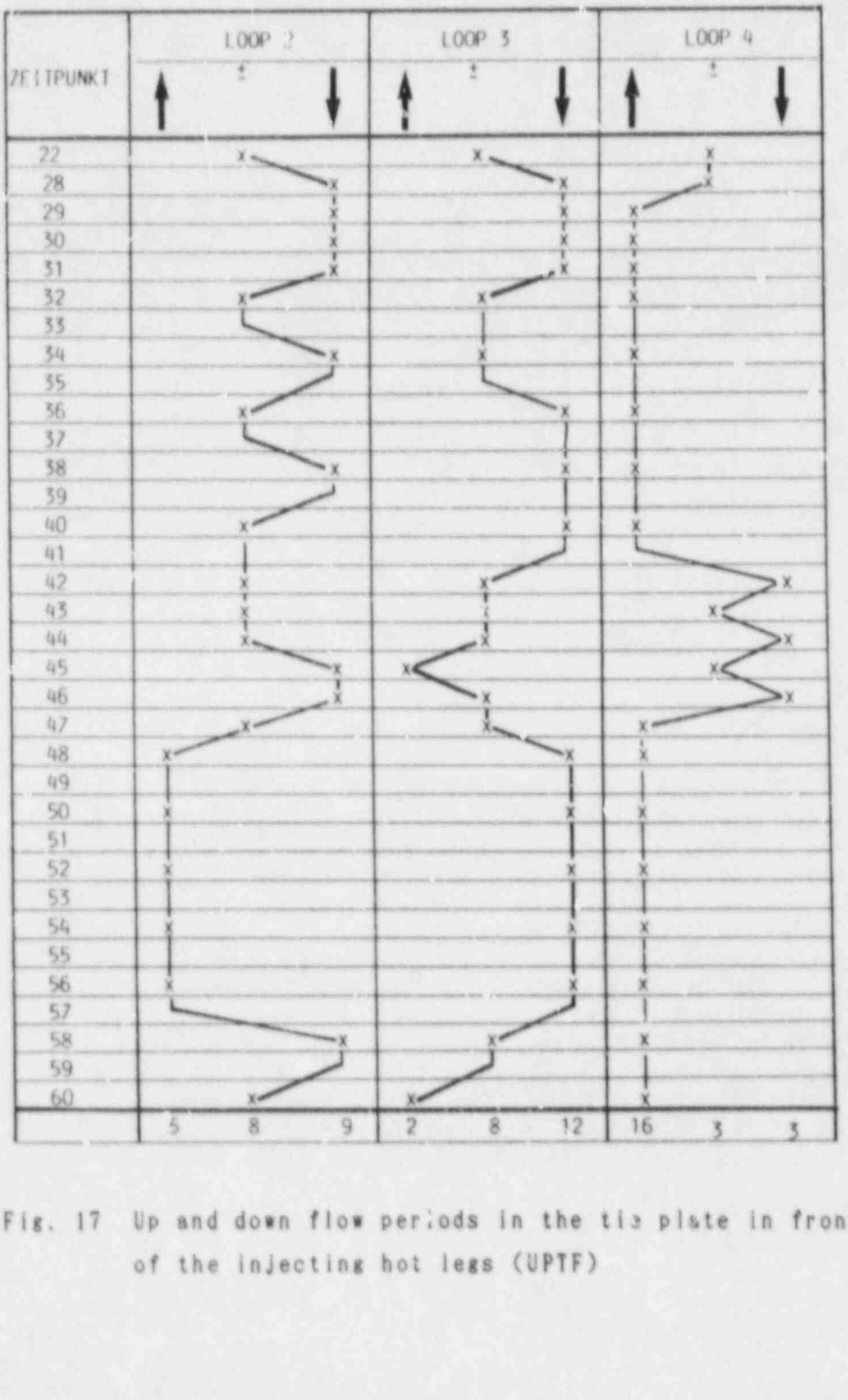


Fig. 17 Up and down flow periods in the tie plate in front of the injecting hot legs (UPTF)

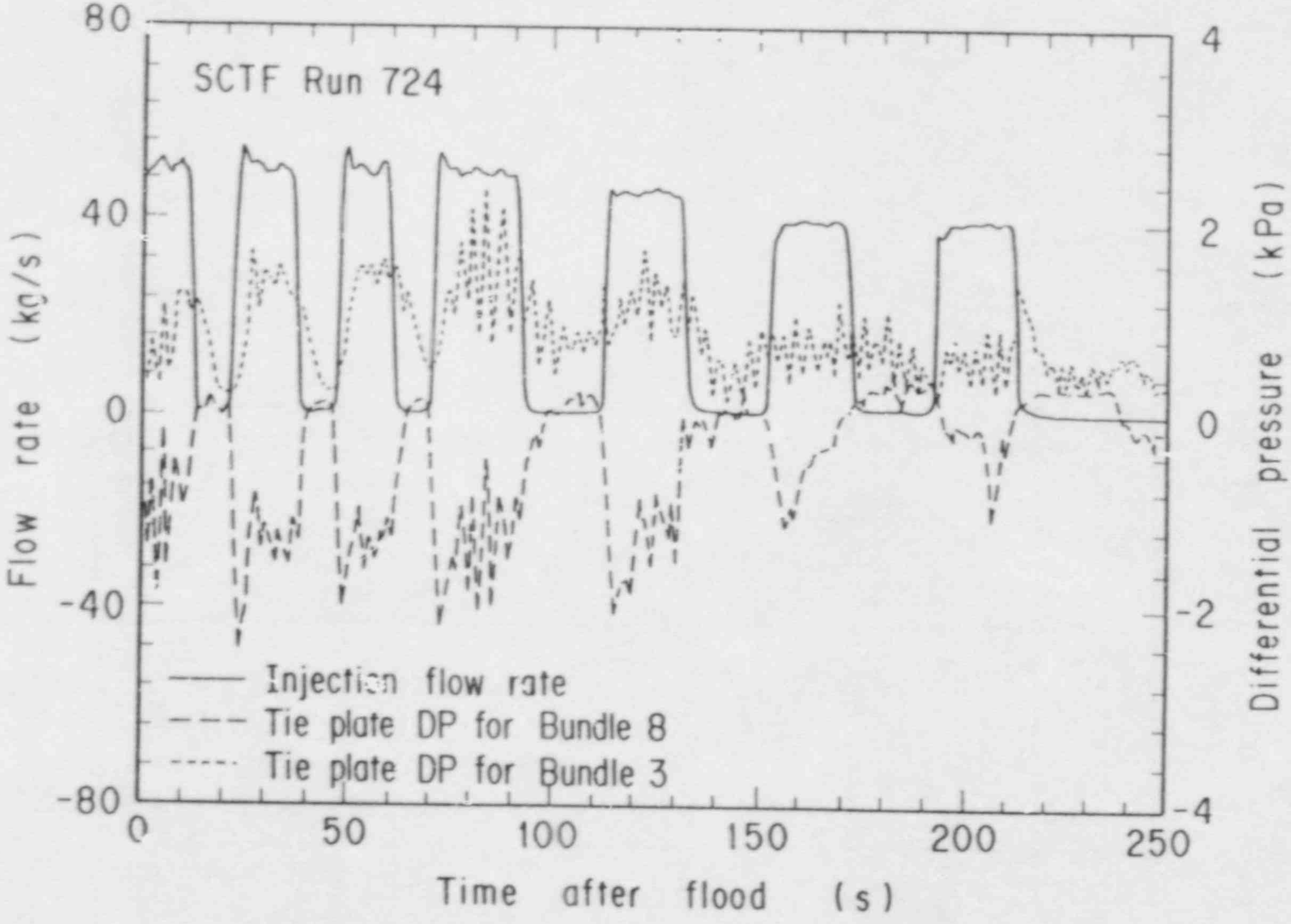


Fig. 18 Response of break-through

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