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CCTF CORE I TEST RESULTS

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(Received September, 1981)

This report presents the results of the following CCTF CORE I tests conducted in FY. 1980.

- (1) Multi-dimensional effect test
- (2) Evaluation model test
- (3) FLECHT coupling test

On the first test, one-dimensional treatment of the core thermo-hydrodynamics was discussed. On the second and third tests, the test results were compared with the results calculated by the evaluation model codes and the results of the corresponding FLECHT-SET test (Run 2714B), respectively.

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

This paper was presented at the USNRC's Ninth Water Reactor Safety Information Meeting, Gaithersburg, Maryland, October 28, 1981.

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JAERI

大型再冠水円筒炉心試験・第1次炉心試験の結果について

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(1982年6月1日受理)

55年度に行われた大型再冠水円筒炉心第一次炉心試験のうち、次の試験についての結果を述べた。

- (1) 多次元効果試験
- (2) 評価モデル試験
- (3) FLECHT 結合試験

(1)については、炉心熱水力挙動の一次元性について検討した。(2)については、評価モデルコードによる計算結果との比較、又、(3)については、対応するFLECHT-SET実験(Run 2714 B)との比較を行った。

本研究は、電源開発促進対策特別会計法に基づき、科学技術庁からの受託によって行われた。本報告書の英文の部分については、昭和56年10月28日ワシントンにおいて、第9回軽水炉安全性研究情報会議において講演した。

+安全解析部原子炉データ解析室

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1. Introduction

The Cylindrical Core Test Facility (CCTF) is one of the facilities of the Large Scale Reflood Test Program. This program is being performed at Japan Atomic Energy Research Institute (JAERI) to study the effectiveness of Emergency Core Cooling System (ECCS) during refill and reflood phases of a postulated Loss-of-Coolant Accident (LOCA) of a Pressurized Water Reactor (PWR).

The objectives of the program are:

- (1) Demonstration of effectiveness of ECC system in a PWR during refill and reflood phases of a LOCA.
- (2) Provision of information for analytical modeling of thermo-hydrodynamic behaviors of refill and reflood phases.
- (3) Verification of JAERI-developed reflood analysis code REFLA and US-developed three-dimensional code TRAC.

The CCTF is the facility for the integral system effect test.

Results of the CCTF CORE I test series in 1979⁽¹⁾ reported at the Eighth Water Reactor Safety Research Information Meeting were as follows:

- (1) The present safety evaluation model closely represents the phenomena observed in the tests with some conservatism except in the downcomer portion.
- (2) Water accumulation in the upper plenum and the significantly large pressure drop at the broken cold leg nozzle were observed.
- (3) The slow water accumulation was observed in the downcomer due to the partial ECC bypass through the downcomer.
- (4) The temperature response of the heated rods was affected by the radial and local power distribution in the core, however, the quench front propagation was nearly one-dimensional.

This report presents the results of the following CCTF CORE I tests conducted in 1980.

- (1) Multi-dimensional effect test
- (2) Evaluation Model (EM) test
- (3) FLECHT coupling test

The objective of the Multi-dimensional effect test was to confirm the one-dimensional core cooling behavior assumed in the system analysis of the safety evaluation model.

The EM test was run under the initial and the boundary conditions based on the safety evaluation calculation. Two analyses were made

with the EM codes, WRAP in the US and WREM in Japan, to compare the prediction with the experiment.

The water accumulation rate in the downcomer will be examined, under the higher ECC injection rate than that of previous tests. The ECC flow rates of the previous tests were thought to be too conservative.

The FLECHT coupling test was run to examine the similarity between CCTF and the FLECHT and/or FLECHT-SET⁽²⁾ facilities and to verify the safety evaluation model which has been developed based on the results of the FLECHT experiments.

2. Test Description

2.1 Test Facility

The CCTF was designed to reasonably simulate the flow conditions in the primary system of a four-loop PWR during the refill and reflood phases of a LOCA. The reference reactors are the Trojan reactor in USA and, in certain aspects, the Ohi reactor in Japan. The vertical dimensions and the length of the flow paths of the system components are kept as close to those of the reference reactors as possible. The each flow area of the system component is scaled down in proportion to the scaling factor, 1/21.4, of the core flow area. The primary loop system consists of three intact loops and a broken loop. The primary loop piping is shown in Fig.1.

Each loop has an active steam generator, a loop seal section, a pump simulator, and an ECC injection port as shown in Fig.2.

Figure 3 shows the cross section of the pressure vessel. The initial wall temperature of the vessel wall is adjusted to simulate the heat release from the wall to the fluid in the downcomer.

The core consists of thirty-two 8×8 electrically heated rod bundles and simulates the 15×15 array fuel assemblies. The core is subdivided into nine power regions. It is possible to control the specific power of each region separately.

2.2 Test Conditions

A series of test was conducted through 1979 to 1980 with varying one parameter at a time from the base case conditions. Test conditions

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of the base case test are shown in Table 1.

Two Tests, an azimuthal asymmetric power distribution test (Asymmetric power test) and an azimuthal asymmetric initial temperature distribution test (Asymmetric temperature test), were conducted.

In the Asymmetric power test, the total core power was equal to that of the base case. In the Asymmetric temperature test, the total energy stored in the core was equal to that of the base case. Test conditions of both tests are shown in Fig.4.

In the EM test, the radial power distribution, the initial rod surface temperature and the ECC flow rate were different from the base case conditions as shown in Table 2.

In the FLECHT coupling test, the test conditions were equivalent to those of FLECHT-SET 2714B as shown in Table 3. The initial downcomer wall temperature was the saturation temperature, and the ECC water was directly injected into the lower plenum.

3. Results and Discussion

3.1 Multi-dimensional effect test

In the Asymmetric power test and the Asymmetric temperature test, the water accumulation was axi-symmetric in the core, the downcomer and the upper plenum. The void fractions in the core of the both tests are shown in Fig.5. The behavior of the quench front propagation is shown in Fig.6 for the Asymmetric power test and in Fig.7 for the Asymmetric temperature test. In the former test, the quench fronts advanced upwards nearly one-dimensionally. In the latter test, the tendency was significant up to 100 sec after the Bottom of Core Recovery (BOCREC), i.e. the reflood initiation. The asymmetry of the quench propagation decreased slowly after that time, however, it remained for a long period. Although the thermal behavior in the core was asymmetric, it was noticeable that the water accumulation were symmetric. Hence it can be considered that the hydrodynamic behavior in the core is one-dimensional even in cases of thermally multi-dimensional condition.

3.2 EM test

Figure 8 shows the core flooding rate of the EM test in comparison

of the base case test are shown in Table 1.

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3.2 EM test

Figure 8 shows the core flooding rate of the EM test in comparison

with the predictions using WRAP and WREM. The core flooding rate of the CCTF test was evaluated by the mass balance over the system. Both WRAP and WREM predict the core flooding rate well. The core flooding rate is less than 1 in/sec after 170 sec. Since the flooding rate might be influenced by many factors in the integral test, it is very important to analyze the reason why the EM codes predict the core flooding rate well.

Figure 9 presents the scheme of the mass and momentum balance in a PWR system. The core flooding rate, \dot{m}_F , can be expressed as follows;

$$\dot{m}_F = \dot{m}_C + \dot{m}_U + \sum_{i=1}^3 \dot{m}_{Ii} + \dot{m}_B \quad ,$$

$$\dot{m}_I = \sqrt{2\Delta P_I \rho_I / K_I} \quad , \quad \dot{m}_B = \sqrt{2\Delta P_B \rho_B / K_B}$$

$$\Delta P_B = \Delta P_I + \Delta P_{BCN} \quad , \quad \text{and}$$

$$\Delta P_I = \Delta P_D + \Delta P_C \quad .$$

The contribution of the each term to the core flooding rate is summarized in Table 4. WREM overestimates the water accumulation rate in the core and underestimates the water accumulation rate in the upper plenum and the mass flow rate through the four loops at 100 sec after BOCREC. The same tendency appears at 200 sec after BOCREC. These discrepancies cancel with each other and the predicted core flooding rate agrees well with the measured flooding rate.

Figure 10 shows the loop K factors in the CCTF test. The K factors increase with time gradually and approaches 25 that is used in the EM calculation. This causes the underestimation of the \dot{m}_I and \dot{m}_B in the WREM calculation.

Figure 11 shows the measured and the predicted clad surface temperatures at the location of the maximum power density. Both EM codes predict similar temperatures with each other. The predicted temperatures are higher than the measured. The predicted vessel pressure was lower than the measured as shown in Table 4.

Giving the measured core boundary conditions, the post-test calculation with the WREM code was performed to check the core heat transfer model. The post-test calculation gives almost the same tendency as the pre-test prediction. It indicates that the discrepancy of the clad

surface temperature is mainly caused by the conservatisms of the core-model.

The collapsed water levels in the downcomer and in the core are compared with the WREM predictions in Fig.12, respectively. The measured collapsed water level in the downcomer is lower than the overflow level, while the predicted collapsed water level in the downcomer is nearly equal to the overflow level. The void generation in the downcomer and the carry over by the steam flowing through the downcomer may result in the lower downcomer water level in the CCTF test. The slow water accumulation observed in the base case test was not appeared in the EM test. That is thought to be due to higher ECC flow rate.

The predicted core collapsed water level has the tendency to increase at a constant rate, while the measured level in the CCTF test approaches a constant level. The measured water accumulation rate is higher than the predicted rate in the initial period, however, the measured rate decreases with time.

As indicated in Table 4 and Fig.12, the significant difference has been recognized in the core water accumulation behaviors between the WREM prediction and the CCTF results.

The core thermo-hydrodynamic model in the WREM code has been developed based on the FLECHT tests. The void fractions of CCTF and FLECHT Run 04516⁽³⁾ (Variable flooding rate test) are compared in Fig. 13. The FLECHT test with hot flow housing gives high void fraction, nearly unity. Therefore it is reasonably thought that the flow pattern in the FLECHT test is the dispersed flow. On the other hand, the void fraction of the CCTF test is relatively low. This indicates that the flow pattern is the slug flow. When the dispersed flow appears above the quench front, the total liquid mass in the core is nearly the same as the liquid mass below the quench front and the total liquid mass in the core is gradually increasing with the quench front propagation.

The carry-over rate correlation developed based on the FLECHT test data should predict the same history of the core liquid mass as the FLECHT test. Therefore the EM codes with the carry-over rate correlation developed based on the FLECHT test data give the gradual water accumulation in the core. The discrepancy of the heat transfer between the CCTF test and EM prediction is probably caused by the difference of the flow pattern between the CCTF and the FLECHT tests.

3.3 FLECHT coupling test

Figure 14 shows the comparison of the core and the downcomer differential pressures between the CCTF and the FLECHT-SET (2714B) tests. The core collapsed water level is higher in the CCTF than in the FLECHT-SET test.

The pressure drops in the loops are shown in Fig.15. In the FLECHT-SET test, the pressure drop in the broken loop is approximately the same as that in the intact loop, while, in the CCTF test, the pressure drop in the broken loop is significantly larger than that in the intact loop. This is caused by the higher pressure of the pressure vessel due to the higher pressure drop at the broken cold leg nozzle.

The overflow piping of the FLECHT-SET downcomer has larger flow area than the correctly scaled. The ECC injection rate was adjusted to prevent the overflow of the downcomer water during the test. On the contrary, in the CCTF, the broken cold leg has the same flow area as that of the intact loop and the overflow of the downcomer water was allowed. The overflow water was accelerated by the exhausting steam flowing from the intact loops. Therefore, the higher pressure drop was induced at the broken cold leg nozzle of CCTF.

The pressure drop at the broken cold leg nozzle of CCTF is one of causes of the increase of the core flooding rate, as shown in Fig.16.

Figure 17 and 18 show comparison of the clad surface temperature at the location of the maximum power density and the quench front envelope between the CCTF and the FLECHT-SET tests, respectively. The temperature response of the CCTF test is different from that of the FLECHT-SET test, however, the quench front envelopes show no significant difference between both tests.

The void fractions and the heat transfer coefficients at the core midplane are compared in Fig.19 and 20, respectively. The lower void fraction in the CCTF test than the FLECHT-SET test appears to be due to the higher flooding rate and the higher vessel pressure in the CCTF test. The void fractions of the CCTF and the FLECHT-SET tests indicate that the flow pattern is not the dispersed flow but the slug flow.

The heat transfer coefficients were calculated with the saturated film boiling correlation developed by Murao and Sugimoto⁽⁴⁾ for the flow like the slug flow. In this calculation, the measured void fraction shown in Fig.19 or the assumption of no void was utilized. The calcu-

lated results for the CCTF and the FLECHT-SET tests are shown in Fig.20 in comparison with test results. The measured heat transfer coefficients are in the range of the calculated.

It can be considered that the flow patterns in the CCTF and also in the FLECHT-SET cores are the slug flow as thought in the discussion of the EM test.

4. Conclusion

The results of the Multi-dimensional effect test, the EM test and the FLECHT coupling test have been studied, and the following conclusions were obtained:

- (1) In the Multi-dimensional effect test, the hydrodynamic behavior in the core was one-dimensional even in the case of thermally multi-dimensional conditions.
- (2) In the downcomer in the EM test, the slow water accumulation rate, which was observed in the base case test, was not appeared, however, the water accumulation was lower than the predicted with the EM codes.
- (3) The measured core water accumulation behavior in the EM test had a tendency to approach a nearly constant level in a short time, while the predicted had a tendency to increase at a nearly constant rate.
- (4) The good agreement of the core flooding rates between the EM test and predictions was obtained, however, the agreement was introduced by cancelling the discrepancy of several factors which influence the flooding rate.
- (5) The pre- and post-test predictions for the EM test showed higher turnaround temperature than the test result.
- (6) In the FLECHT coupling test, the significantly high pressure drop at the broken cold leg nozzle and the resultant higher flooding rate were observed.
- (7) It can be considered that the flow pattern in the FLECHT core is the dispersed flow but those in both CCTF and FLECHT-SET cores are the slug flow. It is thought that the correlations of the EM codes, which were developed from the FLECHT test data, predict the gradual water accumulation in the core and probably the different heat transfer history from the measured.

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Nomenclature

- \dot{m} : Mass flow rate
 ΔP : Differential pressure
K : K factor ($\equiv \Delta P / \frac{1}{2} \rho v^2$)
P : Pressure
 ρ : Density
v : Velocity

(Subscripts)

- C : Core
F : Core flooding
U : Upper plenum
I : Intact loop
B : Broken loop
BCN: Broken cold leg nozzle
D : Downcomer

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Table 1 Test conditions of the base case test and their data bases

Items	Values	Data bases
System pressure	2 kg/cm ² a	2.5 ~ 1.5 kg/cm ² a (Takahama 3.4)
Initial average linear power	1.4 kw/m	1.34 ~ 1.37 kw/m (Trojan 2% over power) (30 sec after shutdown)
ECC injection		(Data referred in FLECHT-SET)
ACC flow rate	280 m ³ /h	378 ~ 287 m ³ /h
ACC water temp.	35 °C	35 °C
ACC injection period	14 sec	14 sec
LPCI flow rate	30 m ³ /h	40 m ³ /h
LPCI water temp.	35 °C	35 °C
Maximum initial clad temp.	600 °C	870 °C (Sendai 1)
SG secondary side water temp.	265 °C	265 °C
Downcomer wall temp. (wall temp. of vessel below cold legs)	198 °C	~ 176 °C (Equivalent wall temp.)
Wall temp. of non-specified structures	119 °C (Saturation temp.)	—
K _{factor} of primary loops	~ 25	24.45 (FLECHT-SET)
Decay curve of power	ANS × 1.2 + Actinide × 1.1 (Delayed neutron effect is considered in the initial power)	ANS × 1.2 + Actinide × 1.1 + Delayed neutron
Radial power factor	1.15	1.435
Axial power factor	1.49	1.546
Local power factor	1.1	1.027
Total peaking factor	1.885	2.278 (Sendai 1)

Table 2 Test conditions of EM test

	EM test	Base case test
Average power (kw/m)	1.4	1.4
Peak power (kw/m)	2.95	2.64
System pressure (MPa)	0.2	0.2
ACC flow rate (m ³ /h)		
from lower plenum	369 (3 sec)	280 (3 sec)
from cold leg	324 (11 sec)	280 (11 sec)
LPCI flow rate (m ³ /h)	39.9	30
ECC water temp. (°C)	35	35
Maximum initial clad surface temp. (°C)	870	600

Table 3 Test conditions of FLECHT coupling test

	CCTF FLECHT coupling test	FLECHT-SET (Run 2714B)
Average power (kw/m)	1.49	1.37
Peak power (kw/m)	2.82	2.76
System pressure (MPa)	0.152	0.145
ACC flow rate (kg/m ² s)	386 (15 sec)	388 x 11(sec)
LPCI flow rate (kg/m ² s)	42.6	variable
ECC water temp. (°C)	67	67.2
Maximum initial clad surface temp. (°C)	594	593

Table 4 Comparison of the core flooding rate between CCTF and WREM

	100 sec after BOCREC			200 sec after BOCREC		
	CCTF	WREM	discrepancy	CCTF	WREM	discrepancy
\dot{M}_C (kg/s)	0.59	1.23	-0.64	0	1.04	-1.04
\dot{M}_U (kg/s)	0.13	0	+0.13	0.41	0	+0.41
$\dot{\Sigma M}_I$ (kg/s)	3.54	3.31	+0.23	3.15	3.04	+0.11
\dot{M}_B (kg/s)	1.68	1.38	+0.30	1.5	1.25	+0.25
ΔP_I (m Aq)	2.8	3.3	-	2.4	2.9	-
ΔP_B (m Aq)	7.1	4.9	-	4.0	5.9	-
ΔP_{BCN} (m Aq)	4.3	1.6	-	1.6	3.0	-
\dot{M}_F (kg/s)	5.94	5.92	+0.021	5.06	5.33	-0.27
P_{core} (kg/cm ² a)	2.8	2.6	-	2.7	2.5	-

Note: $\dot{M}_F = \dot{M}_C + \dot{M}_U + \dot{\Sigma M}_I + \dot{M}_B$

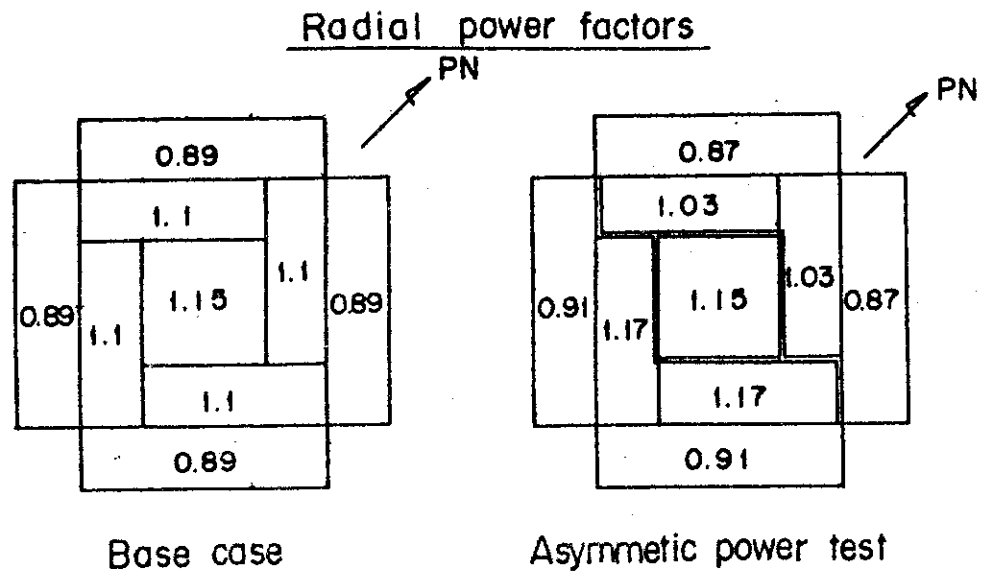


Fig. 4 (a) Initial power distribution of Asymmetric power test

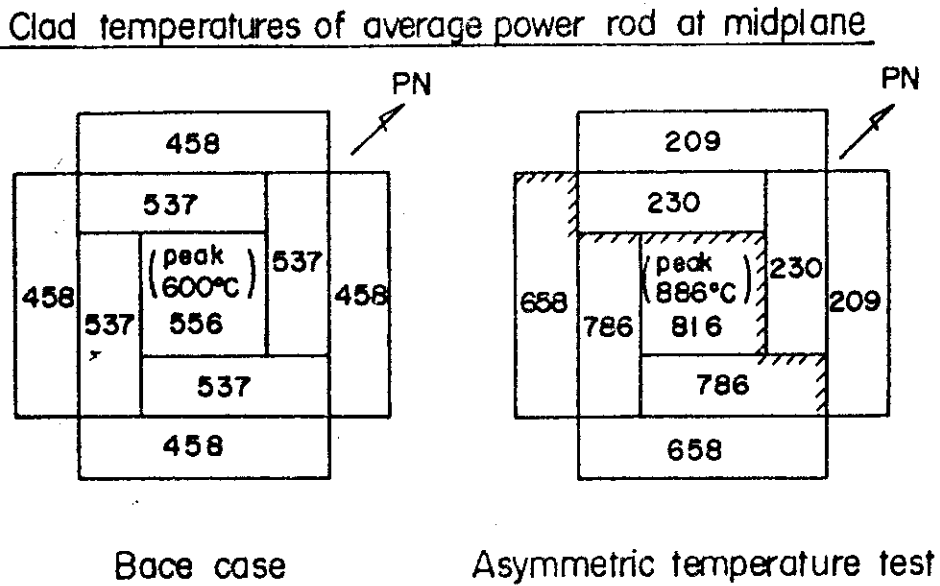


Fig. 4 (b) Initial temperature distribution of Asymmetric temperature test

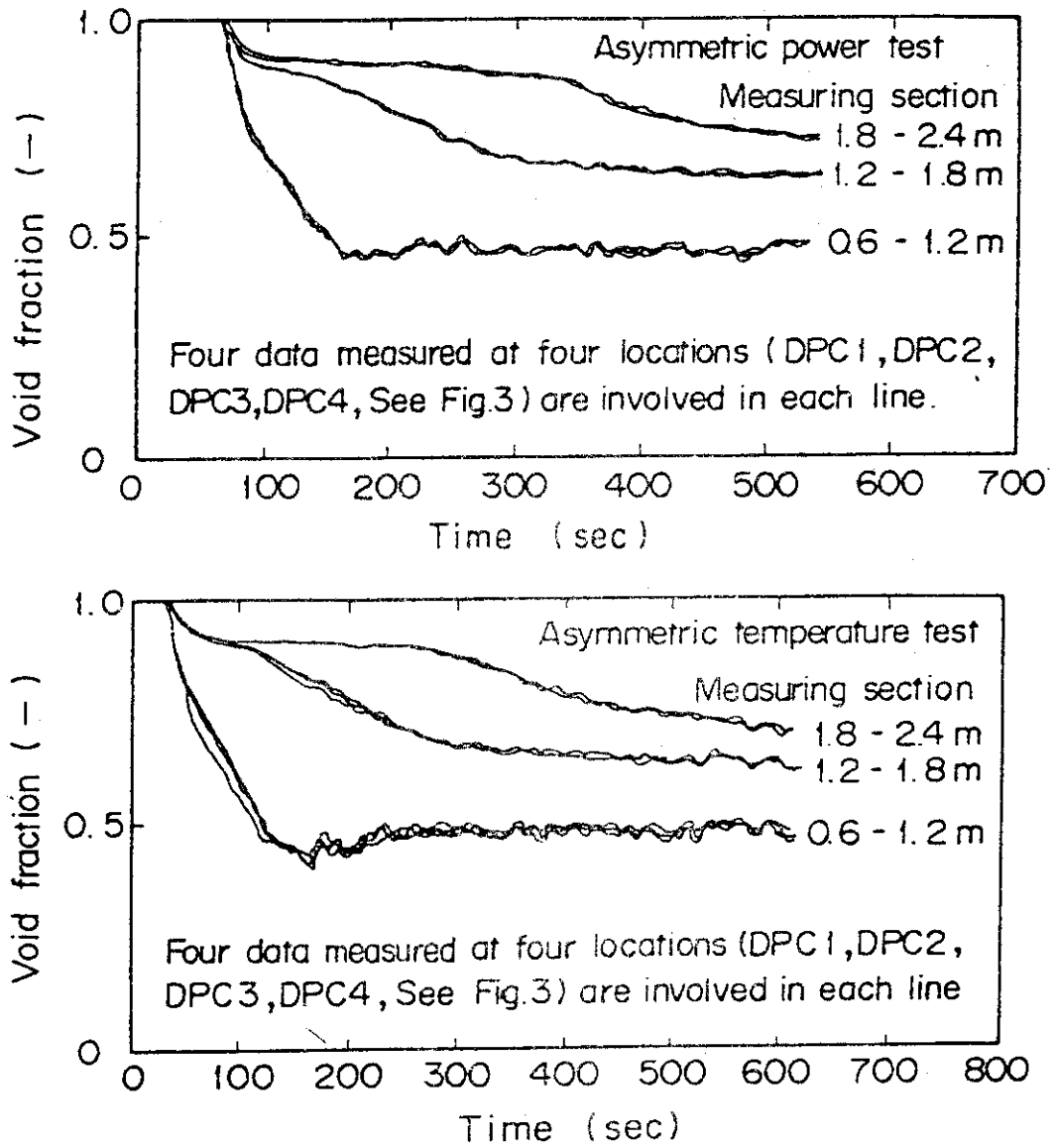
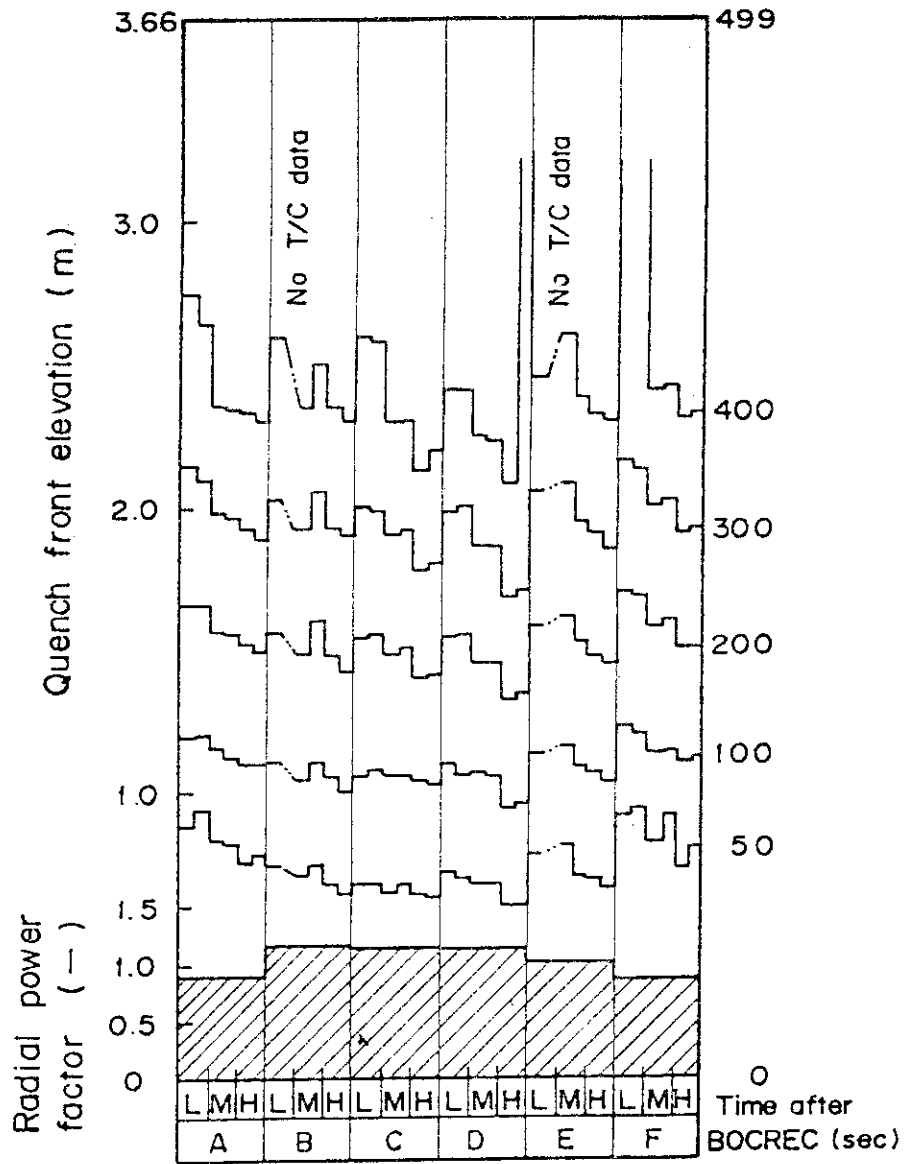


Fig. 5 Symmetry of void fraction in the core



Note 1) A,B,C,D,E,F : Bundle identification (See Fig. 3)

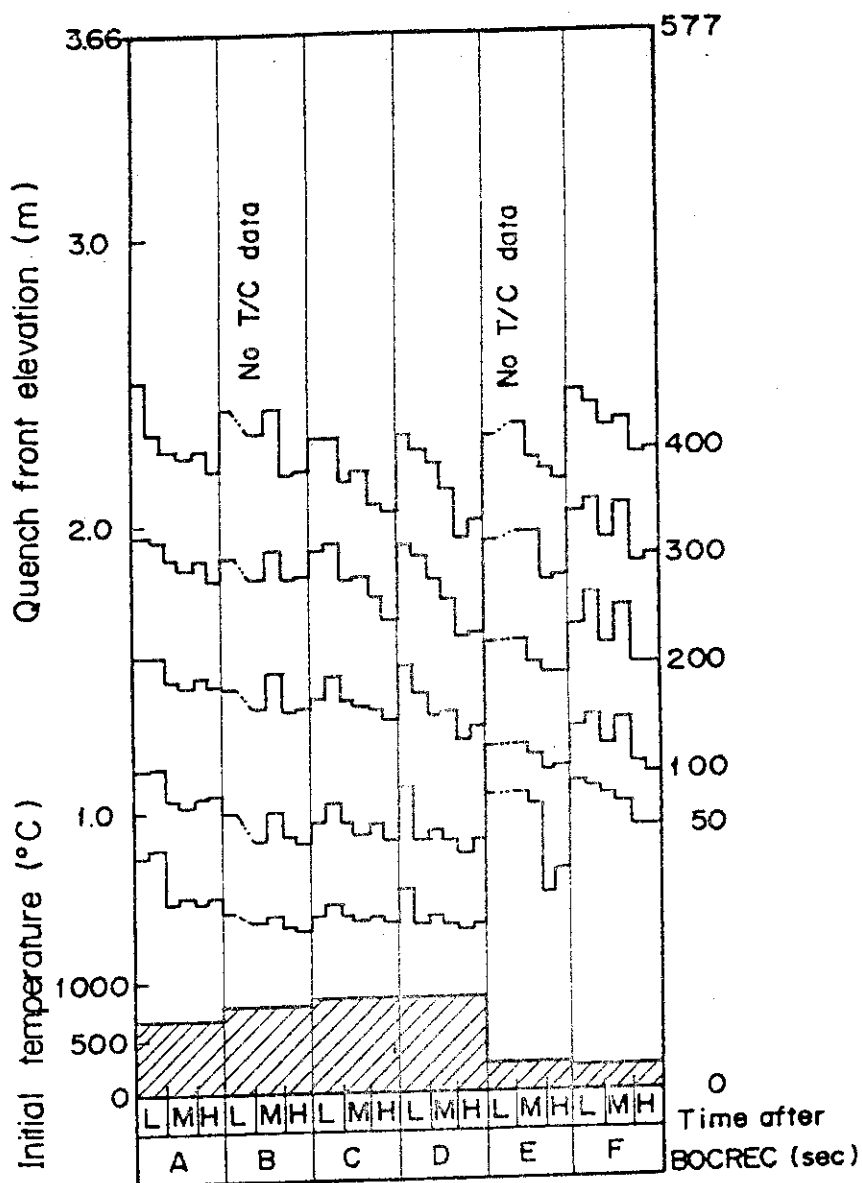
2) L,M,H : Power level identification

L Low power rod

M Medium power rod

H High power rod

Fig.6 Quench front propagation of Asymmetric power test



Note 1) A, B, C, D, E, F : Bundle identification (See Fig.3)

2) L, M, H : Power level identification

L Low power rod

M Medium power rod

H High power rod

Fig.7 Quench front propagation of Asymmetric temperature test

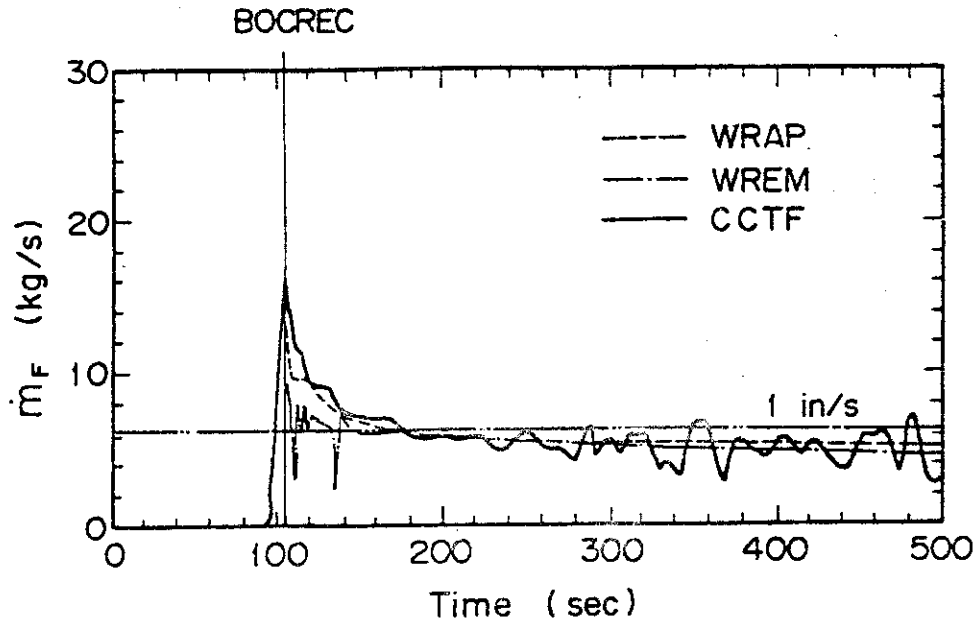


Fig. 8 Core flooding rate

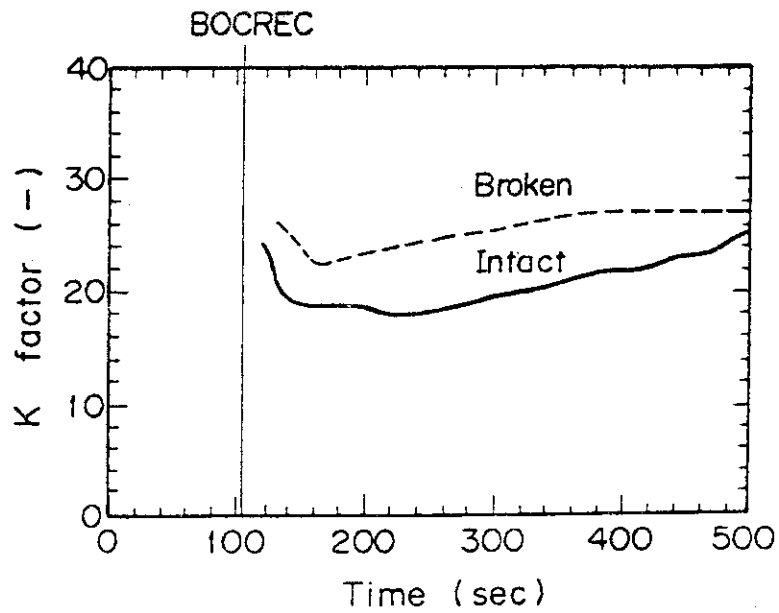


Fig. 10 Loop K factor

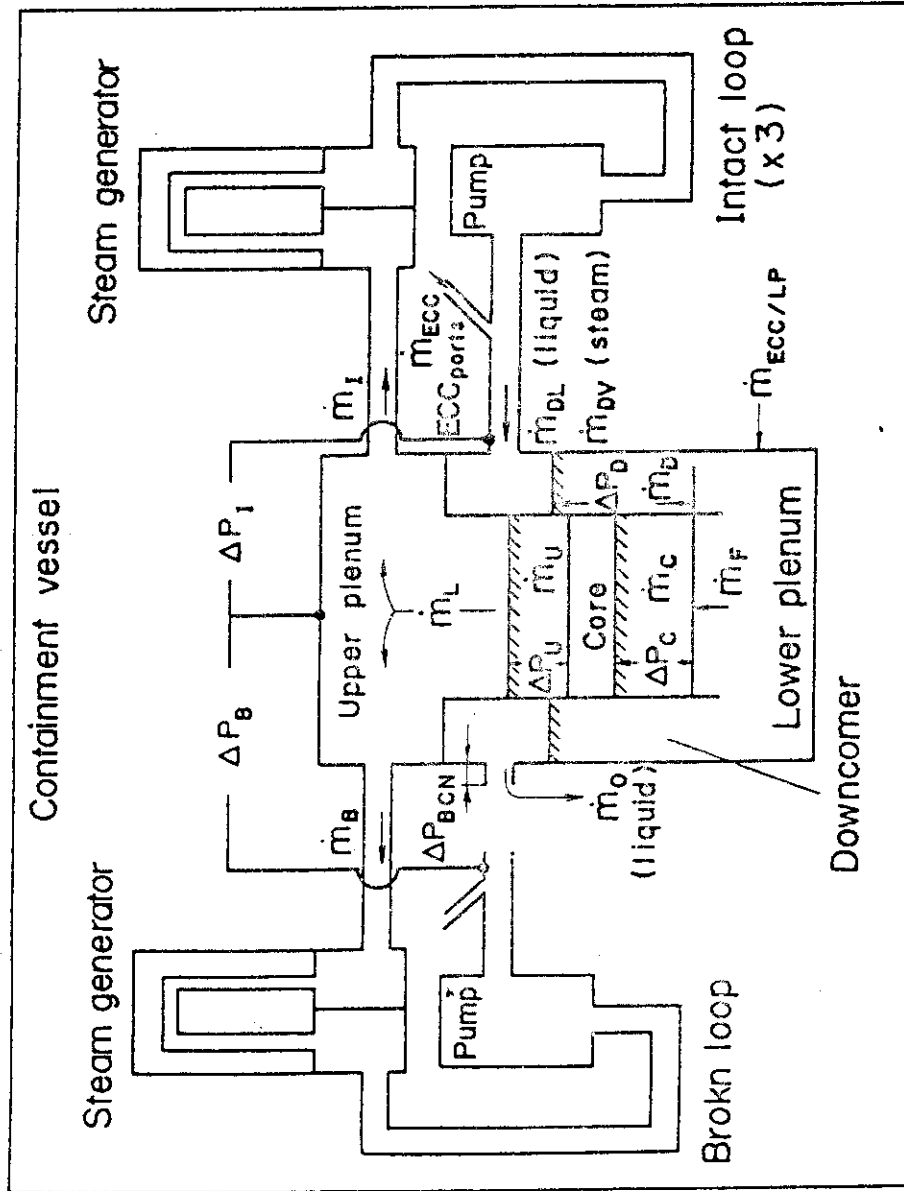


Fig. 9 Mass and momentum balance in PWR system

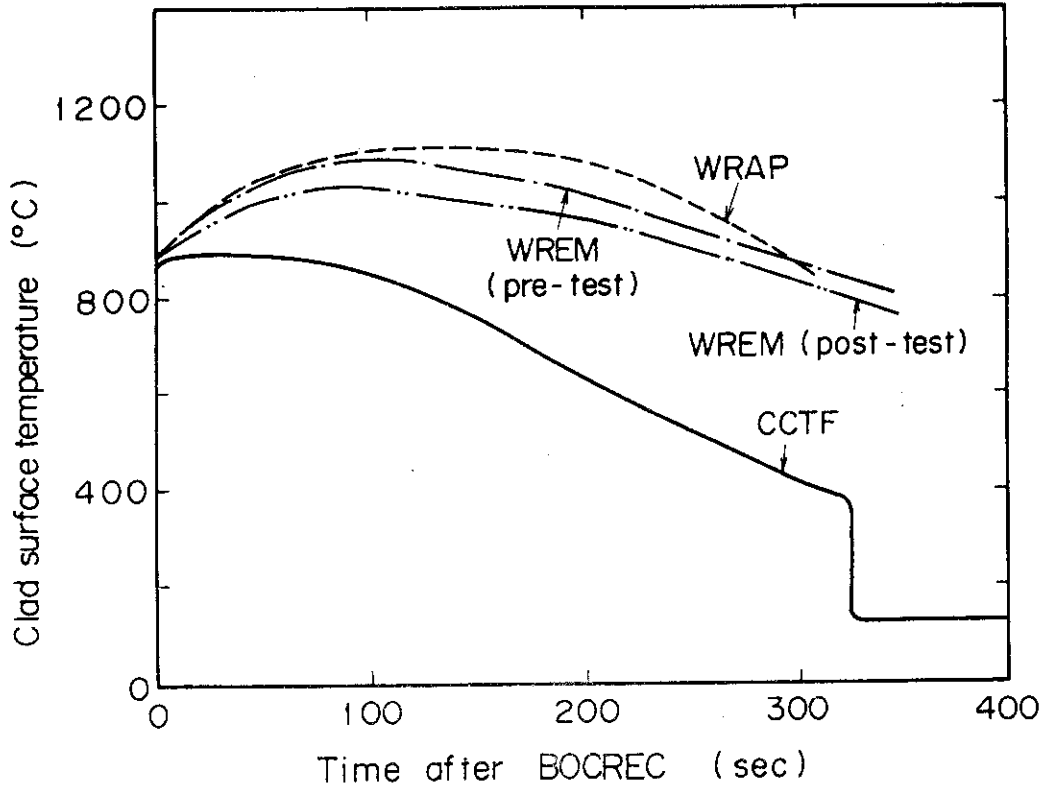


Fig. 11 Clad surface temperature

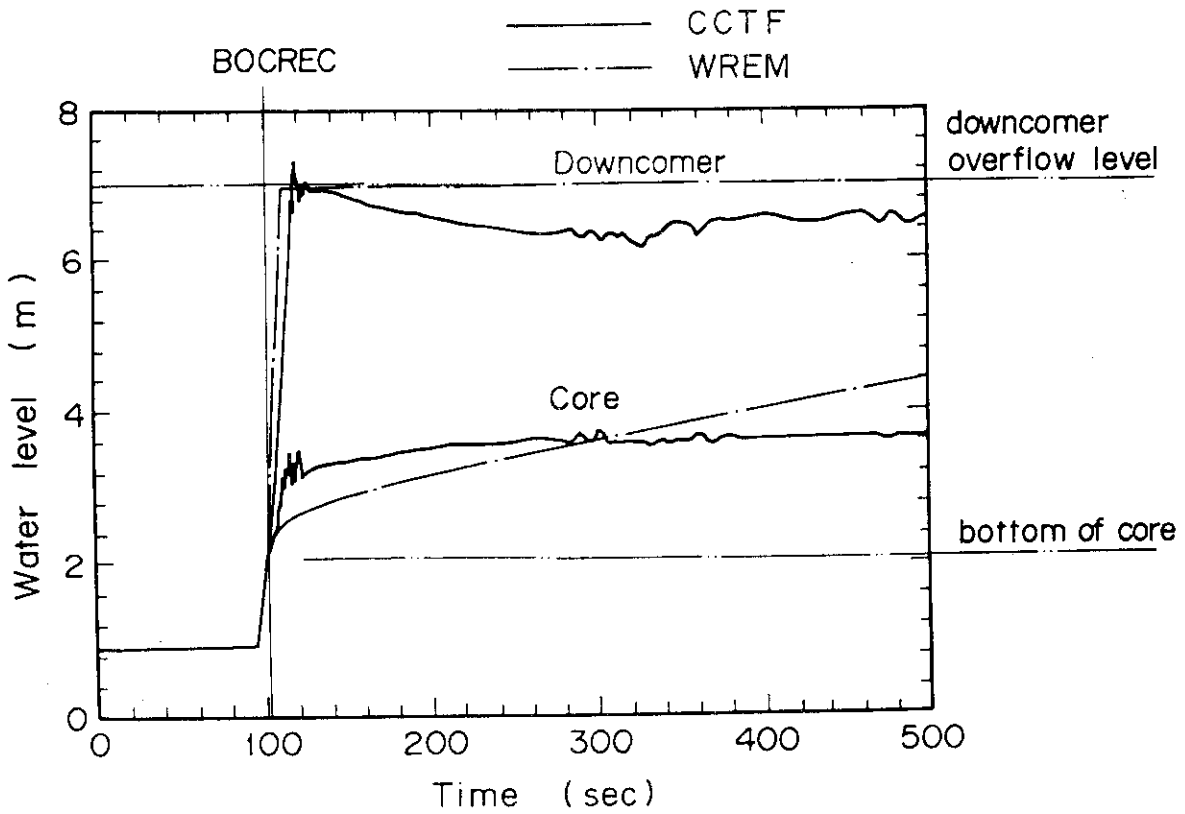


Fig. 12 Collapsed water level in core and downcomer

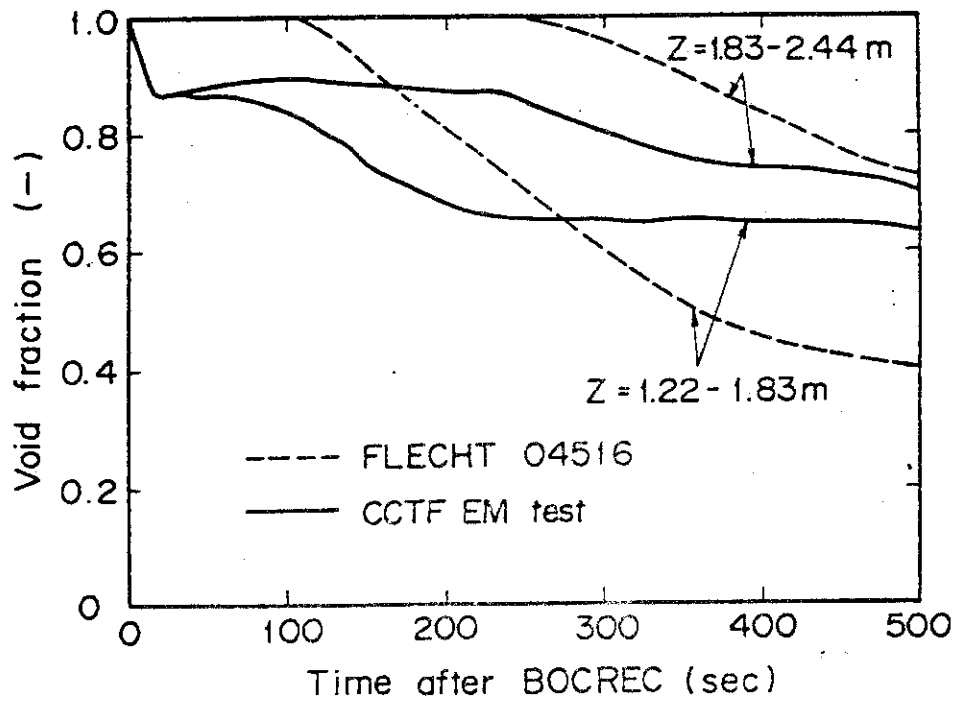


Fig. 13 Comparison of core void fraction between FLECHT LOW FLOODING TEST 04516 and CCTF EM test

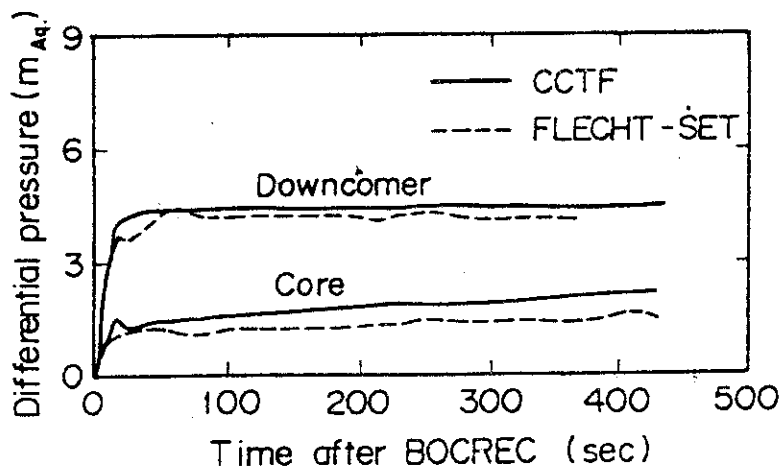


Fig. 14 Comparison of the core and downcomer differential pressures between CCTF and FLECHT-SET

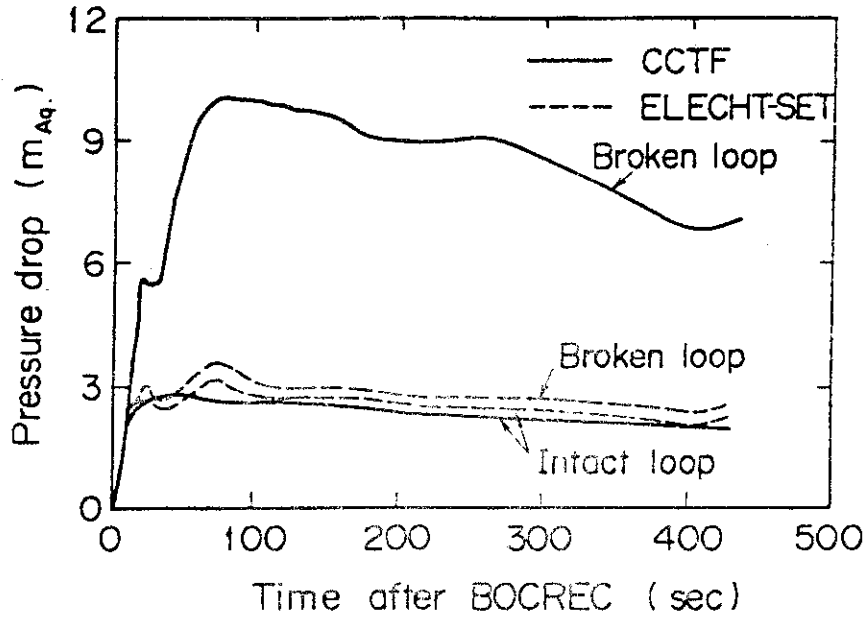


Fig. 15 Comparison of the loop pressure drop between CCTF and FLECHT-SET

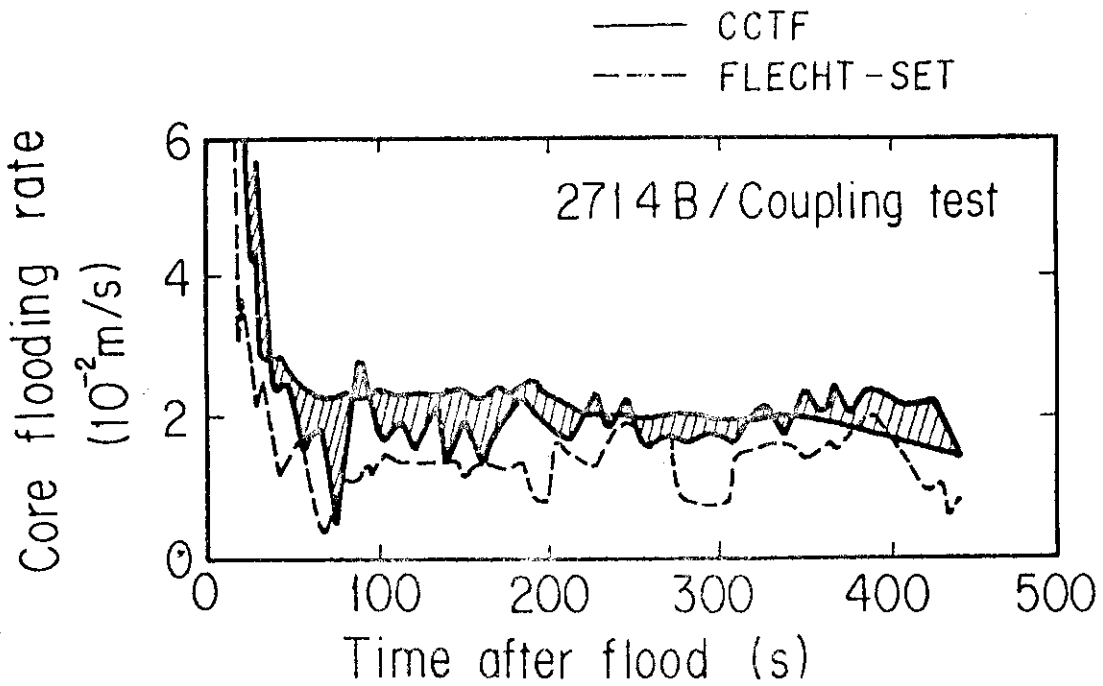


Fig.16 Core flooding rate

(The hatched region indicates the error band of the estimation)

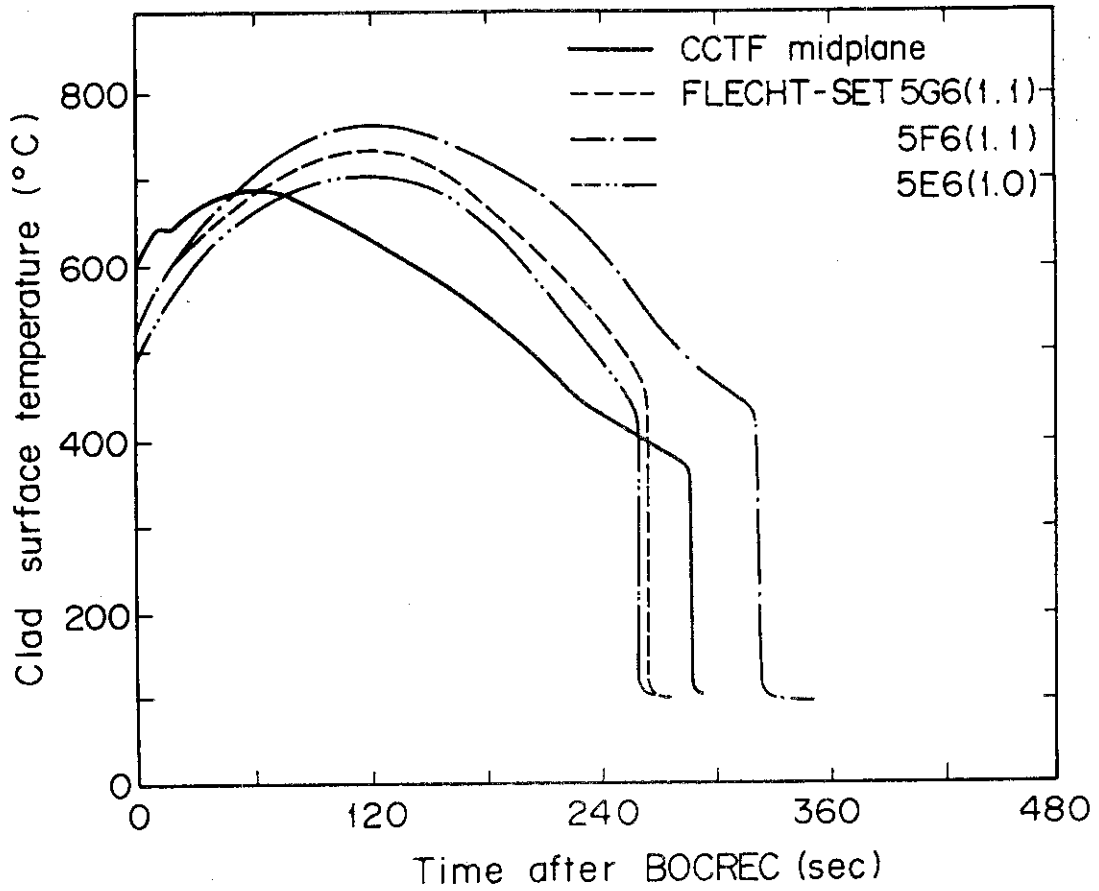


Fig. 17 Responses of the clad surface temperature

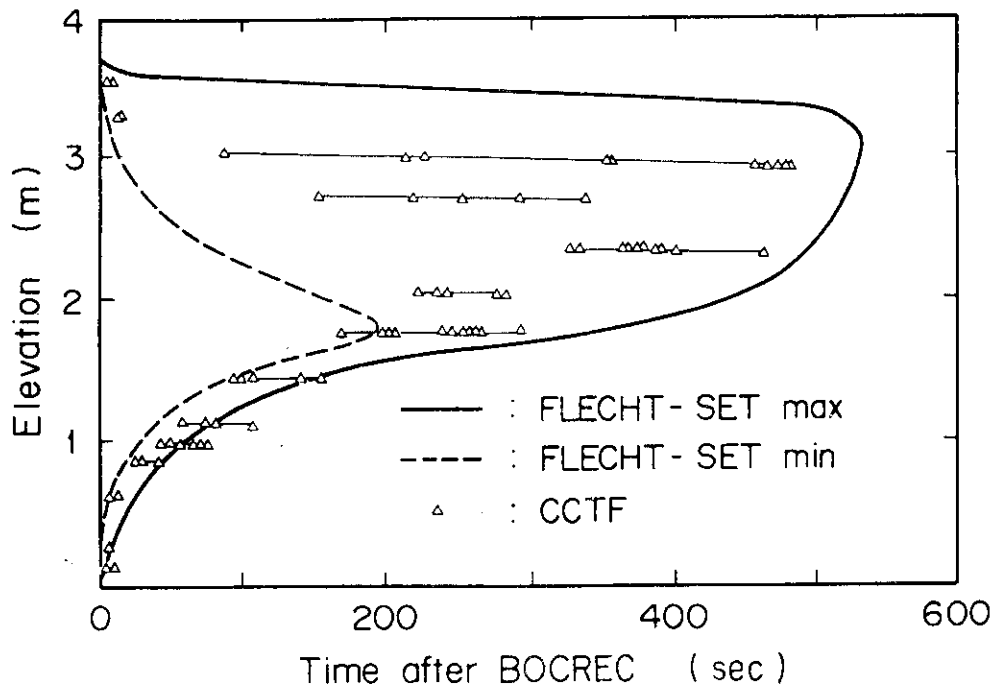


Fig. 18 Comparison of quench envelope between CCTF and FLECHT-SET

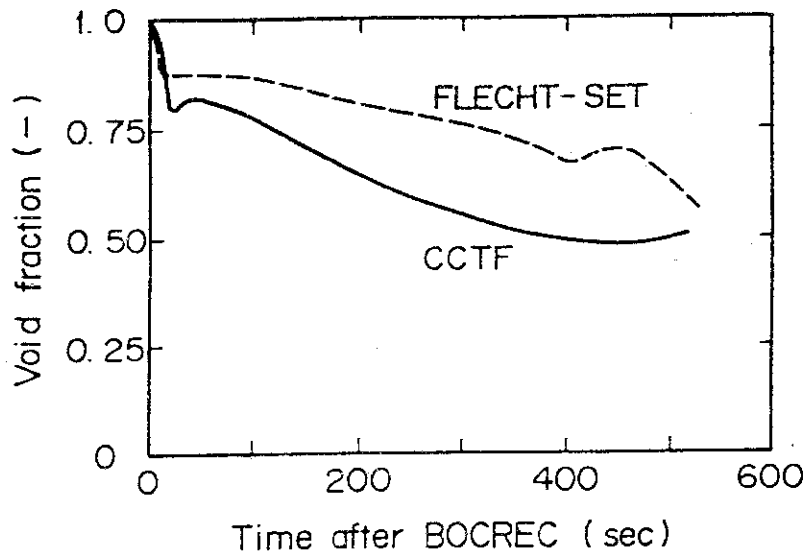


Fig.19 Void fraction at core midplane

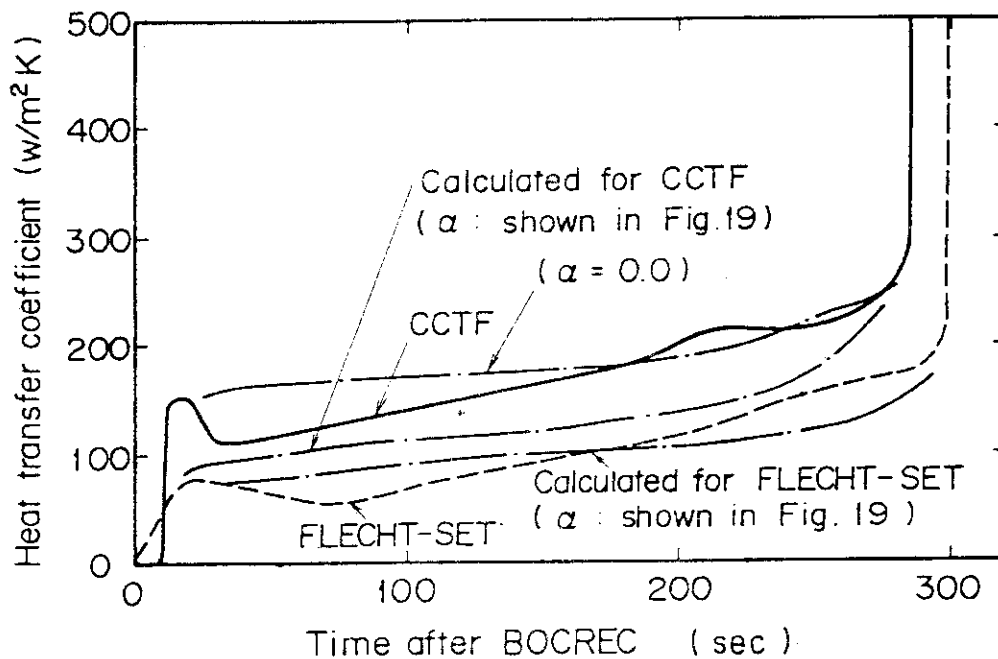


Fig.20 Comparison of the heat transfer coefficients between experiments and the predictions with film boiling correlation

Appendix Description in Japanese

大型再冠水円筒炉心試験・第1次炉心試験の結果について

原研 村尾良夫, 須藤高史, 秋本 肇
井口 正, 杉本 純, 藤木和男
平野見明

1. 序 言

加圧水型原子炉（PWR）の一次冷却水喪失事故（LOCA）時再冠水過程における非常用炉心冷却系（ECCS）の炉心冷却効果を調べる為に、大型再冠水実証試験計画が進められてきた。本試験の目的は、

- (1) LOCA時再冠水過程のECCSによる炉心冷却効果の実証
 - (2) 再冠水現象の実験的把握のためのデータの供給
 - (3) 原研、米国NRCで開発中の最適評価コード（REFLA, TRAC）の検証用データの供給
- である。

円筒炉心試験においては、特に、再冠水現象をPWRシステム全体として総合的に把握し、安全評価基準の総合的評価を行うことを目的としている。

前回報告したように、54年度までに得られた結論は、次の通りであった。

- (1) 観測された現象は、安全評価基準に基づくモデルとほぼ類似したものであり、ダウンコマ部を除き、現在の評価モデルを肯定し、かつ各部分に保守性が見い出された。
- (2) 上部プレナムへの蓄水および、きわめて大きな破断コールドレグノズルでの圧力損失が観測された。
- (3) ダウンコマ部のECC水の部分バイパスにより低速度での蓄水が観測された。
- (4) 炉心発熱体の温度応答は、半径方向、局所出力分布の影響が見い出されたが、クエンチの進行は、ほぼ一次的であった。

今回は55年度以降に行われた試験を中心として、下記の試験について述べる。

- (1) 多次元効果試験
- (2) 評価モデル試験
- (3) FLECHT結合試験

(1)は、炉心の冷却の一次元性を更に実証し、現在の安全評価解析での一次元コードの使用の妥当性を実証することにある。発熱分布を非対称とした試験、初期壁温を非対称とした試験について述べる。

(2)は、安全評価解析計算での再冠水開始条件を参考として、試験条件を選び試験を行い、かつ、試験結果を伏せて、日本側は、WREM、米国側はWRAPコードで計算を行い、比較した。

本試験の目的の一つは、ダウンカマ蓄水位の上昇が遅い原因が、非常用炉心冷却系の流量を保守的に設定しすぎたことが原因と考え、評価計算での計算値に近い値として、ダウンカマ蓄水を調べることにある。

(3) 円筒炉心試験と FLECHT/FLECHT-SET 実験の結果の相似性を調べ、主として FLECHT 実験結果に基づく評価解析の炉心熱水力モデルの妥当性を調べるための試験である。

2. 試験装置と試験方法

2.1 試験装置

本装置は、Fig. 1 に示すように 4 ループ PWR を模擬したもので、Trojan 炉を参照として、炉心流路断面積、一次系流路断面積を実炉の $1/21.4$ に縮小したものであり、垂直方向の寸法は、実炉と同じである。蒸気発生器は、2 ループにつき 1 基あり、一次側は、1 ループ分ずつ分割されている。伝熱管長は、平均 5.3 m 実炉より短い。

ループ部は、Fig. 2 に示すように、蒸気発生器、ライザ部、ポンプ模擬部、ループシール部、ECC 注水口等を含んでいる。ポンプ模擬部は、圧力損失模擬用オリフィス、水の逆流特性模擬用の羽根車模擬体より構成される。

圧力容器の水平断面を Fig. 3 に示す。実炉のコアバツフル部分の断面積は、ダウンカマの断面積に加算されている。ダウンカマ壁温は、実炉のダウンカマ壁からの放熱を模擬するため調節出来るように設計されている。炉心は、 15×15 本棒束の燃料棒を模擬した電気発熱体 8×8 本よりなる燃料バンドル 32 体より構成され、半径方向に 3 分割された領域毎に出力制御が可能となっている。

2.2 試験方法

以前の試験は主として Table 1 に示す基準条件に基づき、系圧力等一項目の条件を変化させた。

多次元効果試験においては、①円周方向出力分布非対称試験、②円周方向初期壁温非対称試験を行った。①においては、平均出力は、基準条件と同一とした。②においては、初期蓄積熱量を基準条件と同一となるようにした。実験条件を Fig. 4 に図示する。

評価モデル試験においては、Table 2 に示すように、半径方向出力分布、初期壁温、ECC 流量を変化させた。

FLECHT 結合試験においては、FLECHT-SET 2714 B と同等な Table 3 に示す条件で、ダウンカマを非加熱として下部プレナムより ECC 水を注入して試験を行った。

3. 試験結果と考察

3.1 多次元効果試験

どちらの試験においても、炉心、ダウンカマ、上部プレナムの蓄水位は、軸対称であった。炉心ボイド率を Fig. 5 に示す。

クエンチ挙動については、Fig. 6に円周方向出力分布非対称の試験結果を、Fig. 7に円周方向初期壁温分布非対称の試験結果を示す。前者においては、クエンチの進行はほぼ一次元的、後者においては、100秒後まで、初期状態の違いが大きく影響しているが、その後、非対称性の影響は徐々に減るが、長期間その影響は残る。それにも拘わらず、炉心の円周方向の差圧、ボイド率分布に非対称性の影響は出なかったと云うことは、水力学的に炉心を一次元的に取扱えることを意味していると考えられる。

3.2 評価モデル試験

実測されたシステム各部の蓄水率、流量より質量バランスに基づいて炉心入口重量流量を求めた。Fig. 8にこの炉心入口重量流量と、WREM, WRAPによる計算値との比較を示す。WREM, WRAPによる炉心入口流量の予測は良好である。170秒以降炉心冠水速度は1インチ/sec以下であった。冠水速度は、多くの因子により影響され、決定されるので、なぜ、計算値と実測値の一致が良いか調べることは重要である。

Fig. 9にPWRシステムでの質量、運動量バランスの概念図を示す。冠水速度 \dot{m}_F は次式で表わされる。

$$\dot{m}_F = \dot{m}_C + \dot{m}_U + \Sigma \dot{m}_I + \dot{m}_B$$

$$\dot{m}_I = \sqrt{2 \Delta P_I \rho_I / K_I}$$

$$\dot{m}_B = \sqrt{2 \Delta P_B \rho_B / K_B}$$

$$\Delta P_B = \Delta P_I + \Delta P_{BCN}$$

$$\Delta P_I = \Delta P_D - \Delta P_C$$

上式からわかるように、炉心入口重量流量は、炉心内蓄水率、上部プレナム蓄水率、ループKファクタ、流体密度、ダウンカマ-炉心水頭差、破断コールドレグ圧力損失に依存していることがわかる。炉心入口重量流量は、炉心圧力、炉心入口水温とともに、炉心冷却に大きな影響を与えることが強制注水試験から確認されているので、円筒炉心(CCTF)の炉心入口流量とWREMの計算結果とについて、各項目の寄与を比較することとする。Table 4に各項を比較する。表からわかるように、炉心内蓄水率はWREM計算値が大で、上部プレナム蓄水率、ループ内重量流量は、CCTFが大であり、互にほぼ打消し合い、炉心入口流量(冠水速度)の予測値、実測値は良い一致を示していることがわかる。

Fig. 10は、CCTFのループKファクタを示している。Kファクタは、EM計算で用いている値、25より低い値であるが、時間とともに徐々に増加し、25に近づく。このためWREMコードにおいて、 \dot{m}_I 、 \dot{m}_B を過小評価する。

Fig. 11に炉心最高出力部分の被覆管表面温度履歴についてのCCTF実測値、WREM、WRAPコードによる計算値との比較を示す。WREM、WRAP計算結果は、ほぼ同じであるが、実測値は、試験開始直後から良好な熱伝達を示し、低いピーク温度を示している。なお、システム計算と実測値との炉心境界条件の違いを除くため、実測値に基づく境界条件を与えて、WREM計算を行った結果も同図に示す。ほぼ他の計算値と同じ傾向であることがわかる。

Fig. 12に炉心蓄水水頭(炉心差圧)とダウンカマ蓄水水頭(ダウンカマ差圧)についてのCCTF実測値とWREMの計算値とを示す。ダウンカマ差圧は、CCTFでは、ダウンカマ内の

ボイド発生又は、ダウンカマを横切る蒸気流によるキャリオバのため、オーバーフロー水位に対応する水頭より低くなっている。炉心差圧は、CCTFでは、短時間に一定値に近づくのに対して、WREMでは、ほぼ一定の割合で増加する傾向がある。

又、CCTFでは初期の蓄水が計算値より大である。

このように、WREMによる予測と実測との間には、炉心蓄水に関して大きな差異があることがわかった。

WREMの炉心熱水力モデルは、FLECHT実験にもとづいて開発されたものである。そこで、炉心ボイド率に関して、CCTFとFLECHT (Run 04516) とを比較することとする。Fig. 13に結果を示す。FLECHTでは、初期(クエンチが生ずる時刻以前に対応する)に、ボイド率がほぼ1.0であり、流動パターンが、噴霧流と考えられるのに対して、CCTFでは、ボイド率から考えて、スラグ流と考えられる。クエンチフロント上部で噴霧流が生ずる場合、炉心全体の蓄水量は、ほぼクエンチフロントより下の蓄水量とほぼ等しく、クエンチフロントの進行と対応して蓄水量も徐々に増加することがわかる。

このように炉心内流動様式の違いを考えれば、CCTFとFLECHTの炉心蓄水挙動の違い、さらに、炉心蓄水挙動についてのCCTF実測値とEMコードによる予測値との違いも説明できると考えられる。熱伝達の違いも炉心内流動様式の違いによると考えられよう。

3.3 FLECHT 結合試験

炉心差圧、ダウンカマ差圧についてのCCTF、FLECHT-SET (2714 B) の実測値の比較をFig. 14に示す。CCTFの炉心差圧の方が大である。ループ差圧の比較をFig. 15に示す。破断ループ差圧に大きな違いが見られる。FLECHT-SET実験において破断ループと健全ループとの差圧がほぼ等しい原因は、破断コールドレグの管径が他の一次系配管径に比べて大であることとオーバーフローが生じないようにECC水の注入量を制御しているためである。

CCTFにおいては、より実際に近い構造に設計され、かつ、オーバーフローが生じないように人為的に制御することは行っていないので、破断コールドレグ圧力損失が大であり、破断、健全ループ差圧に大きな差が生じている。Fig. 16に示すように、破断コールドレグ圧力損失の存在が炉心入口流速に著しい違いを生じさせている。炉容器内の圧力も破断コールドレグ圧力損失の増加により増加している。

Fig. 17に炉心最高出力部の被覆管表面温度の履歴、Fig. 18にクエンチフロント進行についてのCCTF、FLECHT-SET実験の結果の比較を示す。CCTFにおいては、炉心冷却がより良好であり、クエンチはほぼ同等であることがわかる。Fig. 19に中央部のボイド率の比較を、Fig. 20に炉心最高出力部の熱伝達率についての比較を示す。ボイド率の違いは、主に、炉心入口流速、炉心圧力の違いにより生じていると思われる。飽和膜沸騰熱伝達の式⁽¹⁾(村尾、杉本)とFig. 19のボイド率又は、ボイド率=0での熱伝達率計算値をFig. 20に鎖録で示す。上記の式はスラグ流の膜沸騰を対象とした式であり、ほぼ実測値と計算値とは一致しており、又、ボイド率から考えてスラグ流と考えられるので、CCTF、FLECHT-SETともに流動様式は、スラグ流と考えられる。これは、EM評価モデル試験の項で述べたこととも一

致している。

4. 結論

多次元効果試験，評価モデル試験，FLECHT結合試験を行い，次の結論を得た。

- (1) 多次元効果試験においては，現象が熱的に非対称な場合でも，水力学的には対称であった。評価モデル試験においては，
- (2) 基準試験において見られたダウンカマ低速蓄水現象は見られなかったが，評価モデルでの予測値より低いダウンカマ蓄水が観測された。
- (3) 実測された炉心蓄水挙動は，短時間にほぼ一定値に達する傾向があるのに対して，評価モデルでの予測では，ほぼ一定の割合で蓄水し続ける傾向があることがわかった。
- (4) 炉心冠水速度については，実測値と予測値との良い一致が得られたが，これはいくつかの影響因子の効果が打消し合った結果であることがわかった。
- (5) 試験前，後の予測 (Pre-test and Post-test analysis) とともに，実測されたものより高いターンアラウンド温度を与えた。
- (6) FLECHT結合試験においては，破断コールドレグノズル部の圧力損失が著しく大であった。又，その結果として，炉心冠水速度がFLECHT-SET試験に比べて大であった。
- (7) FLECHT試験の炉心内流動様式は噴霧流であり，CCTF，FLECHT-SET炉心ではスラグ流であり，その結果，FLECHTデータにもとづく相関式を含む評価コードによる炉心蓄水挙動の予測値は，実測値と異なると思われる。多分，熱伝達の違いも同じ理由によるものであろう。

記号

\dot{m} : 重量流量	添字
ΔP : 差圧	C : 炉心
K : Kファクター(= $\Delta P / \frac{1}{2} \rho v^2$)	U : 上部プレナム
ρ : 密度	I : 健全ループ
v : 流速	B : 破断ループ
P : 圧力	BCN : 破断コールドレグノズル
	D : ダウンカマ

参考文献

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