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RELAP/REFLA (MOD 0) : A SYSTEM REFLOODING ANALYSIS COMPUTER PROGRAM

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A new computer code RELAP/REFLA has been developed, aiming at analyses of the core reflooding phenomena during the postulated loss-of-coolant accident of PWRs. The code was originated from the combination of two distinct codes, RELAP4-FLOOD and REFLA-1D. The characteristics of the code are: (1) Kinematical model based on the observation and analysis of quench experiments is used for the thermal-hydranlic analysis of reflooding core, (2) it has the capability to analyse the reflooding phenomena in an arbitrary type of PWR or experimental facility, including the system feedback effects, (3) the flow paths in the actual system are represented by the combination of 1-dimentional flow paths, and vapor-liquid equilibrium model is applied except the reflooding core.

This report is a code manual of RELAP/REFLA (version Mod 0) and contains the descriptions of the basic models, basic equations, code structure and input format. The calculated results of two kinds of sample problems, i.e., reflooding problem on the 4 loop PWR and FLECHT-SET experiment, are also presented. Relatively close agreement between FLECHT-SET data and the calculated results was obtained for the lower portion of the core, but poor agreement for the temperature histories in the upper core and carryover ratio.

Running speed and core memory size are almost equal to those of RELAP 4/ Mod 3.

Keywords: PWR, Loss of Coolant Accident, Reflood, ECCS, System Effect, Carryover, Computer Code, Quench Experiment, Manual

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システム再冠水解析コードRELAP／REFLA（Mod 0）説明書

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PWRプラントのLOCA（冷却材喪失事故）における炉心再冠水過程の解析を目的として，システム再冠水解析コードRELAP／REFLAを開発した。このコードは，RELAP4－FLOOD及びREFLA－1Dの2コードの結合によって成り立っており，その特徴としては，(1)再冠水中の炉心熱水力解析にクエンチ実験の観察と解析に基づく基礎的モデルを用いている。(2)任意型式のPWRないしは実験装置による再冠水現象をシステム効果を含めて解析することが可能，(3)システムの流路はすべて1次元流路の組み合わせで表現され，再冠水炉心を除くすべての部分に，気液2相の平衡モデルが適用される等である。

本報告書は，RELAP／REFLA（Version Mod 0）のコード・マニュアルであり，基本モデルと基礎方程式，コードの構成，入力型式について述べている。また，4ループPWR及びFLECHT－SET実験の2種類の例題に関する計算結果についても考察している。現行バージョン（Mod 0）では炉心下半分のクエンチ現象はよく記述されるが，炉心上半分の温度変化及びキャリーオーバ率の評価に改良の余地がある。

計算時間及びコアメモリは，RELAP 4／Mod 3とほぼ同一である。

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1. Introduction

RELAP/REFLA is a computer code for the analysis of reflooding phenomena of a pressurized water reactor (PWR). The reflood phase in a postulated loss of coolant accident (LOCA) of PWR is affected by so-called system effects (downcomer water head, steam binding, loop resistances and so on) and by flow blockages caused by fuel deformation. RELAP/REFLA includes the system effects of the primary system of a PWR but does not analyze the fuel deformation. The program contains a detailed core thermal-hydraulic model based on the one-dimensionally distributed parameters partially together with an unequal-temperature, unequal-velocity (UVUT) model. The code was born from the RELAP4-FLOOD and the REFLA-1D programs. RELAP4-FLOOD is one of the WREM codes, which is the loop analysis code for reflooding phenomena based on the FLECHT correlations. REFLA-1D is the program based on a UVUT model for the calculation of reflooding phenomena within the one-dimensionally modeled heat-up section. The flow model and quench model used in REFLA-1D and also in RELAP/REFLA have been derived from the observation and analysis of many reflood experiments including PWR-FLECHT of Westinghouse. Though some correlations used in REFLA-1D and RELAP/REFLA have been developed by analysing the PWR-FLECHT experimental data, the correlations developed have now general characters, thus the code RELAP/REFLA is independent from any FLECHT-type correlations.

On the other hand the model used in describing the primary loop system (with SG's secondary) has a fundamental assumption of homogeneous and thermal-quilibrium on the state of two-phase fluid flow. Configurations of the system are represented by the combination of fluid volumes (control volumes), flow paths (junctions) and heat conductors. These models come from RELAP4 which is the base code of RELAP4-FLOOD.

User should recognize the limitation of the code capability which come from the homogeneous equilibrium assumption of the loop model. The present version of RELAP/REFLA is based on RELAP4/Mod3 (i.e. RELAP4-EM is WREM), thus having same limitation on the usage of improved models and options. For example, the models built in later version of RELAP4, such as, vertical slip model, local quality calculation for the heat conductors, and the option of computation of a single mixture level in vertically stacked volumes are not included. The code has a wide variety of applications. It was used in evaluation of the ECCS performance at a LOCA for nuclear ship "Mutsu", and applied to the analysis of some reflood experiments. In future, the code will be used for the audit calculations of commercial reactors submitted for licensing in Japan.

The input data for the RELAP/REFLA code are just a stack of two data sets, one for RELAP4-FLOOD and the other for REFLA part. The input data for REFLA portion are placed immediately after a terminator (period or slash) card of the RELAP4-FLOOD input. The input data for the RELAP portion have the same format as given in the WREM manual and a few kind of data (mainly related to FLECHT correlation parameters) are treated as dummy data. So the user who is familiar with RELAP4 can easily prepare the input data of RELAP/REFLA.

The manual is comprised of 5 chapters. Chapter 2 describes the program summary. Chapter 3 represents the calculational model stressed on the thermo-hydraulic models of reflooding core and on the coupling procedure between core and loop calculations. Chapter 4 describes the input data organization and the informations on preparing the input values. A brief explanation of the RELAP part of input and a full description of the REFLA part of input are given there. Chapter 5 is directed toward the demonstration of the code capability showing the calculational results of typical problems.

2. Program Summary Description

RELAP/REFLA is a computer program that was developed to describe the thermal-hydraulic behavior of a PWR primary system subjected to the reflooding of the core during the postulated loss of coolant accident (LOCA). It originated from RELAP4-FLOOD, an optional program of RELAP4-EM for the analysis of reflooding of a PWR, with the replacement of the core thermal-hydraulic analysis by the component code REFLA-1D. The user must specify the model of a system by using the concepts of control volumes, flow passes and heat conductors. The appropriate thermal-hydraulic boundary conditions are also provided by the inputs. On that procedure, reactor core should be represented as a single control volume in conjunction with the program coupling scheme between RELAP part and REFLA one.

2.1 Major Parts

The RELAP/REFLA code is directed toward the reflood analysis thus its capabilities are somewhat limited in comparison with the original RELAP4. The major part of the RELAP4 program were concerned with the fluid equations, heat transfer and reactor kinetics. Among these functions, the reactor kinetics is not used in RELAP/REFLA because the nuclear power level and fluid condition during the reflooding period are far from those in the operational steady state. The power history of the core must be specified by tabular input.

The fluid system to be analysed by RELAP/REFLA must be modeled by fluid volumes and by fluid junctions (flow paths) between the volumes. User specified fluid volumes (control volumes) are used to represent the fluid in the system piping, plenums, reactor core and heat exchangers. Any fluid volume may be chosen independently to represent a region of the system associated with a heat source or sink, such as fuel rods or a heat exchanger. The reactor core must be represented as a single control volume, because the thermo-hydraulic quantities calculated by REFLA portion are averaged and treated as a core average quantity.

Thermal-hydraulic phenomena expected to occur in the reflooding core are analyzed by the REFLA portion of the code. In this analysis, the code solves the fluid mass, energy, and momentum equations using a distributed parameter system with the quench velocity correlation, flow pattern transition assumption, slip between vapor and liquid phases and unequal temperature assumption. The fluid conditions at the core inlet are treated as the boundary conditions of this calculation. The values of any thermal-hydraulic parameters thus calculated are averaged and are used as a quantity related to core fluid volume in the modeled loop system.

The fluid volumes are connected by junctions which are used to transfer fluid into and out of fluid volumes. Junctions are of three types:

(1) Normal (connects two fluid volumes)

(2) Leak (system fluid loss point)

(3) Fill (system fluid gain point, such as ECC injections)

A junction must be located within the elevations specified for the fluid volumes that are connected to the junctions because the fluid path is physically continuous.

The fluid dynamic portion of the RELAP part solves the fluid mass, energy, and flow equations for the system being modeled including reactor core. The choice of the five basic form of the flow equation is provided, that is the same as in the original RELAP4 (See Section 3.7 of reference 1). Among calculated physical quantities, those of core outlet junction and of core fluid volume are overridden by the quantities calculated by the REFLA portion. Coupling scheme between RELAP and REFLA portion will be described in Chapter 3.

A heat conductor model is used to transfer heat to or from the fluid in a volume. The geometry and conditions of the heat conductor are specified by the user. This model may be used to describe the thermal behavior and effects of fuel rods, pipes, and plates. The behavior of fuel rods are calculated by the REFLA portion specially. Other heat conductors are treated as the same as in original RELAP4. RELAP/REFLA, thus, keeps the correlations for calculating the critical heat flux (CHF), pre-CHF heat transfer, and post-CHF heat transfer.

As previously mentioned, RELAP/REFLA is based on RELAP4-FLOOD, one of the program option of RELAP4-EM. Consequently some of the options prepared in the original RELAP4-EM are not available in RELAP/REFLA. These options are:

1) Evaluation Model on the fuel rods, i.e., EM heat transfer logic, pin swelling and flow blockage model.

2) Evaluation Model on the blowdown ECC bypass logic.
3) Gap expansion model.
4) Automatic time step control option.
5) Reactor kinetics calculation.

A RELAP/REFLA calculation consists of a series of time advancements as similar to RELAP4. The sequence, however, is slightly different because of the coupling of two parts of program and of abolishment of the automatic time step control. So the sequence of calculation in each advancement is:

(1) hydraulic effects
(2) core thermal-hydraulics by REFLA
(3) integration over time
(4) thermodynamic balance
(5) heat transfer (quantities calculated by REFLA are retrieved)
(6) editing
(7) time step advancement

2.2 Programming

The RELAP/REFLA code is written in FORTRAN-IV and is operable on the FACOM-230/75 in JAERI. The code uses one external source of data. The water and steam property tables are not contained within the computer until they are retrieved early in the calculation. These tables are generated by the STH2OG program which is stored in the form of a disk file and must be attached in the execution of RELAP/REFLA.

Another use of a computer program in conjunction with RELAP/REFLA is the PLOT5R program which produces both Calcomp and microfilm plots of appropriate variable-versus-time, variables-versus-elevation (only for variables in core), variables-versus-variable from a RELAP/REFLA plot-restart tape.

The running time of a RELAP/REFLA reflooding problem can vary depending primarily upon the problem dimensions, i.e., number of fluid volumes and number of nodes for heat conductors. The stability on the calculation, however, gives other criteria on the time step size. Thus, the running time for the PWR reflooding problem with about 30 fluid volumes may range from 0.5 to 2.0 minutes per 1.0 second in physical time on the FACOM 230/75.

The program structure of RELAP/REFLA has overlaid as shown in Fig. 2.1 and Table 2.1

The sizes of the common blocks associated with the volume and junction data are reduced from the original sizes of RELAP4. Accordingly, the number of the volumes and the junctions are restricted up to 50 and 70, respectively. This reduction of the common block sizes has been done only because of the economy for computer core size and of consideration about the convenience in the execution of program at JAERI's computer center.

Table 2.1 SEGMENT CONTENTS of RELAP/REFLA Mod-0

Segment Number	Segment Name		Contents
1	SEGA (Root Segment)	* (1)	FTMAIN, ALPACK, BLKD1, BLKD2, BLKD3, BLKD4, BLKD5, BLKD6, BLOCKD, BUBB, BUFIN, CELMOD, CHKV, CLDPR, CORQ, DCVIC, DEFORM, ENQADD, ENTSUR, EPLAS, STSCON, FABEND, FAIL, FANG, FLDBAL, FLDHTC, FLDHTX, FLDPRW, FLDRAF, FRICTN, FTXEXP, GAPCON, GAPPRS, GAUSS, HEADC, HEADER, HTRC, IAND, IAPACK, INFLAG, INPPCK, IOR, JPLUSN, LEVCAL, LINES, MOVE, PGCNT, MACH, MCONST, MIXFLO, PCHF, PINI, POLATE, POL2, POROS, POSTW, PREW, PUMP, PUMPS, QDOT, REFLAP, SENG, SLIP, SMOOTH, STH201, STH203, STMCON, SUBPG, SWELL, TAVE, TFFM, THCON, TIMSET, TKANDC, TKRAD, TRIP, VAPOR1, VISC, ZEROUT, ZTEDIT, CTHSTR, ENTRAN
		* (2)	REFLA1, DISPRM, DPHDFR, FLD, FTW, FTWL, FUELTP, GPLT, GPLTX, HIA, INPUT1, INPUT2, PPROP, PRINT1, PRINT2, PTABLE, PX, SATTPF, SBHCL, SBHCV, SBHR, SBHSP, SINGLF, SPHTRM, TRNSRM, VIS, BPRINT
		* (3)	REFLAC, REFLAU, REDAVE, REDUCE, UCHANG
2	SEGB1		INPUT, INPUPK, STH201, INEDIT
3	SEGC1		INP
4	SEGC2		INP2, LINK, MODER, INP8, IZERO, COMZER, COMLEN, TSTMOD
5	SEGD1		INMAIN, INHTXQ, INREAC, INSCRM, INTRIP, INTSTP, INRCD1
6	SEGE1		INVOL, INBUBL, INLVC, INTV, INEM
7	SEGE2		INJUN, CHAIN, INCKV, INFILL, INPM, INPUMP, INSMOO, IPMCK, INENTH, INLEAK
8	SEGE3		INHEAT, INCORE, INGEOM, INMPRO, INSLAB, INWALT, KINITL, SINITL, TEMZ, INRKEN

* Please refer to NOTE

Table 2.1 Continued

Segment Number	Segment Name	Contents
9	SEGE4	FLDIN
10	SEGD2	RESTRT, POSIT, PULLIN, RETRIP, RETSTP, RERCD1
11	SEGD3	PRINTR, CHEK, EDCOM, EDDAT, EDEDIT, EDINED, TSPIN, TSPRNT
12	SEGB2	TRAN, BAL, CCC, EDIT, FILL, FLOSRH, HTXQ, LEAK, MH2OR, MWR, NIFTE, PLTAPE, PRESS, REAC, RCDN, RKEN, RNDO, SCRM, SLABHT, STATE, STH2O4, TEMP, TRDAT, TSTP, COND
13	SEGC3	ECCADJ, MH2EM, MWRIN, MWROUT, PRESWL
14	SEGC4	FLDEBW, FLDEJ, FLDNIF, FLDES

NOTE (1) RELAP4/Mod3 Subroutines

(2) REFLAID Subroutines

(3) RELAP-REFLA Interfacing Subroutines

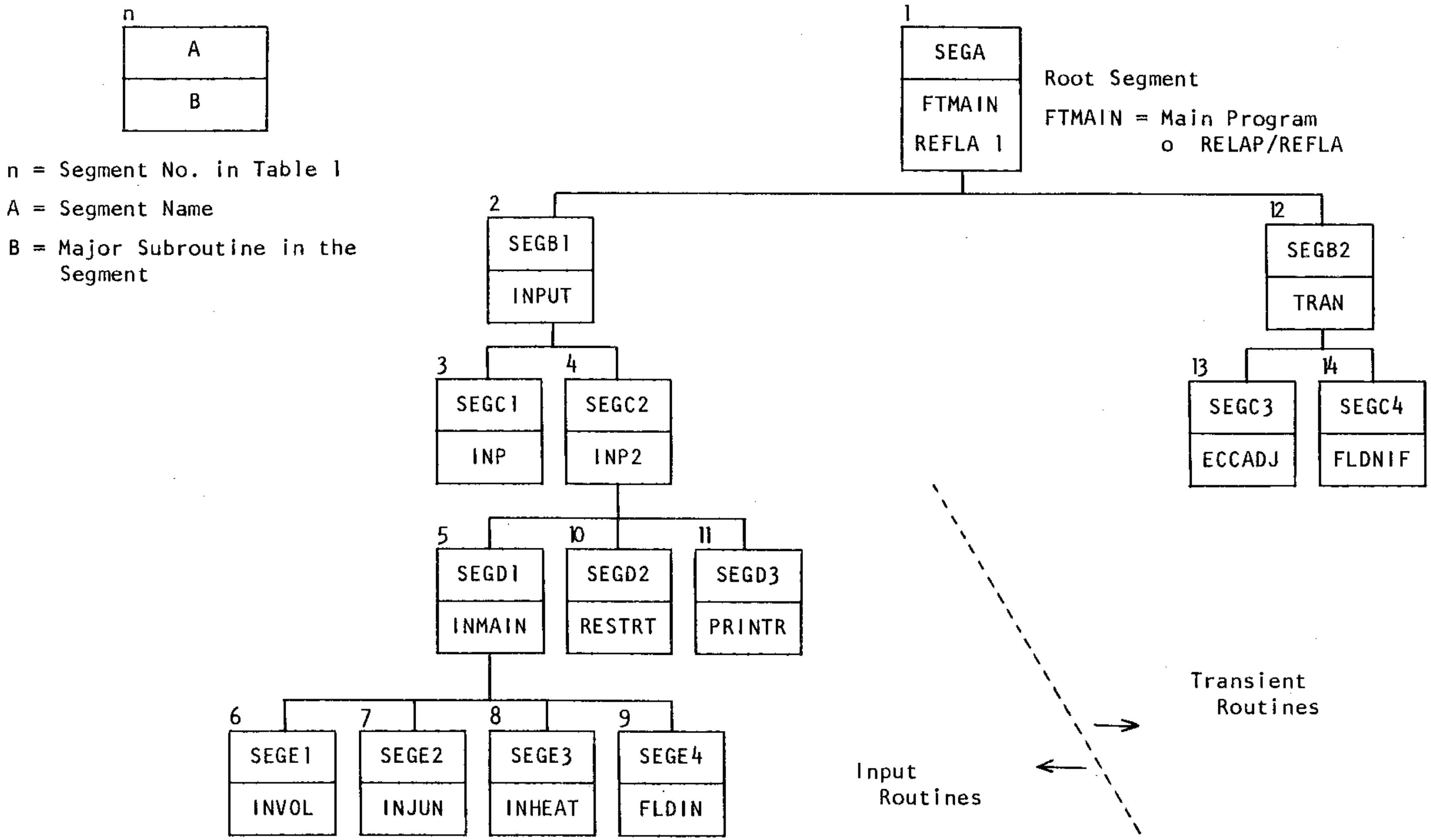


Fig.2.1 Overlay Structure of RELAP/REFLA (Mod 0)

3. Model Description

3.1 Core Reflooding Model

Core reflooding model of RELAP/REFLA is the same as one for as a single channel analysis code REFLA-1D. REFLA-1D is originally developed for the analysis of forced feed reflood tests and its flow model and quench model are based on the observation of experiments using the heated quartz (transparent) tube and detailed analysis of PWR-FLECHT[2] experimental data by Y. Murao (the author of REFLA-1D) and T. Sudo[3]. The original models in REFLA-1D was developed as a tool for the analysis of constant reflooding experiments, thus, some modifications on the coding, that are necessary to adopt the time dependent boundary conditions, have been added when two codes, i.e., REFLA-1D and RELAP4-FLOOD have been coupled.

A full description about the reflood models and its derivation are represented in the original report[4]. Thus we will mentioned only a summary of the models in this report.

3.1.1 Flow Models

We assume the reflooding period of a postulated LOCA of PWR with bottom reflooding due to ECCS. As the emergency coolant starts rising around the heated fuel rods, complex heat transfer and two-phase flow phenomena take place. A segment of the rod experiences free or forced convection cooling by steam, cooling by dispersed flow, film boiling, transition boiling, nucleate boiling and finally convection to the single-phase liquid. This succession of heat transfer and flow regime is reflected to the observed variation of heat transfer coefficient and surface temperature (See Fig. 3.1, 3.2)

It is known that there is a difference between a flow-patter occurred when the reflooding rate (fluid velocity at the core inlet) is rather high and one occurred in the low reflooding rate case. This difference is also related to the inlet subcooling of coolant.

Comparing many data of heat transfer coefficient in PWR-FLECHT experiment, Y. Murao and Y. Sudo[10] found the fact that some group of the heat transfer coefficient curves has a middle steep range but another group has not. They found this classification of heat transfer coefficient curves corresponds to the condition at the quench front so that they

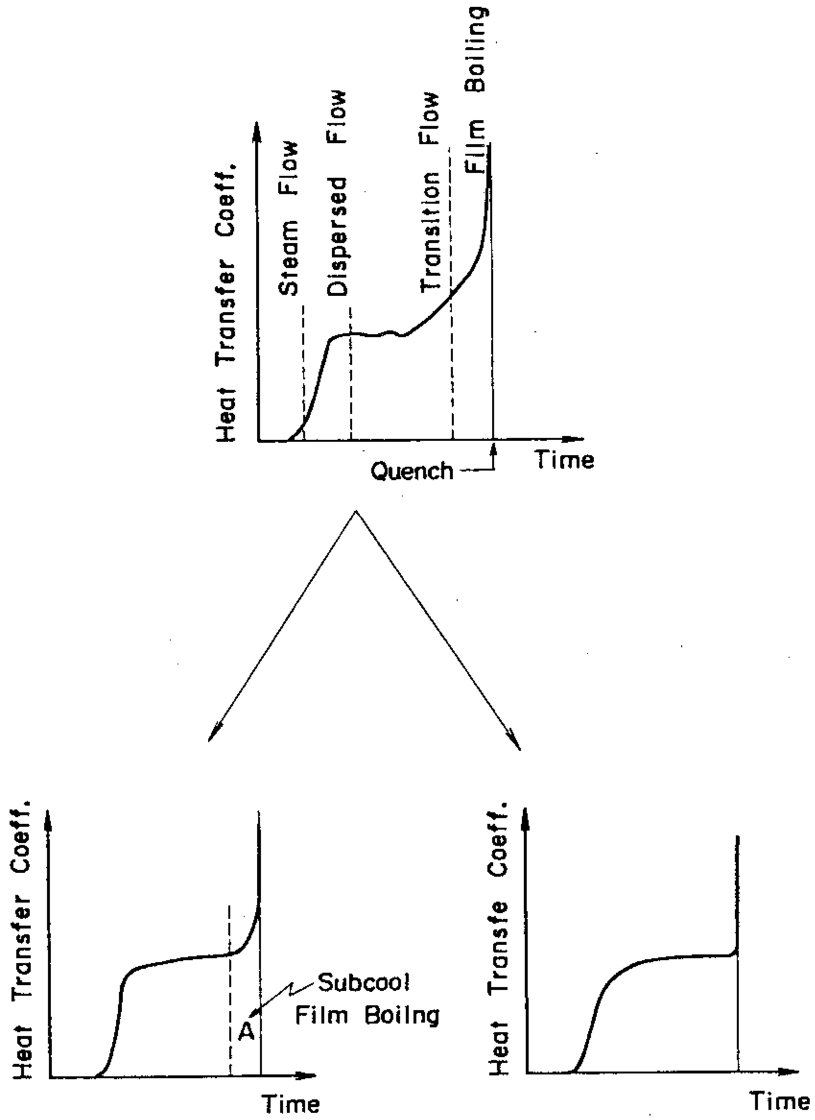


Fig.3.1 Two Types of the Heat Transfer Behavior
(Taken from Reference (4))

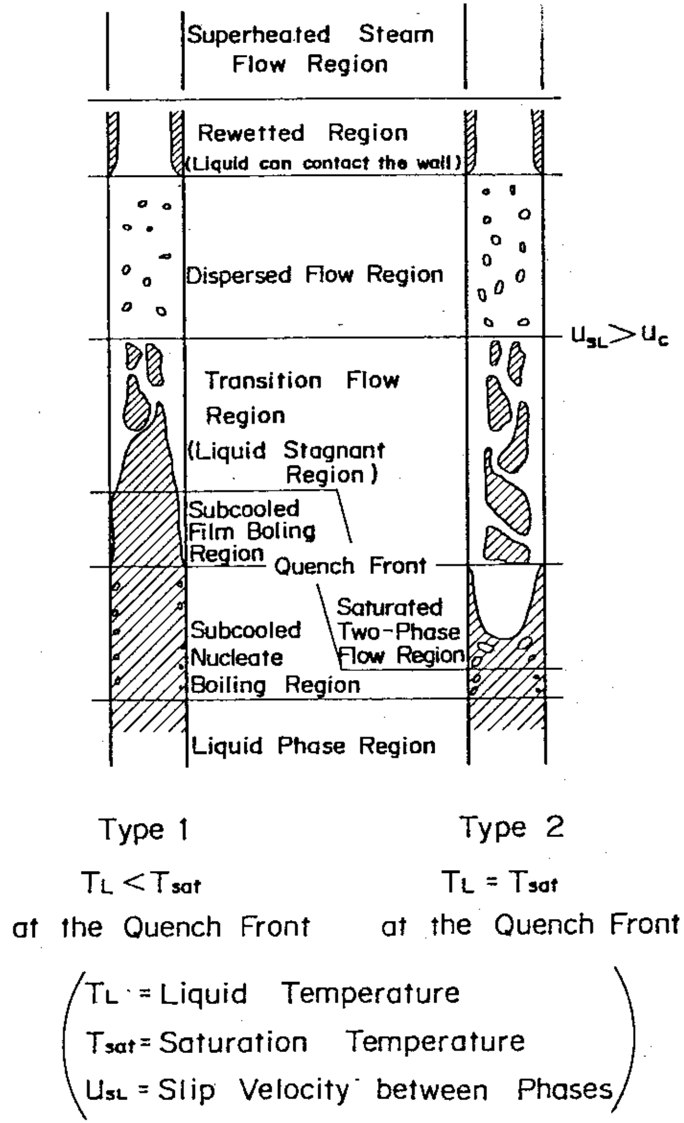


Fig.3.2 Two Types of the Flow Pattern During Reflood Phase
(Taken from Reference (4))

assumed that the steep range of curve was corresponding to subcooled film boiling region. In the first group, the coolant temperature at the quench front still have subcooling, i.e., $\Delta T_{sub} > 0$, but in the second group, the coolant condition reaches saturation.

Based on those arguments, the following flow model shown in Fig. 3.2 was assumed as a reflood flow medel. The type 1 flow pattern appears under the subcooled condition at the quench front. Upstream from (below) the quench front, the water injected enters liquid phase region and subcooled nucleate boiling region downstream from (above) the quench front, subcooled film boiling region ($T_W > T_Q$, $T_L < T_{sat}$), transition flow region ($T_W > T_Q$, $T_L = T_{sat}$, liquid nearly stagnant), dispersed flow region ($T_W > T_Q$, $T_L = T_{sat}$, $T_g \geqq T_{sat}$) and superheated steam flow are expected to occur. If the wall temperature of upper section is low enough, the liquid can contact the wall and then the rewetted region is formed.

The type II flow pattern appears under the saturated condition at the quench front. The flow pattern is nearly the same as the type I flow pattern but except the regions near the quench front where saturated two pahse flow appears instead of subcooled boiling regions.

3.1.2 Quench Model

The Quench model used in RELAP/REFLA is the same as proposed by Sudo and one of the author[3]. This model consists of three types of quenching as shown in Fig. 3.3. i.e.

(1) Liquid column type (Rewetting by subcooled water)
(2) Dryout type (Annular flow type, rewetting by saturated water)
(3) Top Rewetting type (Entire surface temperature higher than rewetting temperature)

In the first and second type, quench front (often refered to also as rewetting front or quenching point) devides the entire heated region into two part. i.e. quenched or rewetted part and non-quenched one. From the non-quenched part to the quenched region, the heat transfer by axial conduction take place so that the temperature of the portion just forward of quench front decreases. And thus the quench front is advancing. The first type occurs when the liquid is subcooled at the quench front and the second type occurs when the liquid is saturated. In the third type, however, there is no quenched part which is supporting the quenching as in the type 1 and 2. This type of quench usually starts from the upper end portion of heated core or the positions of the spacer grids. The critical temperature for the quench (referred to also quench temperature) is assumed to be the maximum liquid superheat, above which the liquid phase cannot exist thermodynamically. The following expression calculated by Groeneveld[5],

$$T_M = 321.05 + 0.237 \times 10^{-4}\ P, \tag{3.1}$$

wjere T_M : maximum liquid superheat (C),
P : pressure $(kg/m^2)a$,

is used in the code.

Evaluation of quench velocity (rate of advancing of quench front) is base on the expression given by Blair[6],

$$u_q^{-1} = \rho_W g\ C_{PW} \cdot (T_W - T_0)/\phi_{eff} \tag{3.2}$$

where T_0 is a critical temperature like a Leidenfrost temperature and ϕ_{eff} is an effective axial heat flux which corresponds to a heat flux from the wall to the coolant at just behind the quench front, ϕ, i.e.

$$\phi/\phi_{eff} = \pi/2 \tag{3.3}$$

In the model of RELAP/REFLA, T_0 is equal to the maximum liquid superheat T_M and the heat flux ϕ is a function of the liquid subcooling at the quench front and of the maximum heat flux ϕ_{max} determined by the experimental data. Actually the data of Westinghouse's PWR-FLECHT experiment are used to estimate of ϕ_{max}.

The correlations of quench velocity are as follows.

1) For the dryout type (type 2) quench

$$u_q^{-1} = \rho_W g \cdot C_{PW}\ (T_W - T_0)\ /\ 2.19 \times 10^6 \qquad (h/m) \tag{3.4}$$

$$\phi_{max} = 3.43 \times 10^{-6} \qquad (kcal/m^2h) \tag{3.5}$$

2) For the liquid column type quench

$$u_q^{-1} = \rho_W g \cdot C_{PW}(T_W - T_0)/\{2.19\times10^6(1+0.2778\cdot10^{-4}\cdot\Delta T_{sub}^3)\} \quad (h/m) \tag{3.6}$$

$$\phi_{max} = 3.43\times10^6\cdot(1+0.2778\cdot10^{-4}\cdot\Delta T_{sub}^3) \tag{3.7}$$

3) For the rewetting type quench, the so-called contact temperature was assumed to be the maximum liquid superheat and the rewetting temperature was obtained as follows:

$$T_R = T_M + K(T_M - T_L) \tag{3.8}$$

and

$$K = C(k_\ell\cdot\rho_\ell\cdot C_{P\ell})^{0.5}/(k_W\cdot\rho_W\cdot C_{PW})^{0.5} \tag{3.9}$$

where C is a factor to take into account the collision rate of water droplet to the heated wall, $C = 1$ for $\alpha = 1.0$ and $C = 0$ for $\alpha = 0.0$.

3.1.3 Heat Transfer

The heat transfer model for the core reflooding model of RELAP/REFLA has been defined by assuming flow regimes, quench boundaries, and a boiling curve. The flow regimes are based on several visual reflood experiments and the PWR-FLECHT tests as described in Section 3.1.1. The core channel is divided into wetted regions and unwetted regions based upon the quench correlations discussed in Section 3.1.2, and further each region is divided into some flow regimes according to the heat-transfer mechanisms and to the flow characters.

The heat transfer correlations for each regime are summarized as follows: (also summarized in the Table 3.1)

(1) Single Phase Forced Convection ($T_W < T_q$, $T_L < T_{sat}$)

$$h = \frac{k\ell}{De}\,Nu \qquad kcal/m^2\text{-}h\text{-}°C \tag{3.10}$$

where the Nusselt number is given by Colburn's correlation[8]

$$Nu = 0.023\ Re^{0.8}\ Pr^{1/3} \qquad Re \geq 2400 \tag{3.11}$$

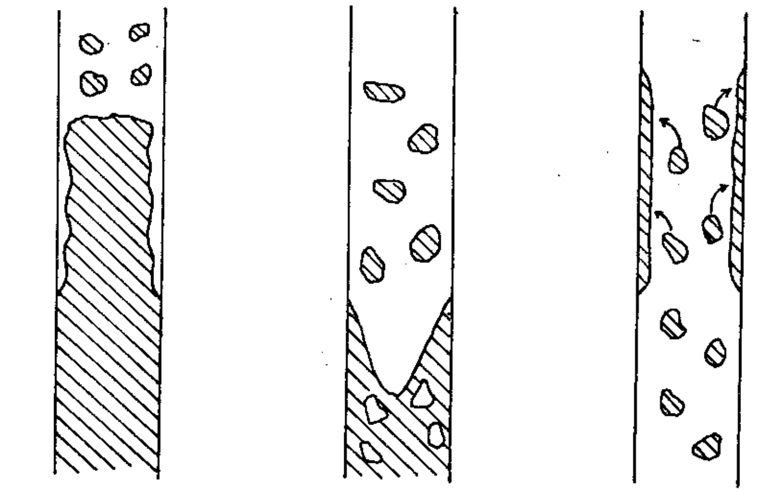
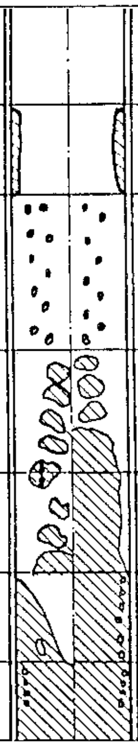


Fig. 3.3 Three Types of Quench Mode (Taken from Reference 4))

Table 3.1 Flow Regimes in the REFLA Model of Reflooding Core (Taken from Reference 4))

Flow Pattern (saturated)(subcooled)	Flow Regime	Hydro-dynamic Model	Heat Transfer Model	Boundary Condition
 L_7	Super heated Steam Flow	Single Vapor Flow	Single Vapor Phase Forced Convection	over the top of liquid $\alpha > 0.9999999$
L_5	Rewetted Regime	Wetting Two-Phase Flow	Nucleate Boiling and/or Single Liquid Phase	$T_w < T_q$ & $\alpha \leq 0.9999999$
L_4	Dispersed Flow Regime	Unwetting Two-Phase Flow (Single Vapor Flow + Drag Force of Droplets)	Two-Step Model (Single Vapor Phase Forced Convection + Vapor to Droplets + Radiation to Droplets)	Slip Velocity > Free Fall Velocity of Droplets & $T_w \geq T_q$
L_3	Transion Flow Regime	Unwetting Two-Phase Flow (Wetting Two-Phase Flow Correlation)	Saturated Film Boiling + Radiation	$T_w \geq T_q$ & $T_L = T_{sat}$
L_2	Subcooled Film Boiling Regime	Unwetting Two-Phase Flow (Single Liquid Flow without Wall Friction)	Subcooled Film Boiling Correlation + Radiation	$T_w \geq T_q$ & $T_L = T_{sat}$
L_1	Bulk Boiling Regime	Wetting Two-Phase Flow	Nucleate Boiling	$T_w < T_q$ & $T_L = T_{sat}$
	Single-Liquid Phase Flow, Regime	Single-Liquid Flow	Single Liquid Phase Forced Convection + Nucleate Boiling	$T_w < T_q$ & $T_L < T_{sat}$

(L_6 : bulk boiling P_t in rewetted regime, L_7 : the upper end of the water level) and

$$Nu = 1.077 \left(Re\ Pr\ \frac{De}{Z}\right)^{1/3}\ ^{9)} \qquad Re < 2400 \qquad (3.12)$$

with the physical properties evaluated at liquid conditions.

(2) Nucleate Boiling ($T_W < T_q$, $T_L = T_{sat}$)

The boiling heat flux is given by the Jens-Lottes correlation

$$\phi_B = 2.197(T_W - T_{wat})^4 \exp(1.54 \times 10^{-6}P)\ \text{kcal/m}^2\text{-h} \qquad (3.13)$$

and the maximum heat flux defined by

$$\phi_{B_{max}} = 3.43 \times 10^6(1 + 0.2778 \times 10^{-4}\ \Delta T_{sub}^3) \qquad (3.14)$$

The maximum heat flux was adjusted for PWR-FLECHT data and the subcooling modifier[3].

(3) Subcooled Film Boiling

The heat transfer is defined as the sum

$$h_{s.f.b} = h_{wall\text{-}liquid} + h_{radiation} \qquad (3.15)$$

For wall to liquid heat transfer, the Bromley correlation is used,

$$h_{sat} = 0.94 \left[\frac{k_g^3\ \rho_g\ (\rho_\ell - \rho_g)H_{fg}\ g^2}{L\ \mu_g\ (T_W - T_{wat})}\right]^{1/4} \qquad (3.16)$$

where the wave length L is defined by

$$L = 2\pi \left(\frac{\sigma}{g(\rho_\ell - \rho_g)}\right)^{1/2} . \qquad (3.17)$$

For subcooled film boiling, a multiplier for h_{sat} is used (Sudo and Murao[10]), that is,

$$h_{w-\ell} = F \cdot h_{sat} \qquad (3.18)$$

$$F = 1.0 + 0.025\ (T_{sat} - T_L) \qquad (3.19)$$

The radiation term is given by

$$h_R = \varepsilon(T_W^4 - T_{sat}^4) /(T_W - T_{sat}) \tag{3.20}$$

where ε is the Stefan-Boltzmann constant.

(4) Transition Region ($T_W \geq T_q$, $T_L = T_{sat}$) (3.21)

$$h = h_{sat} + h_R \tag{3.21}$$

where h_{sat} is defined by Bromley's film boiling correlation (Eq. 3.16), and

$$h_R = (1-\alpha)\varepsilon(T_W^4-T_{sat}^4)/(T_W-T_{sat}) \tag{3.22}$$

In the present stage, we have little information on this region so that we have adopted above correlations temporarily.

(5) Dispersed Flow ($T_W \geq T_q$, $T_g \geq T_\ell$)
The heat transfer for the dispersed flow region is defined by the sum

$$h = h_{wall-vapor} + h_{vapor-droplet} + h_{wall-droplet} \tag{3.23}$$

that is, considered are the convection heat transfer between wall and vapor, between vapor and droplet, and radiative heat transfer between wall and droplet.
The individual correlations are

$$h_{w-v} = \frac{k_g}{D_e} Nu \tag{3.24}$$

where the Nusselt number is defined by Colburn's correlations using physical properties of vapor.

$$h_{v-d} = \frac{k_g}{D_d} Nu \tag{3.25}$$

where

$$Nu_{v-d} = 2.0 + 0.55\ Re_d^{0.5}\ Pr^{1/3} \qquad Re < 1800 \tag{3.26}$$

$$Nu_{v-d} = 2.0 + 0.34\ Re_d^{0.566}\ Pr^{1/3} \qquad Re > 1800 \tag{3.27}$$

D_d = droplet diameter

The radiation term is given by

$$h_{w-d} = F_s \cdot \varepsilon \cdot (T_W^4 - T_{sat}^4)/(T_W - T_{sat}) \tag{3.28}$$

with F_s being the shape factor given by

$$F_s = \frac{s \cdot n}{u_\ell} \frac{\pi\ D_\alpha^2}{C_\ell} \qquad F_s \leq 1.0 \tag{3.29}$$

(6) Superheated Region

$$h = \frac{k_g}{D_e}\ Nu \tag{3.30}$$

Where Nu is given by the Colburn's correlations with the use of gas properties.

(7) Reset Region ($T_W < T_q$ and high α)
Heat transfer in the rewet region is given by forced convection (Colburn)

$$h = \frac{k_g}{D_e}\ Nu \tag{3.31}$$

or by nucleate boiling using Jens-Lottes

$$\phi_B = 2.197(T_W - T_{sat})^4\ \exp(1.54 \times 10^{-6}\ P) \tag{3.32}$$

3.1.4 Fluid Equations

During the reflooding of a PWR core, regions and/or periods of thermal nonequilibrium and separated flow can be expected to occur. Therefore, the set of conservation equations including the effect of such nonequilibrium and separated flow is necessary. The assumptions used in such equations are after called UVUT (unequal velocity, unequal temperature) model. The RELAP/REFLA code describes a UVUT set to be applied in the dispersed flow region, and a reduced UVET (unequal phase velocity, equilibrium temperature model) for all other flow regimes. The basic equations are described in the following sections.

Basic Thermo-hydrodynamic equations for coolant in the quenched region, film boiling, transition and superheated regions

For the regions above, the RELAP/REFLA code assumes the homogeneous two-phase flow with slip between vapor and liquid, or single phase flow. Based on these assumptions, the MacFarlane's method[11] can be used. Flow equations are:

Continuity

$$\frac{\partial}{\partial t}\left[\alpha\rho_g + (1-\alpha)\rho_\ell\right] + \frac{\partial}{\partial z}\left[\alpha\rho_g u_g + (1-\alpha)\rho_\ell u_\ell\right] = 0 \tag{3.33}$$

Momentum

$$\frac{\partial}{\partial t}\left[\alpha\rho_g u_g + (1-\alpha)\rho_\ell\ u_\ell\right] + \frac{\partial}{\partial z}\left[\alpha\rho_g u_g + (1-\alpha)\rho_\ell u_\ell\right] + \frac{\partial P}{\partial Z} + g\left[\alpha\rho_g + (1-\alpha)\rho_\ell\right] + \gamma\frac{\partial\tau}{\partial Z} = 0 \tag{3.34}$$

Energy

$$\frac{\partial}{\partial t}\left[\alpha\rho_g g\cdot H_g + (1-\alpha)\rho_\ell g\cdot H_\ell\right] + \frac{\partial}{\partial Z}\left[\alpha\rho_g g u_g H_g + (1-\alpha)\rho_L g u_\ell H_\ell\right] = \gamma\phi\ \left(= \frac{C_\ell}{S}\frac{k}{D_e}\ Nu\ (T_W - T_L) = \frac{C_\ell}{S}\ h\ (T_W - T_L)\right) \tag{3.35}$$

As an equation of state for two-phase flow, the void fraction is frequently correlated by the following expression with Lockhart-Martinelli two-phase flow parameter.

$$\alpha = F(X_{tt}) \tag{3.36}$$

and

$$X_{tt} = \left(\frac{1-X}{X}\right)^{0.9}\left(\frac{\rho_g}{\rho_\ell}\right)^{0.5}\left(\frac{\mu_\ell}{\mu_g}\right)^{0.1} \tag{3.37}$$

$$F(x) = 1 - \left(1 + \frac{21}{x} + \frac{1}{x^2}\right)^{-0.5} \tag{3.38}$$

The two-phase frictional pressure gradient is frequently represented by an equation of the form

$$\gamma \frac{\partial \tau}{\partial Z} = F_2 \ (X_{tt}) \ \{(\frac{0.1875}{R_e{}^{0.2}}) \ \frac{G^2(1-X)^{1.8}}{2\rho_\ell De}\} \quad (3.39)$$

where

$$F_2(x) = 1 + \frac{20}{X} + \frac{1}{X^2} \quad (3.40)$$

For an equation of state of bulk boiling two-phase flow, instead of the above correlation, the Cunningham-Yeh's correlation[12] is applicable, i.e.

$$\alpha = 0.925 \ (\frac{\rho_g}{\rho_\ell})^{0.239} \ (\frac{J_g}{J_{bcr}})^a \ (\frac{J_g}{J_g + J_\ell})^{0.6} \quad (3.41)$$

where

$$a = 0.67 \quad \text{if} \quad \frac{J_g}{J_{bcr}} < 1$$

$$a = 0.47 \quad \text{if} \quad \frac{J_g}{J_{bcr}} \geqq 1$$

$$J_{bcr} = 1.53 \sqrt{g \ R_{bcr}}$$

$$R_{bcr} = \frac{\alpha}{g \ \rho_\ell}$$

$J_{g,\ell}$ = volumetric flow rate of vapor or liquid

According to the assumption of thermal equilibrium, density and enthalpy of vapor and liquid are equal to the saturation values, i.e.

$$\rho_g = F_3 \ (P) \quad (3.42)$$

$$\rho_\ell = F_4 \ (P) \quad (3.43)$$

$$H_\ell = H_{sat} = F_5 \ (P) \quad (3.44)$$

$$H_g = H_{sat} + H_{fg} = F_6 \ (P) \quad (3.45)$$

The above set of equations are used for two-phase flow and reduced to single-phase flow with one phase assumptions.

For the actual use in the core model, the assumption is made that the reflood phenomena is relatively slow except the early portion of reflood interval and that flow rate change is also slow. With these assumptions, final reduced form of flow equations used in the RELAP/REFLA code are;

(1) Homogeneous two-phase flow

$$\frac{\partial G}{\partial Z} = 0 \tag{3.46}$$

$$\frac{\partial x}{\partial Z} = \frac{1}{G}\left[\frac{\gamma\phi}{H_{fg}\cdot g} - \{(1-X)\rho_g + X\rho_\ell\}\frac{\partial\alpha}{\partial t}\right] \tag{3.47}$$

$$\frac{\partial P}{\partial z} = -\frac{1}{\rho_\ell}\frac{\partial(V'G^2)}{\partial Z} - g\rho_\ell\left(\frac{\alpha}{\beta} + 1 - \alpha\right) - \gamma\frac{\partial\tau}{\partial Z} \tag{3.48}$$

where

$$\beta = \frac{\rho_\ell}{\rho_g} \tag{3.49}$$

$$V' = \frac{\beta X^2}{\alpha} + \frac{(1-X)^2}{1-\alpha} \tag{3.50}$$

(2) Single-phase flow

$$\frac{\partial G}{\partial Z} = 0 \tag{3.51}$$

$$\frac{\partial H_{\ell \text{ or } g}}{\partial t} + \frac{\partial(uH)_{\ell \text{ or } g}}{\partial Z} = \frac{\gamma\cdot\phi}{g\cdot\rho_{\ell \text{ or } g}} \tag{3.52}$$

$$\frac{\partial P}{\partial Z} = -\frac{1}{\rho_{\ell \text{ or } g}}\frac{\partial G^2}{\partial Z} - g\rho_{\ell \text{ or } g} - \gamma\frac{\partial\tau}{\partial z} \tag{3.53}$$

Basic Thermo-hydrodynamic equations for coolant in the dispersed flow region.

For the dispersed flow regions, the equations including the thermal-nonequilibrium effects are used as follows:

Continuity for vapor and liquid phase

$$\frac{\partial(\alpha\cdot\rho_g)}{\partial t} + \frac{\partial(\alpha\rho_g u_g)}{\partial Z} = \dot{Q} \tag{3.54}$$

$$\frac{\partial\{(1-\alpha)\rho_\ell\}}{\partial t} + \frac{\partial\{(1-\alpha)\rho_\ell u_\ell\}}{\partial z} = -\dot{Q} \tag{3.55}$$

Momentum for vapor and liquid phase

$$\frac{\partial(\alpha\rho_g u_g)}{\partial t} + \frac{\partial(\alpha\rho_g u_g^2)}{\partial Z} + \alpha\frac{\partial\rho}{\partial Z} + \alpha\rho_g\, g$$

$$+ (\gamma\frac{\partial\tau}{\partial Z})_{WV} + (\gamma\frac{\partial\tau}{\partial Z})_{VD} = \dot{Q}\, u_1 \qquad (3.56)$$

$$\frac{\partial\{(1-\alpha)\rho_\ell u_\ell\}}{\partial t} + \frac{\partial\{(1-\alpha)\rho_\ell u_\ell^2\}}{\partial z} + (1-\alpha)\frac{\partial P}{\partial Z}$$

$$+ (1-\alpha)\rho_\ell g - (\gamma\frac{\partial\tau}{\partial Z})_{VD} = -\dot{Q}\, u_1 \qquad (3.57)$$

Energy for vapor and liquid phase

$$\frac{\partial(\alpha\rho_g g H_g)}{\partial t} + \frac{\partial(\alpha\rho_g g u_g H_g)}{\partial Z} = (\gamma\phi)_{WV} - (\gamma\phi)_{VD} + \dot{Q} g H_g \qquad (3.58)$$

$$\frac{\partial\{(1-\alpha)\rho_\ell g H_\ell\}}{\partial t} + \frac{\partial\{(1-\alpha)\rho_\ell g u_\ell H_\ell\}}{\partial Z} = (\gamma\phi)_{VD} + (\gamma\phi)_{WD} - \dot{Q} g H_g \qquad (3.59)$$

Assuming the temperature of liquid phase is saturation temperature and the vapor behaves as an ideal gas, the constitutive relations are:

$$H_\ell = H_{sat} \qquad (3.60)$$

$$H_g = H_{sat} + H_{fg} + C_{pg}(T_g - T_{sat}) \qquad (3.61)$$

$$\rho_g = F(H_g, P) = H_{sat} + H_{fg} + C_{pg}(T_g - T_{sat}) \qquad (3.62)$$

$$1-\alpha = n\, V_d/V_\ell \qquad (3.63)$$

where V_d is a volume of droplet and n is an number flux of droplet. Again assuming that the fluid transients are rather slow the approximation is made by dropping the time derivatives in the continuity and momentum equations. By also assuming $(1/\rho_g)\partial P/\partial z$ is negligible, the continuity and momentum equations are reduced to:

$$\frac{\partial(u_g\ \alpha)}{\partial z} = \frac{\dot{Q}}{\rho_g} - \frac{\alpha u_g}{\rho_g}\cdot\frac{\partial\rho_g}{\partial Z} \qquad (3.64)$$

$$\frac{\partial\{u_\ell(1-\alpha)\}}{\partial z} = -\frac{\dot{Q}}{\rho_\ell} \qquad (3.65)$$

$$\frac{\partial P}{\partial Z} + \rho_g u_g\frac{\partial u_g}{\partial Z} = \frac{\dot{Q}}{\alpha}\cdot(u_\ell - u_g) - \rho_g g$$

$$-\frac{1}{\alpha}\{(\gamma\frac{\partial\tau}{\partial z})_{WV} + (\gamma\frac{\partial\tau}{\partial z})_{VD}\} \qquad (3.66)$$

$$\frac{1}{2}\frac{\partial u_\ell^2}{\partial Z} = -g + \frac{1}{(1-\alpha)\rho_\ell}(\gamma\frac{\partial \tau}{\partial Z})_{VD} \quad . \tag{3.67}$$

The energy equations are written as:

$$\dot{Q} = \{(\gamma\phi)_{VD} + (\gamma\phi)_{WD}\} \,/\, \{H_{fg} + C_{pg}(T_g - T_{sat})\}g \ , \tag{3.68}$$

$$\frac{\partial H_g}{\partial t} + u_g\frac{\partial H_g}{\partial Z} = \frac{1}{\alpha\rho_g g}\{(\gamma\phi)_{WV} - (\gamma\phi)_{VD}\} \ . \tag{3.69}$$

The Transition Criteria from Transition Flow to Dispersed Flow

The transition from transition flow to dispersed flow is assumed to occur when the slip velocity between vapor flow and liquid flow exceeds to critical value determined from the force balance between vapor flow and droplet, and from the critical Weber number, W_{ec}. The force balance is described for the droplet in the vapor flow as follows:

$$C_D\frac{1}{2}\rho_g\,\Delta u^2\,\frac{\pi\,D_d^2}{4} = \frac{4}{3}\pi(\frac{D_d^2}{2})\rho_\ell\,g \quad . \tag{3.70}$$

In this equation C_D is the drag coefficient for the droplet and is determined by Ingebo's correlation[13]:

$$C_D = 27 \cdot Re_d^{-0.84} \ , \tag{3.71}$$

where Re_d is the Reynolds number for the droplet, i.e.,

$$Re_d = \frac{\Delta u\ D_d}{\nu} \quad . \tag{3.72}$$

The minimum value of C_D is set as

$$C_{D\,min} = 0.4 \quad . \tag{3.73}$$

The Weber number is defined as:

$$W_e = \frac{\rho_g\ \Delta u^2 D_d}{\sigma} \quad . \tag{3.74}$$

In the transition flow region, the slip velocity is not large enough to break a piece of water into small droplets, so at the transition point the Weber number reaches the critical Weber number, i.e.,

$$W_e = W_{ec} \quad .$$

When the droplets are generated, the relation between the droplet size and the slip velocity can be presented by the equation (3.74).

Arranging the equations (3.70), (3.71), (3.72), (3.73), and (3.74), we can obtain the following correlation of the slip velocity as the transition criteria.

$$\Delta u_{crit} = \min(\Delta u_2,\ \Delta u_3) \tag{3.75}$$

where

$$\Delta u_2 = 0.53713(\sigma W_{ec})^{0.3801}\ \rho_g^{-0.5868}\ \nu^{-0.1736}(\rho_\ell g)^{0.2066}$$

(when C_D is given by the Eq. (3.71))

$$\Delta u_3 = 1.3512\ \left(\frac{\rho_\ell g \sigma W_{ec}}{\rho_g^2}\right)^{0.25}$$

(when C_D is equal to 0.4, i.e., Eq. (3.73))

min(a,b) = minimum of the value a and b .

The number flux of the droplet (defined as the number of droplets which passes through unit area per unit time) can be written as follows with the mass balance of the liquid phase:

$$n = (1-\alpha)u_\ell \ / \ \left\{ \frac{4}{3}\ \pi\left(\frac{D_d}{2}\right)^3 \right\} \tag{3.76}$$

This number is necessary to consider the heat transfer between vapor and droplet, wall and droplet.

3.2 Loop Model

The primary loop of PWR consists of fluid volumes inside of pressure vessel, loop pipes, plenums and U-tubes of steam generators, primary coolant pumps and pressurizer. The primary system is divided into these components and is modeled by the concepts of RELAP4, i.e., fluid volumes (control volumes), flow paths (junctions), and heat conductors. The last is modeling the heat generating or conducting materials, such as fuel pins, vessel walls, pipe walls and heat exchanging narrow pipes in the steam generators.

The secondary side of steam generator is interacting with the primary loop system through the heat exchanging pipes, thus it can be said to strongly couple with primary loop system. Therefore the secondary side of steam generator is also included as a part of the primary loop model in the following representation.

Basic assumptions and modeling schemes are just the same model as that of RELAP4. In this section, thus we will mention only about the basic equations and some special features useful in the reflood calculation. More detailed informations about the models and options are available in original manual[1].

3.2.1 Nodalization

The RELAP/REFLA code assumes a general nordalization for the reactor vessel area of a plant model. This consists of single hydraulic volume for the core region, upper plenum, lower plenum, and downcomer. Also, single junctions connecting these volumes are assumed. The broken cold leg nozzle is represented by two junctions simulating the horizontally separated flow. The foregoing secial volumes and junctions must be entered on the code by the use of the Junction and Volume Number Data Card described in Section 4.3.

3.2.2 Fluid Equations

The numerical equations solved in the RELAP part are obtained by integrating the equations of change of mass, momentum and energy over a control volume. Integrated form of these equations are as follows:

First the mass conservation equation becomes

$$\frac{dM_i}{dt} = \sum_j W_{ij} \tag{3.77}$$

where

M_i = mass in volume V_i

W_{ij} = flow into volume V_i from junction j.

The fluid momentum equation for a flow path in Fig. 3.4 is written as:

$$I_j \frac{dW_j}{dt} = (P_K + P_{Kgj}) - (P_L + P_{Lgj}) - F_{fK} - F_{fL} - F_{fr} - \int_{K_o}^{L_i} dF - \int_{K}^{L} \frac{d(uW)}{A} \qquad (3.78)$$

where

$I_j = \frac{K}{2A_K} + \frac{L}{2A_L}$ or geometric inertia

W_j = mass flow at junction j

P_K, P_L = thermodynamic pressure at volume centers

P_{Kgj} = gravity pressure differential from the center of volume K to junction j

P_{Lgj} = gravity pressure differential from junction j to the center of volume L

F_{fK}, F_{fL} = Fanning friction pressure loss within each half-volume or

$= 4\ f\ (\frac{\ell}{2De})\ (\frac{\rho \bar{u} |\bar{u}|}{2})\ \Phi_{2p}$

F_{fr} = residual friction term defined by steady state conditions

$\int_{K_o}^{L_i} dF$ = expansion or contraction friction between volumes K and L

$\int_{K_o}^{L_i} \frac{d(uW)}{A}$ = momentum flux terms for area and density changes between volumes K and L

f = Fanning friction factor

ℓ = volume length

A = volume flow area

K, L = subscripts referring to volumes K and L

j = subscripts referring to junction j

Φ_{2p} = two-phase multiplier for increased friction

$\bar{u}$ = average fluid velocity in volume

The Fanning friction factor for turbulant flow is based on the Karman-Nikuradse[14),15)] equation:

$$\frac{1}{\sqrt{f}} = -0.4 + 4\ \log_{10}(Re\sqrt{f}) \qquad (3.79)$$

and for laminar flow is:

$$f = 16/Re \qquad (3.80)$$

Two-phase multiplier, Φ_{2p}, is optional correction factor calculated from the Baroczy[16)] correlation.

The energy equation for homogeneous flow is:

$$\frac{dU_i}{dt} = -\frac{\ell_i}{2A_i}\frac{d}{dt}\left(\frac{\bar{W}_i^2}{\rho_i}\right) + \sum_j W_{ij}\left(H_{ij} + \frac{u_{ij}^2}{2} + z_j - \bar{z}_i\right) + Q_i \qquad (3.81)$$

where

U_i = total fluid internal energy within volume V_i

$\bar{W}_i$ = average mass flow in volume V_i

H_{ij} = local enthalpy at junction j of the fluid entering or leaving volume V_i

u_{ij} = local fluid velocity at junction j of the fluid entering or leaving volume V_i

$z_j-\bar{z}_i$ = elevation change from the center of mass of volume V_i at $\bar{z}_i$ to junction j

Q_i = heat energy transfer rate into volume V_i.

3.2.3 Other Basic Models about the Loop System

Bubble Rise Model

Bubble rise model is a simplified slip model used in modeling certain vertical section in the reactor system. This model allows a concentration of bubbles to vary linearly in the vertical direction in a control volume. Coefficient of variation and the velocity of bubbles escaping from the mixture surface are determined by the input data. Using these parameters bubble rise model also allows a formation of steam dome above the two-phase mixture, i.e., the mixture level calculation becomes possible. User must be careful to use the bubble rise model applying to a series of vertically stacked volumes. In such case, so called a "layer-cake" phenomena may occur in which each volume has a steam and liquid, that is unrealistic situation.

This model is used both in blowdown calculation and in reflood calculation. The objective fluid volumes, however, are different between those calculations. In the reflood calculation, volumes to be applied the bubble rise model are at least, downcomer, core and core bypass region. Water head of these volumes are important factors to decide the driving force of water entering heated core.

The assumed bubble distribution in the mixture is

$$\rho_{gb} = a \frac{z}{z_m} + b \tag{3.82}$$

where

ρ_{gb} = partial steam density within a mixture (bubbles)
z = height above the bottom of the volume
z_m = time dependent height of mixture interface.

Parameters a and b are time dependent.
In the RELAP4 code, a and b are expressed by using a single parameter C_o (equals to input value directly) as follows:

$$a = 2C_o \frac{M_{gb}}{V_m} \tag{3.83}$$

$$b = (1-C_o) \frac{M_{gb}}{V_m} \tag{3.84}$$

for

$$0 < \frac{M_{gb}}{\rho_g V_m} \leq 0.5$$

and

$$a = 2C_o \left(\rho_g - \frac{M_{gb}}{V_m}\right) \tag{3.85}$$

$$b = (1+C_o) \frac{M_{gb}}{V_m} - C_o \rho_g \tag{3.86}$$

for

$$0.5 < \frac{M_{gb}}{\rho_g V_m} \leq 1.0$$

where

M_{gb} = mass of gas bubbles entrained in the mixture
ρ_g = vapor density = $(\rho_g)_{sat}$
V_m = volume of the mixture.

In the derivation of equations (7) - (10), a relation:

$$0 < \rho_{gb} \leq \rho_g \quad \text{(at any elevation)} \tag{3.87}$$

and the fact that integral of ρ_{gb} over the mixture equals to M_{gb}, were considered. Fig. 3.5 represents an example of bubble distribution schematically.

To keep track of the mixture interface level, we must know the change of mass of steam within the mixture. The mass balance is described as:

$$\dot{M}_{gb} = \dot{M}_s - \sum_j \psi_j x_j W_j - A\, u_{bub} (\rho_{gb})_{z_m} \qquad (3.88)$$

where

M_s = total mass of steam within the volume

Ψ_j = fraction of steam flowing at the junction j and terminating or originating within the steam dome

x_j = junction quality

W_j = mass flow at junction j

u_{bub} = bubble velocity relative to the mixture interface

$(\rho_{gb})_{z_m}$ = gas bubble density at the mixture interface.

Appropriate values of input parameters, C_o and V_{bub}, are depending on the problem and should be determined by comparing the calculational results with experiments. If, however, user desires the conservative evaluation of reflood rate, a very large value of V_{bub} should be supplied for downcomer volume. In such case, the vapor generated in the mixture escapes from interface almost instantaneously, thus a collapsed liquid level is calculated in the downcomer. That leads minimum driving head against the water which enters reflooding core.

Heat Transfer

Heat transfer model to be mentioned here is the model to be applied to the heat conductors except the fuel pins in the core. Special reflood heat transfer model of REFLA is applied to the core section heat conductors.

RELAP/REFLA has the same 'standard' heat transfer model as that of RELAP4-EM without the EM logic on the heat transfer mode selection. The assumed regimes are listed in Table 3.2.

Others

RELAP/REFLA reserves other calculational model in RELAP4-EM, such as, critical flow model, pump simulation model, check valve model, etc. Among of these, critical flow model is recommended not to use in the reflood analysis. Because adequate critical flow model for superheated vapor and stratified flow (both appeared at the breaks during reflood phase) are not built in yet.

3.2.4 Special Model for the Reflood Calculation

Steam Generator Model

During the reflood phase of a loss-of-coolant-accident, heat is transferred in the steam generator from the secondary to primary side. Such heat transfer occurs because the pressure and temperature of SG's secondary are kept close to the values in steady state operation under the isolation of systems. This heat addition to the primary coolant plays an important role because evaporates the droplets which are carried-over from the core, thus causes "steam binding" and limits the reflooding rate.

Each side of steam generator is modeled by one or more control volumes and heat conductor representing the U-tubes is between two sides. Water flow in the secondary side is assumed to be negligible during reflood phase. The secondary side heat transfer is therefore natural convection. RELAP/REFLA has the option for the natural convection at the secondary side surfaces of U-tube heat conductors which had been first built in RELAP4-FLOOD. Heat transfer coefficient is calculated by the equation given by Brown and Marco[24)] for long vertical cylinders as:

$$h = 0.13 \frac{k_\ell}{L} [Gr\ Pr]^{1/3} \tag{3.98}$$

where

k_ℓ = thermal conductivity of water (Btu/hr-ft-F)

L = typical length .

If the user desired to use this natural convection option, the optional Steam Generator Volume Data Cards (See Section 4.3) must be supplied.

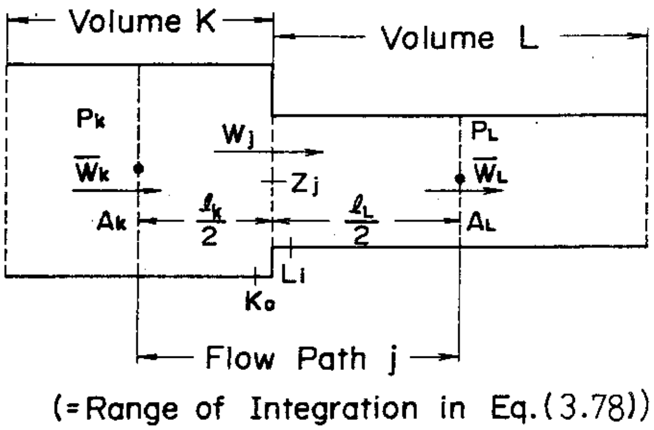


Fig.3.4 Flow-path Contorol Volume in RELAP4

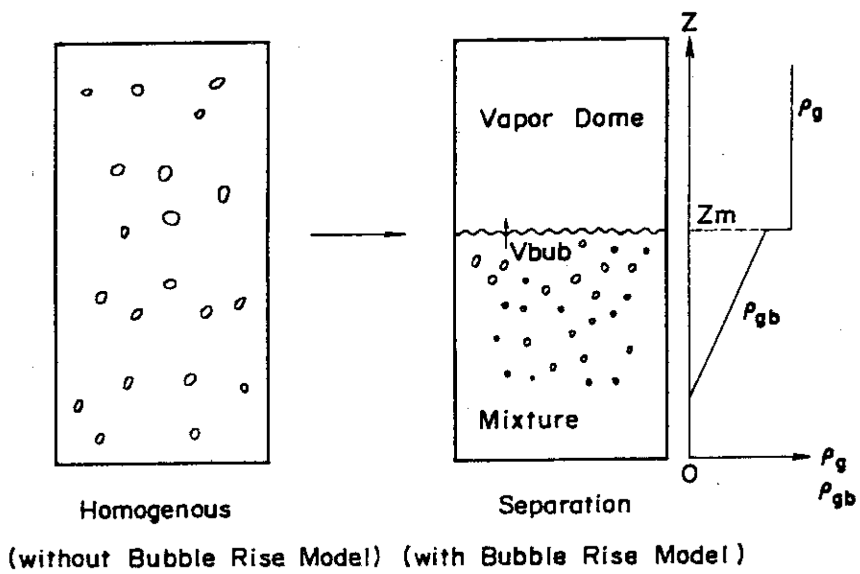


Fig.3.5 Application of the Bubble Rise Model and Distribution of Bubble Vapor Mass.

Table 3.2 Heat Transfer Correlations for General Heat Conductors in RELAP/REFLA

Model 1.*) Subcooled Liquid Forced Convection; Dittus-Boelter[17]

$$h = 0.023 \frac{k}{D_e} Pr^{0.4} Re^{0.8} \tag{3.89}$$

Model 2. Nucleate Boiling; Thom[18]

$$\phi = 2.712 \left[\frac{\Delta T_{sat} \exp\left(\frac{14.22P}{1260}\right)}{0.04}\right]^2 \tag{3.90}$$

Model 3. Forced Convection Vaporization: Schrock-Grossman[19]

$$h = (2.5)(0.023) \frac{k_\ell}{D_e}(Pr)_\ell^{0.4}[(Re)_\ell(1-x)]^{0.8}\left[\left(\frac{x}{1-x}\right)^{0.9}\left(\frac{\mu_g}{\mu_\ell}\right)^{0.1}\left(\frac{\rho_\ell}{\rho_g}\right)^{0.5}\right]^{0.75} \tag{3.91}$$

Model 4. Transition Boiling; McDonough, Milich and King[20]

$$\phi = \phi_{CHF} - (2.712*1.8)C(P)(T_W - T_{W,CHF}) \tag{3.92}$$

Pressure(psi)	C(P)
2000	979.2
1200	1180.8
800	1510.2

Model 5. Stable Film Boiling; Groeneveld[21]

$$h = 0.052 \frac{k_g}{D_e} (Pr)_W^{1.26}\left\{(Re)_g\left[x + \frac{\rho_g}{\rho_\ell}(1-x)\right]\right\}^{0.688}$$

$$\times \left[1.0 - 0.1(1-x)^{0.4}\left(\frac{\rho_\ell}{\rho_g} - 1\right)^{0.4}\right]^{-1.06} \tag{3.93}$$

Mode 6. Pool Film Boiling; Berenson[22]

$$\phi = 2.712\ F(P)\ (1.8\Delta T_{sat})^{0.75} \tag{3.94}$$

Pressure(psi)	F(P)
15	128
100	236
500	412
1000	510
1500	615
2000	705

Mode 7. Transition Pool Boiling

$$\phi = 2.712 * 20000\ \frac{\Delta T_{min}}{\Delta T_{sat}}\ \frac{1.504}{\ell n(\frac{\Delta T_{min}}{20})} \tag{3.95}$$

where; $\Delta T_{min} = [\frac{20000}{F(P)}]^{4/3}$

F(P) is defined in Mode 6.

Mode 8. Superheated Vapor Forced Convection; Dittus-Boelter[17]

$$h = 0.023\ \frac{k}{D_e}\ Pr^{0.4} Re^{0.8} \tag{3.96}$$

Mode 9. Low Pressure Flow Film Boiling; Dougall-Rohsenow[23]

$$h = 0.023\ \frac{k_g}{D_e}\ (Pr)_g^{0.4}\ \{(Re)_g[x = \frac{\rho_g}{\rho_\ell}\ (1-x)]\}^{0.8} \tag{3.97}$$

(*) Mode number is printed in the RELAP part of output.

If some volume numbers are specified as NSGVOL's in this card, the program distinguishes the heat conductors which have one of NSGVOL's as a volume number at its either surface. Then natural convection heat transfer is applied on the surfaces of those heat conductors. If the total number of NSGVOL's is zero (no optional cards entered), the standard RELAP4-EM correlations are used for the secondary side of heat conductors.

Broken Loop Cold Leg Nozzle Model

This model was developed to simulate the separated two-phse flow with slip expected in the broken cold leg nozzle, and first built-in to the RELAP4-FLOOD program. Part of the steam which is generated in the core during reflood passes through the intact loops to the downcomer and then flows around the top of downcomer and out the broken cold leg nozzle to the containment. In some cases, the downcomer water level will exceed the elevation of the cold leg nozzles and downcomer will overflow. The two-phase flow regime expected in such case is that of a horizontal separated flow with slip between the liquid and the vapor as shown in Fig. 3.6 Since RELAP4-EM had no provision for slip flow of this type, a special model was developed for RELAP4-FLOOD and it is reserved in RELAP/REFLA. The model is shown in Fig. 3.7. The broken loop cold leg is divided into two junctions, one for the liquid flow and another for the vapor flow. Each junction has a variable area and area of the liquid slip junction is equal to the liquid covered area in the true nozzle pipe (area of nozzle under the mixture level of downcomer). The steam slip junction area is, thus, the true junction flow area minus the liquid slip junction area. Since each junction has a common pressure drop to the containment or volume in downstream, each will flow at the velocity required to reach that pressure drop, thus simulating slip between phases. The friction at the liquid-vapor interface is neglected in this model. The elevation of the intact loop nozzle is artificially raised by one-half the nozzle diameter to prevent direct mixing of the steam with the water in the downcomer.

3.3 Coupling between Core and Loop Calculation

The RELAP/REFLA has a combined structure of the two parts, i.e. RELAP4-FLOOD and REFLA. The system calculation for the PWR primary loop is made by the RELAP4-FLOOD part with the core reflooding analysis by the REFLA part. The calculational model for the primary loop system (including the steam generator secondary side) is the same as one used in RELAP4, i.e., one-dimensional volume and junction model with the assumption of homogeneous equilibrium.

On the other hand, the thermal-hydraulic phenomena of core reflooding include the unequilibrium states with non-homogeneous flows. They are analysed by the model of REFLA.

The philosophy how to couple the core reflooding analysis in the REFLA program and the system calculation in the RELAP4-FLOOD program is described below in Section 3.3.1.

3.3.1 Basic Idea

Consider a model for the primary loop of PWR, where the system is expressed by control volumes and connecting junctions, especially with the core of a single volume. The change of junction mass flows during any time step (Δt) are calculated by solving the simultaneous equations for the time derivatives of mass flows ($\dot{W}$), of volume internal energies ($\dot{U}$) and of volume masses ($\dot{M}$), starting from the state of the system at the previous time step. Then all junction mass flows are updated and after that, the mass and the internal energy of each volume are updated by using the new values of junction flows. In these calculations the control volume for the core is included as a part of the primary loop. The behavior in the core, however, cannot be described by using the ordinary solution technique of RELAP4 because of its homogeneous equilibrium assumption.

When the junction flow of the core inlet junction (W_{in}) has been calculated (at the same time, the junction flow of the core outlet (W_{out}) has also been calculated as a part of the solutions of the simultaneous equations), REFLA part is called and REFLA calculates the core thermal-hydraulic behavior specially. In REFLA calculation, the core inlet flow, and the fluid temperature at the core inlet are used as the boundary conditions. These boundary conditions are transfered from the RELAP part to the REFLA one by the arguments.

After the REFLA calculation finished, various quantities about the core behavior are in turn sent back to the RELAP. Using the temperatures, the core average pressure, the linear heat generation rate of fuel,

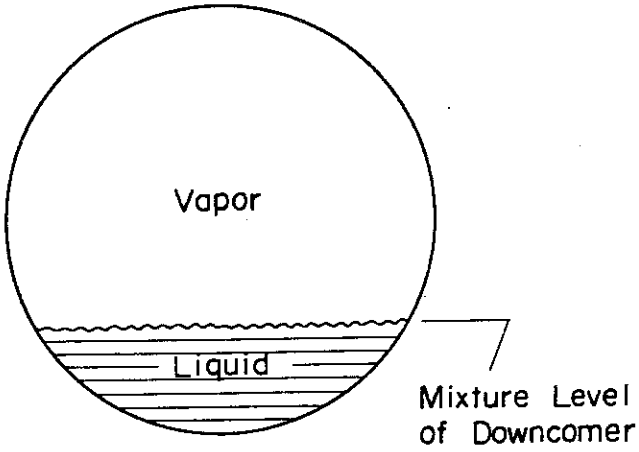


Fig.3.6 Flow Separation in Cold Leg Nozzle.

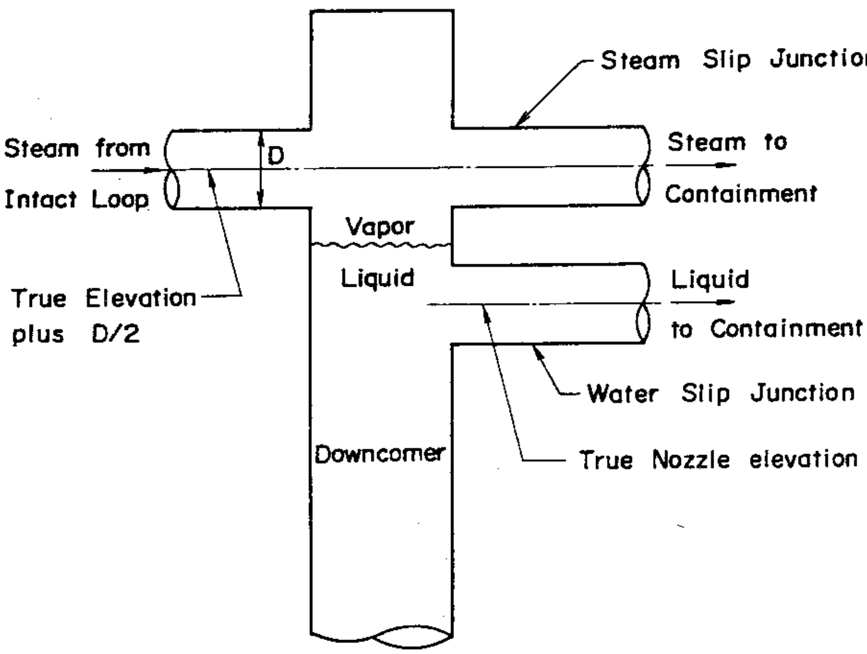


Fig.3.7 Nodalization for Cold Leg Nozzle Slip Flow Model
(Taken from Reference (1))

velocities and void fractions of liquid and steam at the core outlet, the total mass flow of the core outlet and the average core outlet enthalpy are calculated. In the RELAP4-FLOOD part, these values are used to replace the core outlet flow (W_{out}) and the core outlet enthalpy that have been once given by the loop calculation.

The processes described above are shown schematically in Fig. 3.8.

The core-contribution term in the pressure losses of the RELAP core inlet-, and outlet-junction data may be revised by the pressure losses between bottom to center, and center to top given by REFLA for the core section, respectively. This is an option in the present version of RELAP/REFLA(Mod 0). If this option is not used, the pressure loss terms of core inlet- and outlet-function data re prepared by the common way as for other junctions by using the core average flow condition.

In RELAP4-FLOOD, the average pressure of the core volume is specially set equal to the upper plenum pressure plus the pressure loss ΔP at the core outlet junction. This step is kept also in RELAP/REFLA. This core average pressure is used to determine the core inlet flow, W_{in}, in the next time step. Therefore, if the option is chosen, more realistic W_{in} value might be calculated in the next time step, although the REFLA-origin ΔP value may cause a numerical instability into the RELAP loop calculation thereafter.

REFLA also calculates the temperature changes of the rod in one point approximation along the radial direction. The temperature gradient inside the rod during the reflooding period is so small that this approximation causes no difficulty in almost all cases. The rod temperatures and the surface heat fluxes calculated by REFLA are also used in the RELAP4-FLOOD part for the surface conditions of the core section heat conductors after some averaging step. (The averaging step is needed the code.) The heat transfer coefficients are also set to be the values calculated by REFLA, but in this case not the averaged value but the representive point value (for the center elevation for each conductor).

After having reset these quantities associated with the core thermal-hydraulics, the RELAP4-FLOOD part calculates the energy and mass transfer, new conditions of state and advances the time step. This step of calculation is basically the same as of the original RELAP4-FLOOD, just with the revised values as mentioned above.

3.3.2 Program Flow Structure

The main control routine of RELAP/REFLA originated from the main routine of RELAP4-FLOOD. The combination scheme of the RELAP4-FLOOD part and REFLA part is shown in Fig. 3.9. The upper part of this figure shows the combination scheme for data input and initialization, while the lower part shows the combination structure for transient calculation.

At data input and initialization, the input routines of the RELAP4 first runs and the input data for the RELAP-FLOOD part are read in. In the midst of editing input data for the system calculation, the program calls the REFLA part through the subroutine INJUN. The center routine of the REFLA part, REFLA1, is called then, through further two interface subroutines, REFLAC and REFLAU. (The functions of these subroutines will be explained later.)

Then the code reads the input data for the REFLA part and the initialization of the core channel calculation is made.

After REFLA initialization, the program control returns to the RELAP4-FLOOD part and initialization continues for the system data, partly using the REFLA's data. These values are the pressure loss terms due to friction and gravity head in the core, heat transfer coefficients and surface heat fluxes at the rod surface. The substitution of these values are carried out in the following subroutines,

(Subroutine name)	(REFLA's result considered)
PREW	Pressure loss in core due to friction
HEADC	Pressure loss in core due to gravity head
SINITL	Heat transfer coefficient and surface heat flux of the rod

These subroutines call the entry points in the subroutine REFLAU and takes the appropriate physical quantities from the stored data in REFLAU and replaces the RELAP4-FLOOD data by them. Other functions of data editing, data check and initialization of RELAP4-FLOOD have not been changed.

In transient calculation, the RELAP4-FLOOD part governs the time step control. Therefore automatic time step control of RELAP4 is also available, although it has not been tried yet when we use the RELAP/REFLA. The REFLA part is called once in each time step in the subroutine FLDNIF, which was used in RELAP4-FLOOD to re-calculate W_{out} using the carryover rate correlation. The RELAP/REFLA uses the value calculated by REFLA for W_{out}. In addition, the program substitutes the REFLA results for the RELAP values in the following subroutines,

(Subroutine name)	(REFLA's result taken into consideration)
PREW	Pressure loss in core due to friction
SLABHT	Rod temperature, heat transfer coefficient and heat flux
HEADC	Pressure loss in core due to gravity head
FLDBAL	Core outlet enthalpy

These subroutines call the entry points in REFLAU and data replacements are carried out as the same manner as in initialization.

The interface subroutines REFLAC and REFLAU, which play a role to connect the RELAP4-FLOOD part and the REFLA part, have the functions as stated below.

REFLAC converts the common variables needed for the REFLA calculation into the local variables, and sends these variables to REFLAU.

REFLAU plays the most important role in the connection of the two parts. REFLAU convertes the unit of the these values sent from the RELAP4-FLOOD part, from British to MKS unit. At the same time REFLAU changes the double precision variables to the single precision one. And then REFLAU calls the REFLA1, the central program of REFLA part. The arguments of the subroutine REFLA1 are listed in Table 3.3.

The output values from the REFLA part are stored in REFLAU and used in the RELAP4-FLOOD part, by calling the entry points in REFLAU and making substitution, whenever these values become necessary in the RELAP4-FLOOD part. DATAS1 to DATAS8 in Fig. 3.9 are all of the entry points in REFLAU.

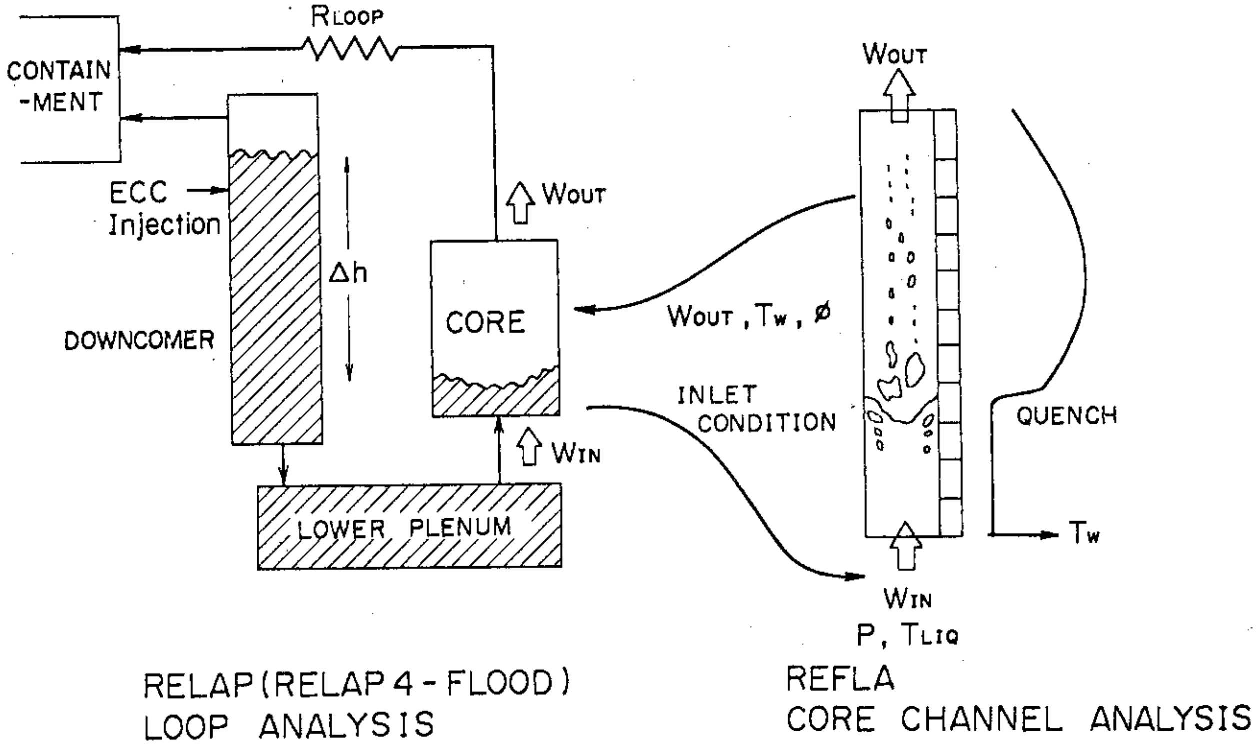


Fig.3.8 Schematic Representation of the Coupling between Two Programs.

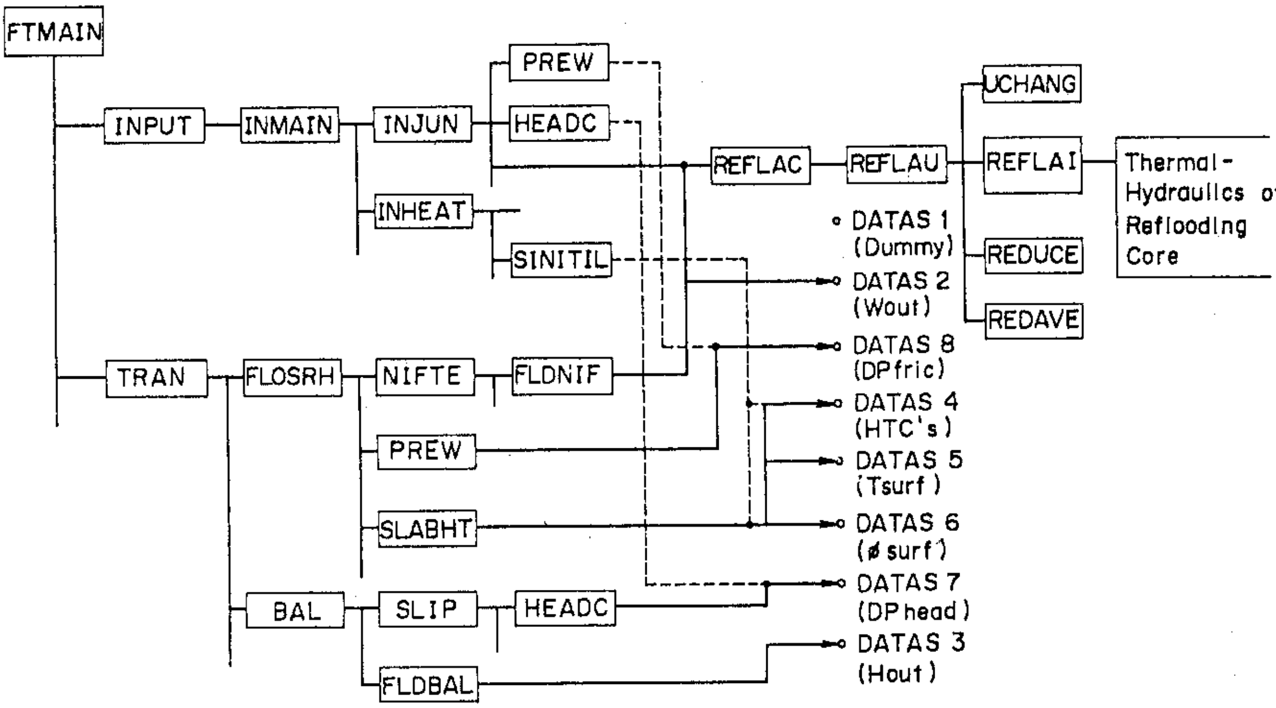


Fig.3.9 Program combination Scheme of RELAP/REFLA

Table 3.3 Argument List of subroutine REFLA1

argument	I/O*	description	unit	note**
TIMEDA	I	time after phenomena started	sec	dummy
TIMERF	I	reflooding time	sec	dummy
DTSDA	I	time step size	sec	
PIN	I	pressure at the core inlet	$(kg/m^2)a$	
POUT	I	pressure at the core outlet	$(kg/m^2)a$	
CMASS	0	stored mass in core	kg/m^2	dummy
QMAXDA	I	peak power generation rate	kW/m	
ULIN	I	velocity of core inlet flow	cm/sec	
TLIN	I	core inlet fluid temperature	C	
ULOUT	0	liquid velocity at the core outlet	cm/sec	
UGOUT	0	vapor velocity at the core outlet	cm/sec	
AGOUT	0	void fraction at the core outlet	—	
TLOUT	0	liquid temperature at the core outlet	C	
TGOUT	0	vapor temperature at the core outlet	C	
PDA	I	pressure at the center of core	$(kg/m^2)a$	
HTDA	0	heat transfer coefficients (array)	$kcal/m^2h \cdot C$	
AGDA	0	void fraction distribution (array)	—	dummy
TWDA	0	wall temperature distribution (array)	C	
PHIDA	0	surface heat flux (array)	$kcal/m^2h$	
DPHED	0	pressure loss due to gravity head (array)	(kg/m^2)	
DPFRC	0	pressure loss due to friction (array)	kg/m^2	
JEND	I	flag for the end trip	—	

* I ; input for REFLA1
  0 ; output of REFLA1

** Dummy arguments are not used in the present version but will be used in the future version.

4. Input and Output Description

4.1 Control Cards

The control cards necessary for input, output, tape setup, completion and execution of the RELAP-REFLA code will not be discussed here in detail. Here we only describe about general tape input and output needed in execution.

Input Tape

(1) Plot-Restart Tape: This tape contains information from a previous run that is to be restarted. Restart information is represented in Section 4.
(2) Boundary Condition Tape: The tape is a plot-restart tape from a previous run to be used for volume data retrieval (boundary conditions) as specified in the volume data card for this run (See the descriptions in reference (1)).
(3) Output tape: The output tape to be generated will be a plot-restart tape if requested by the tape control variable on the Problem Dimension Data Card in RELAP part.

4.2 Data Deck Organization

The input data cards deck for the RELAP/REFLA run is just a stack of two decks, each for RELAP part and for REFLA part.

The RELAP part of input deck is essentially the same as for the reflood code RELAP4-FLOOD. It starts with the title card and consists of comment cards, data cards, and a terminator card. It contains miscellaneous control data, volume data, junction data, heat conductor data and material property tables. The card format for these data is the same as for the original RELAP4-FLOOD[1)] with some requirements on the values of a few kind of data. These requirements are related to the RELAP/REFLA code coupling model and will be described in Section 4.3.

The REFLA part of input deck is necessary to be placed immediately after the terminator card (it contains only period or slash) of the RELAP part. This part consists of the core channel geometry data, material property data, axial power distirbution and initial temperature distribution data. The card format for this part is mentioned in Section 4.4.

Two part of input data are read by different input subroutines separately both early in the calculation. The specifications for the data fields in the cards are slightly different between two parts as mentioned in the following paragraphs. The user should take care about this point.

Two parts of data must be consistent so that they are read and used simultaneously by RELAP/REFLA. The data which must be consistent to each other are 1) geometrical data of the core channel and 2) initial temperature distribution of the rod surface. Speaking about the geometrical data, it is necessary to make the hydraulic diameter of the core volume and rod outer diameter (in RELAP part) equal to the REFLA core data. Initial cladding temperatures in RELAP4 part must be equal to the average values of the temperature data for REFLA part, because the maximum number of core section heat slabs is 12 in RELAP4-FLOOD and REFLA usually uses 90 axial meshes for the fuel rod.

On the modeling of the primary system (with secondary sides of steam generators) of a PWR, the following restrictions are imposed on the numbers of control volumes, junctions and heat conductors, i.e.,

number of volumes $\leqq$ 50
number of junctions $\leqq$ 70
number of heat conductors $\leqq$ 50

4.3 Data Card Summary (1) RELAP Part

The cards necessary are the same as the input cards for RELAP4-FLOOD, so that we will not present all of the data card information. Instead, the decription of the additional option cards (which are necessary only for RELAP4-FLOOD and not necessary for usual RELAP4 runs) are presented.

The general rules on the input data card format for the RELAP part is the same as of original RELAP, so that the copy from the WREM manual[1] is presented in the following: (The word "RELAP4-EM" is replaced by "the RELAP part" or "RELAP/REFLA" in the following explanations.)

The input for the RELAP part consists of a title card, comment cares (optional), data cards, and a terminator card. A listing of the cards is printed at the beginning of each RELAP/REFLA problem. The order of the title, data, and comment cards is unimportant except that the last title card or the last data card with a duplicate card number will be used.

When a card format error is detected, a line containing a dollar sign ($) located under the character causing the error, and a comment giving the card column of the error is printed. An error flag is set such that input processing continues, but the RELAP4 problem is aborted at the end of input processing. Usually another error comment is produced during input processing when the program attempts to process the erroneous data.

Title Card

A title card must be entered for each RELAP/REFLA problem. A title card is identified by an equal sign (=) as the first nonblank character. The title (the remainder of the title card) is printed as the second line of every page. The title card is normally placed first in the problem.

Comment Cards

An asterisk (*) or a dollar sign ($) appearing as the first nonblank character identifies the card as a comment card. Any information may be entered on the remainder of the card. Blank cards are treated as comment cards. The only processing of comment cards is printing of contents. Comment cards may be placed anywhere in the input deck.

Data Cards

The data cards contain a varying number of fields which may be integer, floating point, or a alphanumeric. Blanks preceding and following fields are ignored.

The first field on a data card is a card number which must be an unsigned integer. If the first field has an error or is not an integer, an error flag is set. Consequently, data on the card are not used and the card will be identified by the card number in the list of unused data cards. After each card number and the accompanying data are read, the card number is compared to previously entered card numbers. If a matching card number is found, the data entered on the previous card is replaced by the data on the current card. If the card being processed contains only a card number, the card number and the data entered on the previous card are deleted. If a card causes replacement or deletion of data, a statement is printed indicating that the card is a replacement card.

Comment information may follow the data fields on any data card by preceding the comment with an asterisk or dollar sign.

A number field is started by either a digit (0 through 9), a sign (+ or -), or a decimal point (.). A comma or a blank (with one exception subsequently noted) terminates the number field. The number field has a number part, and optionally, an exponent part. A number field without a decimal point or an exponent is an integer field; a number field with either a decimal point, an exponent, or both is a floating-point field. A floating-point field without a decimal point is assumed to have a decimal point immediately in front of the first digit. The exponent denotes the power of ten to be applied to the number part of the field. The exponent part has an E or D, and a sign (+ or -) followed by a number giving the power of ten. These rules for floating-point numbers are identical to those for entering data in FORTRAN E or F format fields except that no blanks (one exception) are allowed between characters. Floating point data punched by FORTRAN programs can be read. To permit reading of floating-point data, a blank following an E or D denoting an exponent is treated as a plus sign. Acceptable ways of entering floating-point numbers are illustrated by the following six fields all containing the quantity 12.45:

12.45, +12.45   1245+2 1.245+1, 1.245E1 1.245E+1

A field starting with a letter is an alphanumeric field. The field is terminated by a comma, a blank, or the end of the card. All characters except commas and blanks are allowed.

Terminator Card

The input data for the RELAP part is terminated by a period card or slash card. Comments may follow the slash or period on the terminator card. Strictly speaking, RELAP4-FLOOD is one of the optional programs of RELAP4-EM. It is necessary to choose correctly the 'Program Option Flag' in 'Problem Dimension Card', then the optional cards for the execution of RELAP4-FLOOD become necessary as additional input data to the ordinary RELAP4 input. The input of RELAP/REFLA are the same as of RELAP4-FLOOD except there are some requirement on the values of data. In the following description of the data cards, only the additional requirements on the usual RELAP4 input data are given. User should also refer to the original manual of RELAP4-EM (WREM manual).

In the following description of the data cards, the card number is given along with a descriptive title of the data contained on the card. The order of the data (W1, W2, ------), the format (I or R), the variable name, and the input data requirements are given as exactly same way as in RELAP4.

(1) Problem Dimension Data Card 010001

W1 to W15, and W17: abbreviated (See reference 1))

W16-I NCOR = number of core section heat conductors
= 10 should be chosen.

W18-I ISPROG = Program option flag
= 2 should be chosen.

(2) Entrainment Correlation Option Card 400001

W1-I IENT = Entrainment correlation
= 1 should be chosen.

(3) FLECHT Heat Transfer Correlation Data Card 400002

W1-R DTSUB = Inlet subcooling temperature (F)

W2-R TINIT = Dummy

W3-R QMAXED = maximum linear power (kW/ft)

W4-R BFFF = Dummy

W5-R HRAD = Dummy

H6-R CORCHL = Core channel length (ft)

(4) Initial Clad Surface Temperature Data Cards 4001YY

YY ($1 \le YY \le 10$) indicates the card sequence number

W1-R TS(1) = Surface temperature of the 1st core heat conductor (F)

W2-R TS(2) = Surface temperature of the 2nd core heat conductor (F)

.
.
.
.

W10-R TS(10) = Surface temperature of the 10th core heat conductor (F)

(5) Steam Generator Volume Data Cards 4002YY

This card is optional. The user may model his own steam generator if he does not choose to use the RELAP4-FLOOD steam generator heat transfer model. YY, ($1 \leq YY \leq 12$) indicates the card sequence number.

W1-I NSGVOL(1) = Steam generator secondary volume number for each steam generator primary volume number. A secondary volume number must be entered for each primary volume, even if this volume is common to several primary volumes.

W2-I NSGVOL(2) = Volume number. As same as above.

.
.
.
.

Wn-I NSGVOL(n) = Volume number, where $n \leq 12$

(6) Core Outlet Enthalpy Data Card 400004

This card is optional and not recommended. If not specified, code calculates the outlet enthalpy. By this card user can specify the constant outlet enthalpy so that it may be convenient in a kind of sensitivity study.

W1-R HCOUT = Core outlet enthalpy (Btu/ℓbm)

(7) Junction and Volume Numbers Data Card 400005

W1-I JUNIN = Core inlet junction number
W2-I JUNOUT = Core outlet junction number
W3-I JUNSWL = Water slip junction number
W4-I JUNSSL = Steam slip junction number
W5-I NCVOL = Core volume number
W6-I NUPVOL = Upper plenum volume number
W7-I NLPVOL = Lower plenum volume number
W8-I NDCVOL = Downcomer volume number

4.4 Data Card Summary (II) REFLA part

As mentioned previously, the input for the REFLA portion should be placed immediately after the terminator card of the input data for the RELAP part. The rules to fill up the number fields on cards is somewhat different from the rules for the RELAP part. At first, each card has no card number, thus the order of input cards is important in contrast with the RELAP case. Other rules about the number field are almost parallel with the RELAP case. Exceptions are,

(1) A floating-point field without a decimal point is assumed to have a decimal point immediately after the last digit (non in front of first digit) in number part.
(2) When a floating-point field has an exponent part, only character E is allowed (D is not allowed) followed by a number of 2 ranks giving the power of ten. Accordingly, the expressions like 1245+2, 1.245+1 and 1.245E1 in Section 4.3 are not allowed.
(3) Comment information may follow the data fields on any data card by initiating the comment with an astrisk (*) (($) is not usable).

In the following description of the data cards, the order of the data (W1, W2, ------), the format (I or R), the variable name, and the input data requirements are given.

1. Core Channel Data

W1-I	N	= Number of axial mesh (fixed to 90)
W2-I	IFBMOD	———
W3-R	DIA	= Diameter of rod (1∿100 mm or 0.001∿0.1 m)
W4-R	PITCH	= Pitch of rod array (1∿100 mm or 0.001∿0.1m) IF PITCH < 0.001, flow channel is inside of cylindrical tube and equivalent diameter = DIA
W5-R	CLENG	= Length of channel (10∿5000 mm or 0.01∿5 m)

2. Control Data

W1-R	WEC	= Critical Weber Number
W2-R	WEC1	———
W3-R	DTS	= Time step size (=1st time step size of RELAP)(sec)
W4-I	MINOR	= Number of time steps per REFLA's minor edit
W5-R	VOL	———
W6-R	SW3	———
W7-I	MAJOR	= Number of minor edits per REFLA's major edit

3. Fuel Data

W1-I	N5	———
W2-R	RC	———
W3-R	CKF	= Thermal conductivity of fuel rod (kcal/mhrK)
W4-R	DF	= Averaged density of fuel rod (kg/m^3)
W5-R	CF	= Heat Capacity of fuel rod (kcal/kg·K)

Comment:

CKF is not used in present version.

DF and CF should be equal to rod averaged values.

4. Axial Power Profile Data

W1-I IAXMOD = Index of axial power distribution
= 1: Chopped consine type with parameters CNHEAT and CSAVE (See Fig. 4.1)
= 2: PWR-FLECHT type (Step wise shape)
= 3: JAERI-Reflood experiment type
= 4: Power distribution for the nuclear ship "MUTSU" reactor
= 5: Chopped cosine type for typical PWR (to be revised)
= 6: LOFT power distribution
= 7, 8, 9, 10: Flat type (also reserved for future use)

W2-R CNHEAT = No heated length of rod from each end (m)
If IAXMOD ≠ 1, CNHEAT = 0.0

W3-R CSAVE = Core saving (m)
If IAXMOD ≠ 1, CSAVE = 0.0

5. Sequence Control Data 1

W1-R	TIME1	———
W2-R	TEMP1	———
W3-R	QMAX1	= Initial peak linear power (kW/m)
W4-R	ULINI	———
W5-R	PSYS1	= Initial core pressure (kg/cm^2·abs)
W6-R	TLINI	= Inlet Subcooling < 0.0 (K)

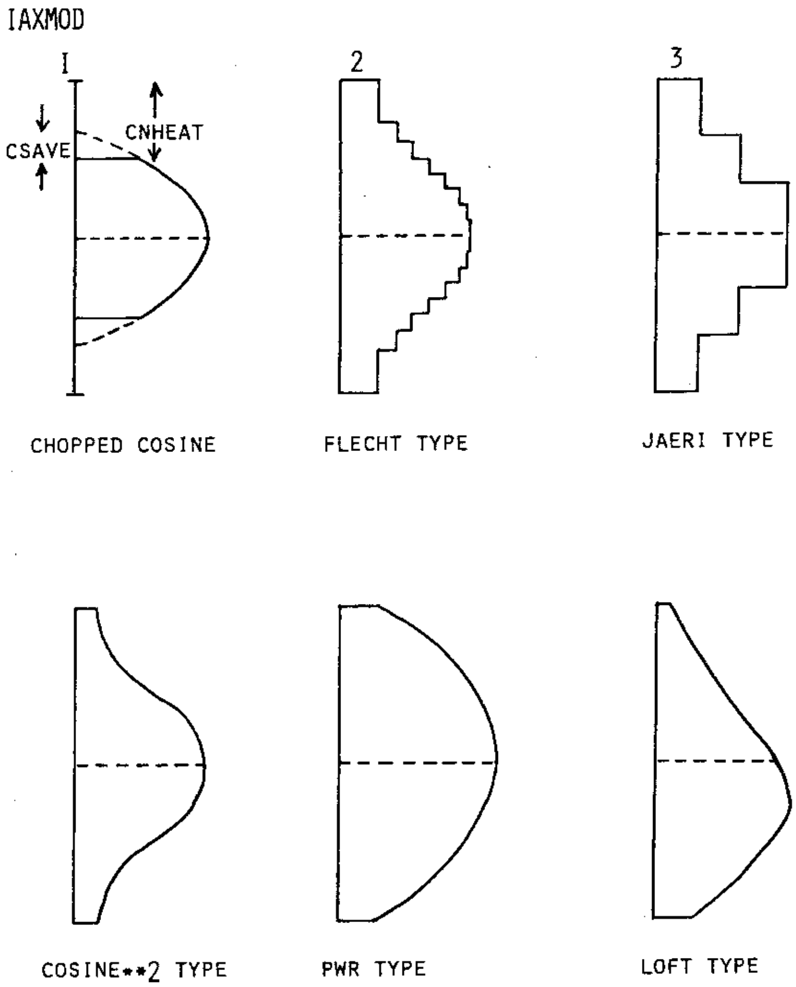


Fig. 4.1 Axial Power Distribution

6. Sequence Control Data 2

W1-R	TIME2	———
W2-R	TEMP2	= Lower limit of rod temperature to initiate reflood (C)
W3-R	QMAX2	———
W4-R	ULIN2	———
W5-R	PSYS2	———
W6-R	TLIN2	———

7. Sequence Control Data 3

W1-R	TIME3	———
W2-R	TEMP3	———
W3-R	QMAX3	———
W4-R	ULLN3	———
W5-R	PSYS3	———
W6-R	TLIN3	———

8. Sequence Control Data 4

W1-R	TIME4	———
W2-R	TEMP4	———
W3-R	QMAX4	———
W4-R	ULIN4	———
W5-R	PSYS4	———
W6-R	TLIN4	———

9. Sequence Control Data 5

W1-R	TIME5	= Maximum Computing time for REFLA (sec) (Use sufficient large value)
W2-R	TEMP5	———
W3-R	QMAX5	———
W4-R	ULIN5	———
W5-R	PSYS5	———
W6-R	TLIN5	———

10. Initial Temperature Distribution Data

W1-R	TW(1)	= Initial rod surface temperature for each mesh
:	:	elevation. Indices corresponds from bottom to
W(N+1)-R	TW(N+1)	top of the core consecutively.

11. Option Control Data

W1-I	NMAT	= Number of material tables (=2 × No. of material) If NMAT = 0, following cards are neglected and CKF, DF and CF on card No.3 are used as temperature independent material properties.
W2-I	JTDPND	= Index for the use of temperature dependent material properties. = 1. Use = 0. Not use If NMAT = 0, JTDPND must be 0
W3-I	JTOPQN	= Index for the use of top rewetting model = 1. Consider top rewet = 0. Not consider

12. Material Property Data A

W1-I	NP_i	= Number of points in table with $0 < NP_i \leqq 20$

13. Material Property Data B (Table)

W1-R	TBKT(i,1)	= Temperature (C)
W2-R	TBKC(i,1)	i= odd; Thermal Conductivity (kca/mhrK) 1= even; Volumetric Heat Capacity (kcal/m^3K)
W3-R	TBKT(i,2)	
W4-R	TBKC(i,2)	NP_i pairs must be input. Sample points must be arranged in ascending order of temperature.
:		
W($2NP_i$-1)-R	TBKT(i,NPi)	
W($2NP_i$)-R	TBKC(i,NPi)	

NMAT pairs of card 12 and 13 are necessary.

The i-th pair of cards describes:

thermal conductivity of fuel rod if i = Odd.

volumetric heat capacity of fuel rod if i = even.

If there is no card hereafter, input for the REFLA part is finished. Cards hereafter are used only when thermal conduction effect in the rod is considered in contrast with the original one-point approximation model of REFLA.

14. Heat Conductor Geometry Data

W1-I	NR	= Number of regions with $0 < NR \leq 5$
W2-R	RO	= Inner radius of conductor when ITYPE = 1 (mm)
W3-I	ITYPE	= Geometry type, 0 - Rectangular, 1 = Cylindrical

15. Heat Conductor Noding Data

W1-I	ND_i	= Number of nodes for region i
W2-R	XR_i	= Region width of region i (mm)
W3-I	$IKRG_i$	= Indicator on the thermal conductivity for region i
W4-I	$ICRG_i$	= Indicator on the heat capacity for region i
W5-R	QV_i	= Heat Generation Rate for region i (Kcal/m^3sec)

16. Initial Boundary Condition Data

W1-I	IL	= Left boundary condition indicator = 0; adiabatic = 1; temperature constant = 2; heat transfer boundary of kind 1 = 3; heat transfer boundary of kind 2
W2-R	HL	= Heat transfer coefficient for left surface (kcal/m^2·hr·K) when IL = 2. In other cases = 0.0
W3-R	TL	= Specified temperature (IL = 1) or bulk coolant temperature at left surface. (IL = 2). (C)
W4-I	IR	= Right boundary condition indicator. (same with IL)
W5-I	HR	= Heat transfer coefficient for right surface (kcal/m^2·hr·K)
W6-R	TR	= Specified temperature (IR = 1) or bulk coolant temperature at right surface (IR = 2). (C)

17. Supplementary Condition Data

W1-R TPI = Initial temperature of left surface (C)
(to be revised to have array)

W2-R EPS = Conversion criteria for temperature calculation (C).
defaut value = 0.1 C

18. Boundary Conditions on Transient Calculation

W1-I IL = Left boundary condition indicator

W2-I IR = Right boundary condition indicator

4.5 Input for Tape Editing

The code has an capability to re-edit the plot information stored in the plot-restart tape. This ability, however, comes from original RELAP4 program so that it can be adopted only for the RELAP part of data.

An old plot tape must be mounted on FORTRAN Unit 3. The normal RELAP/REFLA program is used with the following input definitions.

(1) Title Card

The first 12 columns of the last title must be identical to the first 12 columns of the title card of the problem which is to be edited.

(2) Problem Dimensions Data Card 010001

W1-I LDMP = -3

W2-I NEDI = Number of minor edit(*) variables where
$0 \le NEDI \le 9$

W3-I NTC = Edit frequency control card count where
$1 \le NTC \le 20$

W4-I NTRP = 0

These are the only control integers required for a tape edit.

(*) Minor edit is one of the edited form in the output of calculation. (See Sec. 4.7)

(3) Edit Variable Data Card 020000

One card is required if NEDI (on Card 010001) > 0, and this card specifies the variables to be printed in the minor edits. NEDI specification must be entered. Each specification consists of an alphanumeric entry and an integer entry as follows:

W1-A   Symbol variable
W2-I   Region (volume, junction or heat conductor) number

All symbol variables are listed in Section 3.9 of reference 1).

(4) Edit Frequency Control Data Cards 03XXX0
The number of cards totaling NTC (on Card 010001) must be entered with XXX = 001, 002, -----, NTC.

W1-I   NMIN = Number of plot records per minor edit
W2-I   NMAJ = Number of minor edits per major edit
W3-R   DELTM= Time step size (sec) between plot records, if known (0 < DELTM).
W4-R   TLAST= End of current edit frequency control data ($TLAST_{i-1} < TLAST_i$)

4.6 Input for Restarting

An old restart data tape to be used must be mounted on FORTRAN Unit 3 and a blank tape (to store new record) must be mounted on Unit 4. The RELAP4 program is used with the following input definitions.

(1) Title Card
The first 12 columns of the last title must be identical to the first 12 columns of the title card of the problem which is to be restarted.

(2) Problem Dimension Data Card 010001

W1-I   LDMP = N, the restart number of the old problem where restart is to begin where 1 ≤ LDMP ≤ 999.
W2-I   NEDI = Number of minor edit variables where 0 ≤ NEDI ≤ 9.
W3-I   NTC = Time step card count where 1 ≤ NTC ≤ 20.
W4-I   NTRP = Number of trip control cards where 0 ≤ NTRP ≤ 20. NTRP = 0 will cause the trip control values from the restart tape to be used. (See Section 3.9 of ref. 1))

(3) Edit Variable Data Card 020000

One card is required if NEDI (on Card 010001) 0, and the same rules apply as for the case of tape editing.

(4) Time Step Data Cards 03XXX0

The number of cards totaling NTC (on Card 010001) must be entered with XXX = 001, 002, -----, NTC.

W1-I NMIN = Number of time steps per minor edit (also per plot tape edit). 0 is interpreted as 1.

W2-I NMAJ = Number of minor edits per major edit. 0 is interpreted as 50.

W3-I NDMP = Number of major edits per restart dump. 0 is interpreted as 20.

W4-I NCHK = 1. Option for time step control should be one with no time step control.

W5-R DELTM = Maximum time step size (sec) (0 < DELTM).

W6-R DTMIM = 0.0

W7-R TLAST = End of current time step data (sec).

(5) Trip Control Data Cards 04XXX0

NTRP (on Card 010001) cards must be entered with XXX = 001, 002, -----, NTRP.

W1-I IDTRP = Action to be taken (1 ≤ IDTRP ≤ 20)

W2-I IDSIG = Signal being compared (1 ≤ IDSIG ≤ 10)

W3-I IX1 = Volume or junction index

W4-I IX2 = Optional volume

W5-R SETPT = Signal setpoint

W6-R DELAY = Delay time for initiation of action after reaching setpoint (sec).

(6) Terminator Card '.' (Period) or '/' (Slush)

(7) REFLA Editing Control Card (without card No.)

W1-I MINOR = Number of time steps per REFLA's minor edit. If set to be 0, the value of original run is used.

W2-I MAJOR = Number of minor edit per REFLA's major edit. If set to be 0, the value of original run is used.

4.7 Output Format

The RELAP/REFLA code gives two kinds of output, i.e., ordinary printed output and the combination plot-restart file. The latter is optionally selected by users.

As the printed output, the format is almost the same as the original RELAP4-FLOOD's or RELAP4's format, followed by additional output given by REFLA. Thus, the code provides major edits and minor edit of both RELAP part and REFLA part. The frequency of these edits is specified in the input data [Section 4.3 and 4.4].

Both major edit follow a fixed format. In the RELAP's major edit, variables necessary to describe the state of the system are listed for each volume, heat conductors and junctions. In the REFLA's major edit, the axial distributions in the core channel are listed about the thermodynamic and hydrodynamic quantities, for example, void fraction, heat transfer coefficient, heat flux, velocity of fluid, wall temperature and fluid temperature.

In the RELAP's minor edit, the variables to be edited are chosen by user, for frequent printout, up to nine variables from a large number of calculated variables. All of the variables available for minor edit are stored on the plot-restart tape (or disk) for plotting purposes and for generating additional sets of printed output (tape re-editing, see Section 4.5).

On the other hand, the REFLA's minor edit follows fixed format in contrast with RELAP's minor edit, but it also provides frequent printout of h.t.c, wall temperature, location of flow boundaries and so on.

5. Sample Problems

Among the code applications, we here mention about two types of problems.

First one is the reflood problem on the large scale PWR with 4 primary coolant loops. Input data of this problem are based on one of the check-out problems attached to the RELAP4/MOd5 code package which was sent to JAERI from the OECD-NEA Computer Code Library. We studied many cases with varying parameters such as pressure, initial clad temperatures and ECC flow rate. Some of them could not run due to error caused in REFLA portion. However in succeeded cases, calculated results show rather stable trends with small variation of the value of parameters, thus we present here two cases with different pressures and different ECC injection rates. Comparisons are also made with the results by RELAP4-FLOOD.

The second type of sample problem is the simulations of the reflood experiments in FLECHT-SET B-series test program[25]. Two cases are selected among them, which are RUN 2714B and 3105B, each is typical expeirment with pressure 20 spia and 59 psia, respectively. Comparisons between calculated results and experimental data are represented, so that the capability of the code can be seen with some limits.

In the presentation about these sample problems, we should ask to allow for using the figures which are plotted in the British units. This comes from mainly the limitation on the plotting program and also from the convenience on the comparisons between calculated result of RELAP/REFLA and of RELAP4-FLOOD and between calculated results and reported experimental data.

The critical Weber number is fixed to 1.0 through the calculations because it is recommended value by another analysis[4].

5.1 Examples of 4-Loop PWR

Here we discuss the reflood problem of a large scale PWR plant under a postulated loss of coolant accident which caused by the double ended guillotine break of the cold leg piping. The PWR system has 4 primary recirculating loops and reactor core with 12 feet high. The thermal power is 3479.2 MW and primary system pressure is 2250 psia in the steady state. The primary system conditions, however, has drastically changed during the blowdown period. At the beginning of the reflood period (which is often called as 'BOCREC', it means 'Bottom of Core Recovery'), pressure has decreased to 20 or 60 psia and reactor power has become about 5 % of the steady state value. Thus we assumed the initial conditions (at the initiation of reflood, not means the steady state values) as follows:

Reactor Power	185.8 MW (5.3% of steady state)
Primary system pressure	20 psia (Case 1) 52 psia (Case 2)
Peak linear power	0.586 kW/ft
Fuel clad temperature	1120 F
Inlet subcooling	75 F
ECC injection rate	420 lb/s (Case 1) 5400 lb/s for 2.2 sec, 420 lb/s onward (Case 2)
Decay heat	Approximate the value of 1.2×ANS after 40 sec.

Primary system and secondary side of steam generator were modeled by using 26 control volumes, 30 junctions and 14 heat conductors as shown in Fig. 5.1. Lower plenum and the lower portion of downcomer below core buttom level were filled with water. Bubble rise model was applied to downcomer, core bypass and core with large bubble velocity (complete separation is assumed). Fill junction which represented ECC injection system was located in the bottom of downcomer instead of cold leg where the ECC injection lines were attached in the real plant. The reason to do this was, if water was injected to cold leg of modeled system, water would begin to enter the core through the lower plenum after it filled cold leg and downcomer. In other words, present model (which is in the status of RELAP4/Mod3) cannot simulate the penetration of ECC water through the downcomer annulus, so that we have made the assumptions mentioned above. In addition, temperature of injected water was set to be close to saturation temperature to prevent the water packing problem.

Secondary side of steam generator was modeled by 2 volumes. Lower volume represented the water or water-steam mixture and another corresponded to the steam done. Consequently the boundary of two volumes were equal to the nominal water level in the secondary side. Primary coolant pumps were assumed to be locked. Their behaviors were simulated by setting the revolution speed to very low value. The containment pressure was kept constant through the reflood period. This pressure is refered to as "system pressure" in the explanation about the calculated results.

5.1.1 Case 1: 20 psia, without Accumulator Flow

In this case, the containment pressure was kept 20 psia throughout the calculation and the injection of water due to accumulator was neglected. The expected phenomena during reflood, therefore, were rather smooth and quasi-steady type. Results of calculation are shown in Figs. 5.2 through 5.9. Calculational results of RELAP4-FLOOD are also plotted in figures.

Mass flow rates at core inlet and outlet are shown in Fig. 5.2 and 5.3, respectively. It was seen that flow rate calculated by RELAP/REFLA showed more oscillating behavior than the result of RELAP4-FLOOD after 30 seconds in reflood. In RELAP4-FLOOD, the carryover rate fraction (CRF) defined as:

$$CRF = W_{out}/W_{in} ,$$

where W_{out}: Mass flow rate at core outlet,
W_{in} : Mass flow rate at core inlet,

was calculated by using a correlation and then the core outlet flow was decided by multiplying the value of CRF to core inlet flow. Therefore, core inlet and outlet flow were varying in in-phase and the feedback effect from the loop resistance acted negatively, then the flow behavior becomes rather smooth one. On the contrary, changes of flow rates at core inlet and outlet were not always in-phase in the RELAP/REFLA calculation, so oscillatory flow may occur more easily than in RELAP4-FLOOD. The overall behavior of the core inlet flow are very similar between the result of RELAP/FEFLA and the one of RELAP4-FLOOD.

Fig. 5.4 shows core outlet enthalpy which is averaged value for the vapor-water (droplet) mixture flow. Both results showed that in the first 40 seconds, outlet flow was in superheated state and after that time outlet enthalpy decreased because water fraction increased (more droplets were contained). The core outlet enthalpy calculated by RELAP/REFLA was lower than that of RELAP4-FLOOD for almost all interval in reflood.

Water inventory of core volume, shown in Fig. 5.5, were very close between two calculations in the first 30 seconds but some difference appeared thereafter. This difference was caused by the fact that carryover rate fraction by RELAP/REFLA become slightly greater than that of RELAP4-FLOOD for the interval of 40 through 80 seconds.

Fig. 5.6 compares water inventories in downcomer calculated by two codes. Water inventory and level increased slowly because ECC flow injected by accumulator was not considered in this case. It must be noted that in the typical reflood analysis of commertial PWR, downcomer water level does overflow immediately after the initiation of reflood due to large quantity of water from accumulator.

Fig. 5.7 shows the surface temperatures of fuel rod for the lower half of the core calculated by RELAP/REFLA. The upper half of the core was not quenched up to 200 seconds in reflood. After maximum clad temperature had been reached temperature for each elevation decreased along concave line and this interval corresponded to the film boiling heat transfer (transition flow regime). This type of shape for the rod temperature history is typical in the calculation by RELAP/REFLA.

Fig. 5.8 compares the surface temperatures calculated by two codes, RELAP/REFLA and RELAP4-FLOOD for 6-foot (center of core) and 7-foot (maximum temperature occurred) elevations. In the result by RELAP4-FLOOD, 6-foot elevation did not quench up to 200 seconds in reflood.

The different quench time is mainly due to different quench criteria. Quench level was not defined in RELAP4-FLOOD and a heat conductor in the core was regarded to begin to quench when surface heat transfer coefficient evaluated from the FLECHT-HTC correlation exceeded 50 Btu/ft^{2}hr°F. In this case, surface heat transfer coefficent of RELAP4-FLOOD for the heat conductor located in 6- to 7.2-foot elevation was increasing very slowly and was rather small as shown in Fig. 5.9. This was mainly due to low reflooding rate and low system pressure, and small HTC led the later quench time. As shown in Fig. 5.5 water inventory in the core did not so differ between two calculations. Thus the precursory cooling which is considered in RELAP/REFLA but not in RELAP4-FLOOD, affected to the temperature responses. This aspect of different cooling assumption also reflects in the rod temperatures after it reached maximum value, that is, rod temperatures in RELAP/REFLA began to decrease but in RELAP4-FLOOD rod temperatures were kept high for long period.

5.1.2 Case 2: 52 psia, with Accumulator Flow

The pressure in the primary system started with 52 psia which is equal to constant pressure in the containment volume in this case. Water injection by the accumulator connected to the intact loops was supponsed to continue until 2 seconds in the reflood. Other conditions were the same as in Case 1.

Because of the large quantity of water injected, some rapid changes of flow inside of the pressure vessel were expected. This type of calculation was somewhat challenging problem for RELAP/REFLA. The reasons were:

(1) Some of the time derivatives in the momentum equation were neglected in the approximation procedure of the code development. Therefore calculational errors might have been accumulated in such problem.

(2) In the present version of RELAP/REFLA, core inlet flow with negative direction could not be handled exactly. The error caused by this flow reversal problem is neglected in the code and this treatment could be allowed when the intervals with reversed flow are very short. The problem considering accumulator injection, however, likely included the situation of such flow reversal at the core inlet according to the manometer type of oscillations.

Fortunately the calculated result of this case showed that interval of reversed core inlet flow was very short (less than 0.5 seconds) and appeared only once, so that remaining prlblems due to the approximation were mainly corresponding to the neglection of some of the time derivative terms in the momentum equations.

Results of calculation are shown in Fig. 5.10 through 5.16, in which the results by RELAP4-FLOOD are also plotted. Fig. 5.10 shows the core inlet flow. Initial flow rate was about 3700 lbm/sec (out of range of Fig. 5.10) and it decreased rapidly in the first 10 seconds. The calculation of RELAP4-FLOOD decreases faster than of RELAP/REFLA. This difference corresponded to the estimation of core outlet flow shown in Fig. 5.11. Core outlet flow by RELAP4-FLOOD jumped to about 40 lbm/sec at 2 seconds, accordingly core inlet flow was suppressed at the same time due to the increase of pressure drop through the loop piping. Both core inlet and outlet flow by RELAP/REFLA behaved more oscillatory than by RELAP4-FLOOD as similar as Case 1.

Fig. 5.12 illustrates the core outlet enthalpy. This shows core outlet flow was the mixture (containing dispersed water droplets) throughout the calculation.

Fig. 5.13 and 5.14 show the water inventories of the core volume and the downcomer volume. Water levels in the downcomer volumes of two calculation were very close but water levels in the core were slightly different.

Fig. 5.15 illustrates the clad surface temperatures for the lower half of the core. Small oscillations for the 3-foot and 4-foot elevations in the interval of 5 to 25 seconds corresponded to the change of core inlet flow.

Fig. 5.16 compares the clad surface temperatures of two calculations for the middle elevation of the core. Temperature for the 7-foot elevation by the RELAP/REFLA was very close to the temperature of heat conductor with the height of 6 to 7.2-foot in the RELAP4-FLOOD calculation.

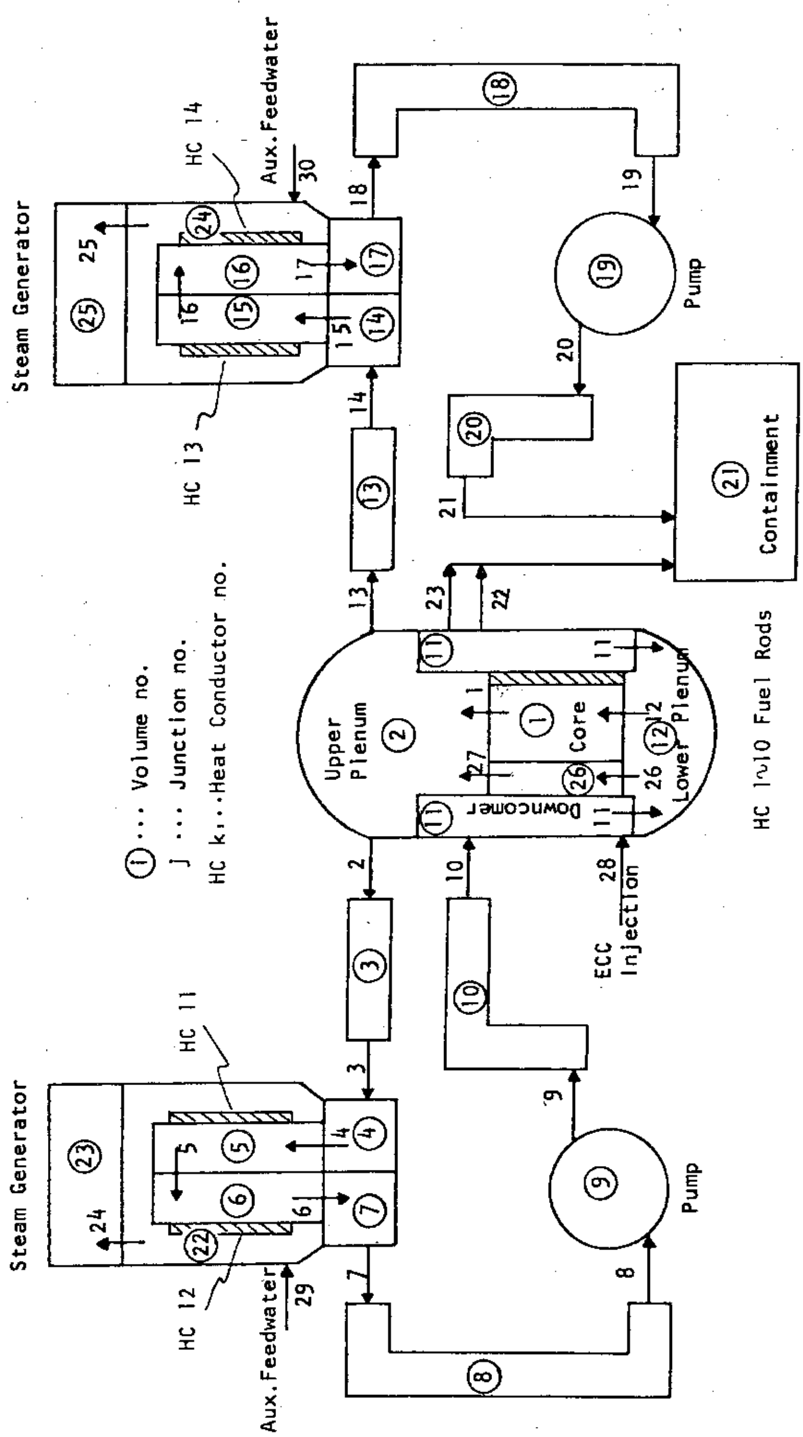


Fig. 5.1 4 Loop PWR Nodalization for RELAP/REFLA

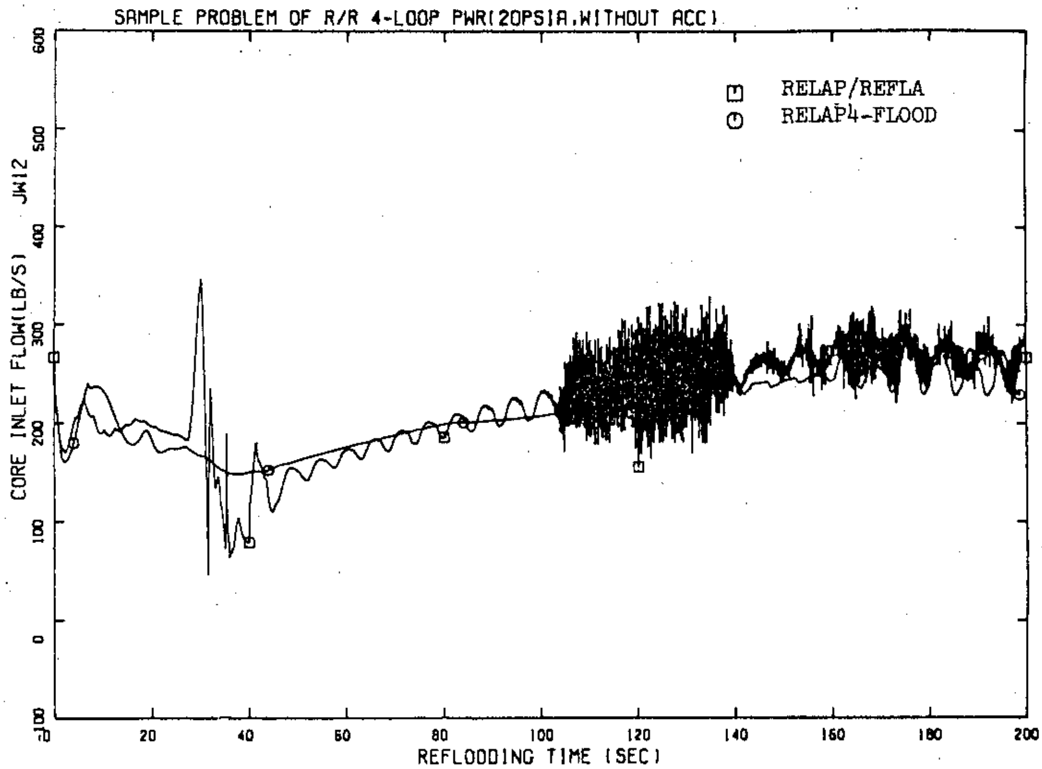


Fig. 5.2 Reflood of 4 Loop PWR, Case 1; Core Inlet Flow

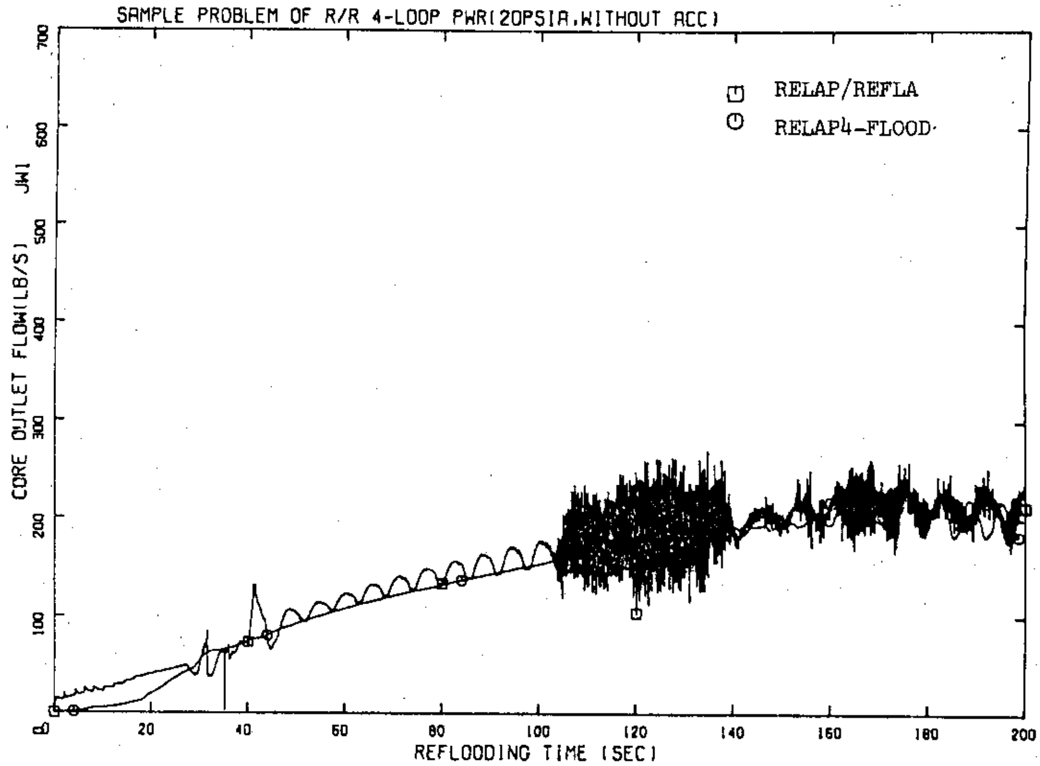


Fig. 5.3 Reflood of 4 Loop PWR, Case 1; Core Outlet Flow

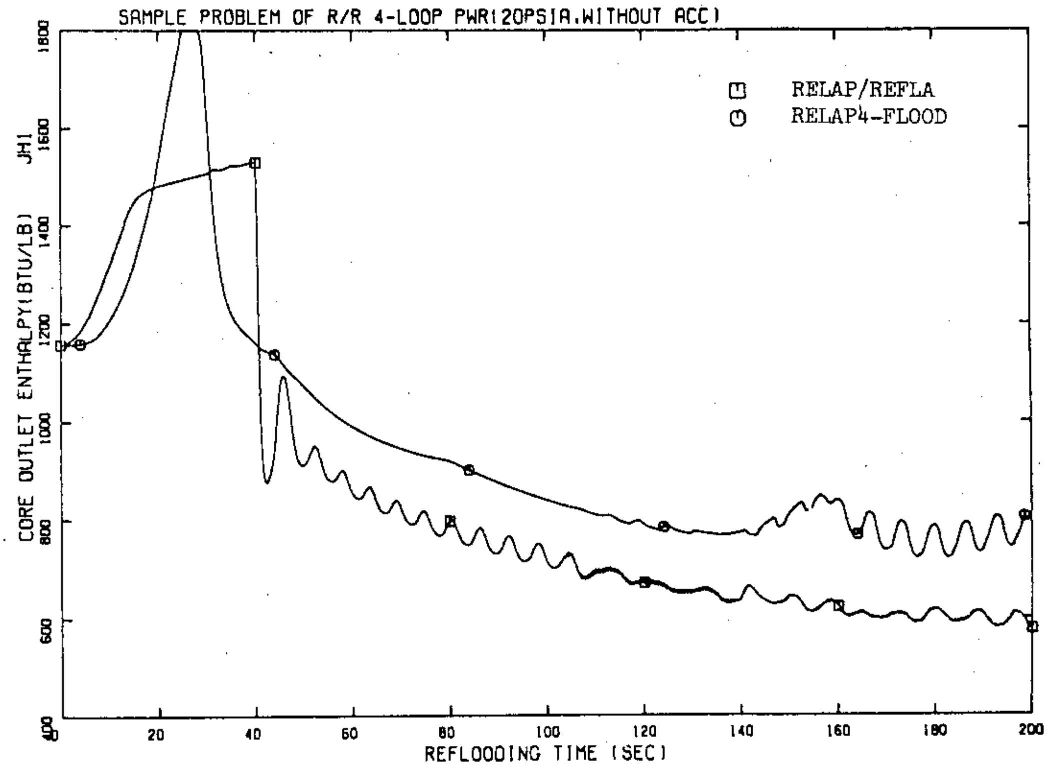


Fig. 5.4 Reflood of 4 Loop PWR, Case 1; Core Outlet Enthalpy

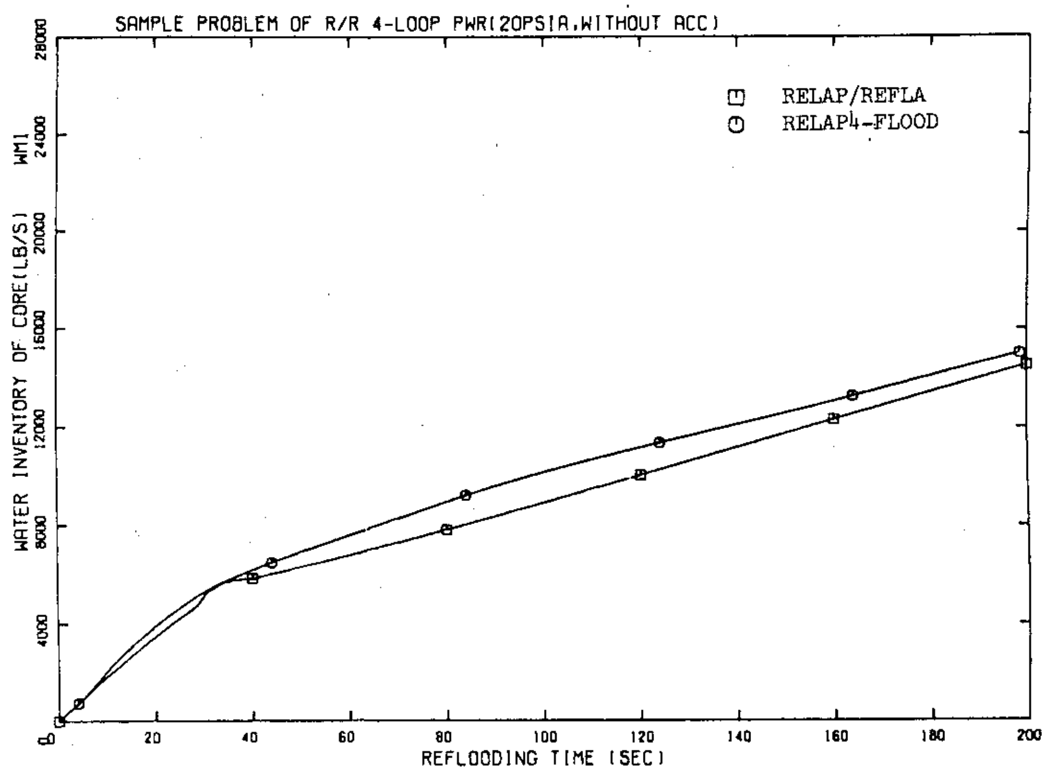


Fig. 5.5 Reflood of 4 Loop PWR, Case 1; Water Mass in the Core Volume

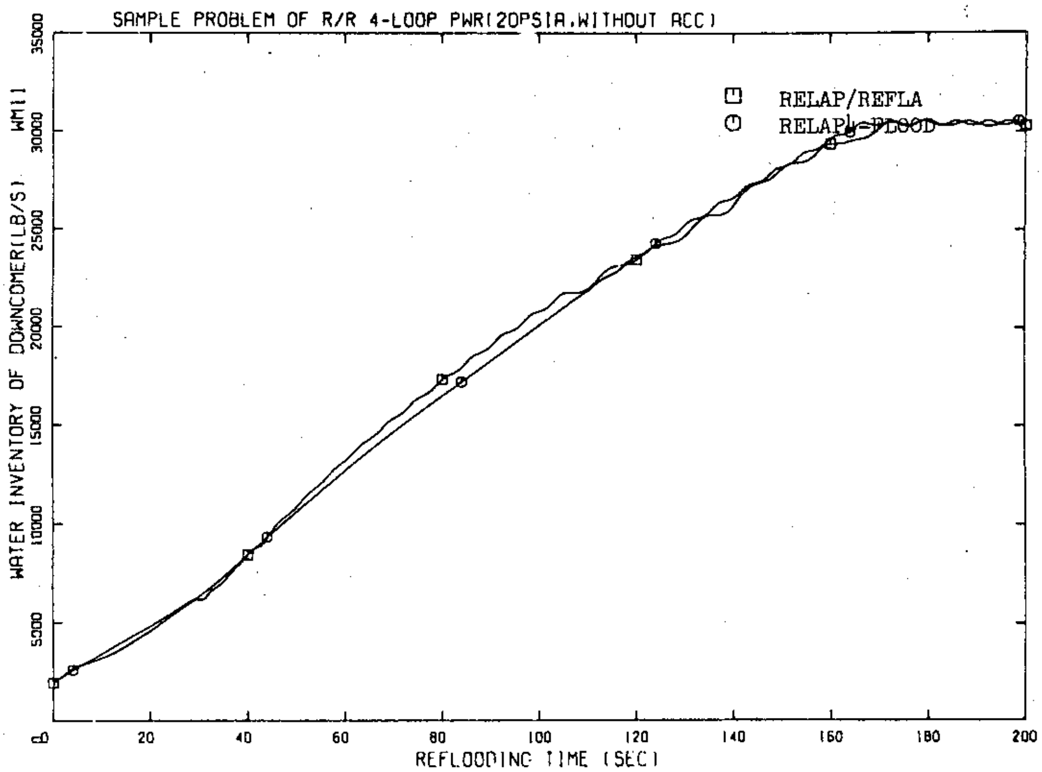


Fig. 5.6 Reflood of 4 Loop PWR, Case 1; Water Mass in the Downcomer Volume

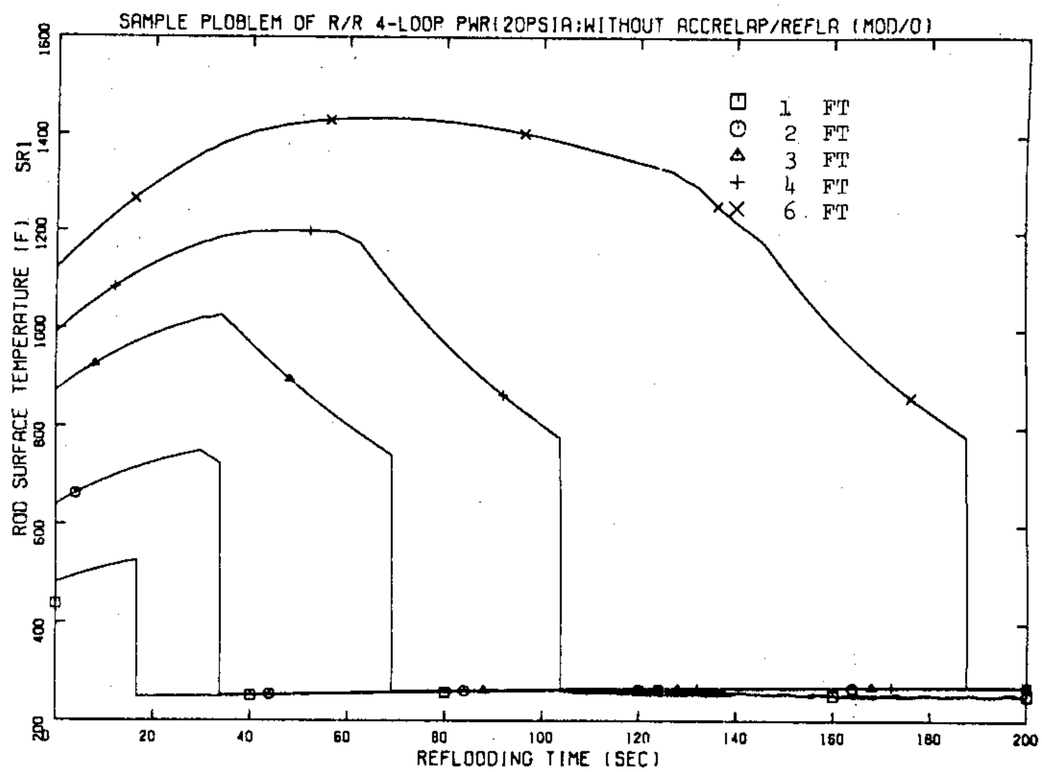


Fig. 5.7 Reflood of 4 Loop PWR, Case 1; Clad Surface Temepratures for Lower Half of the Core

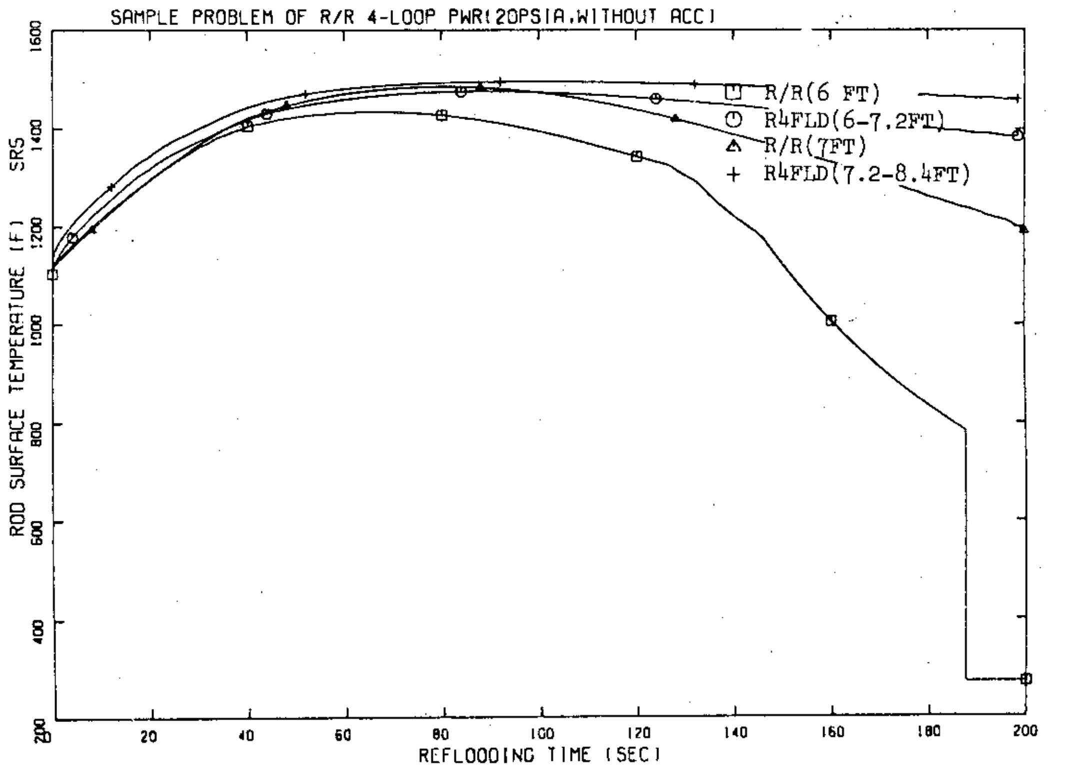


Fig. 5.8 Reflood of 4 Loop PWR, Case 1; Clad Surface Temperatures for the Middle of the Core

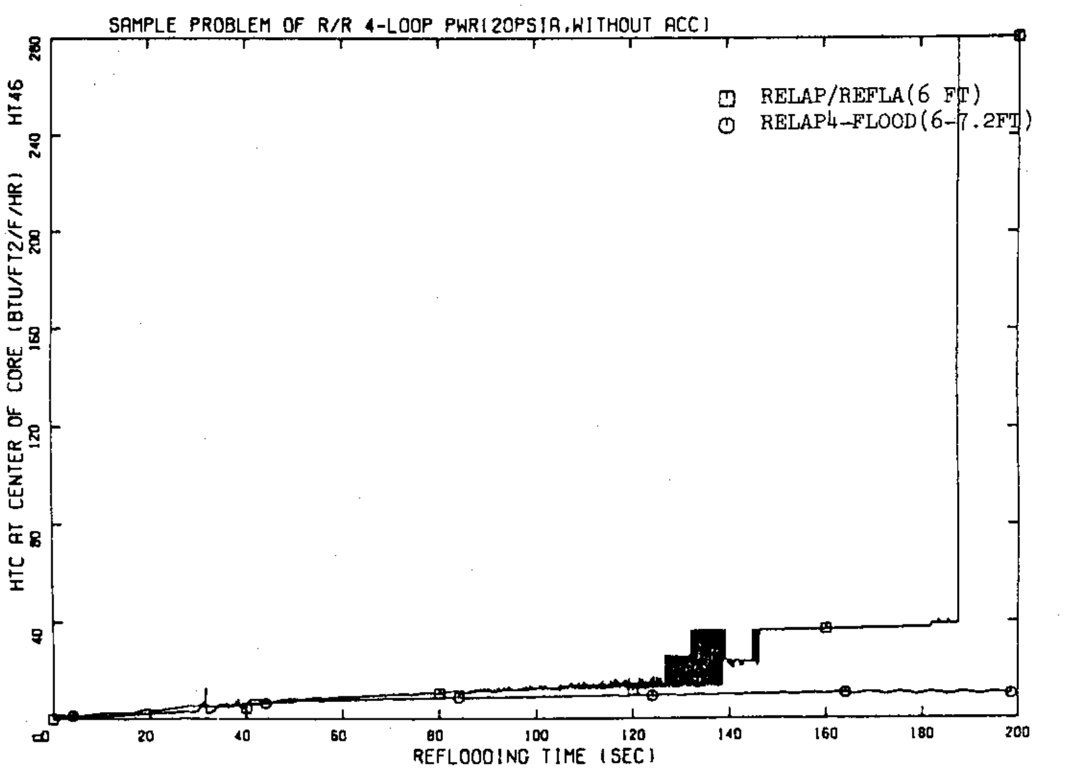


Fig. 5.9 Reflood of 4 Loop PWR, Case 1; Heat Transfer Coefficient for the Middle of the Core

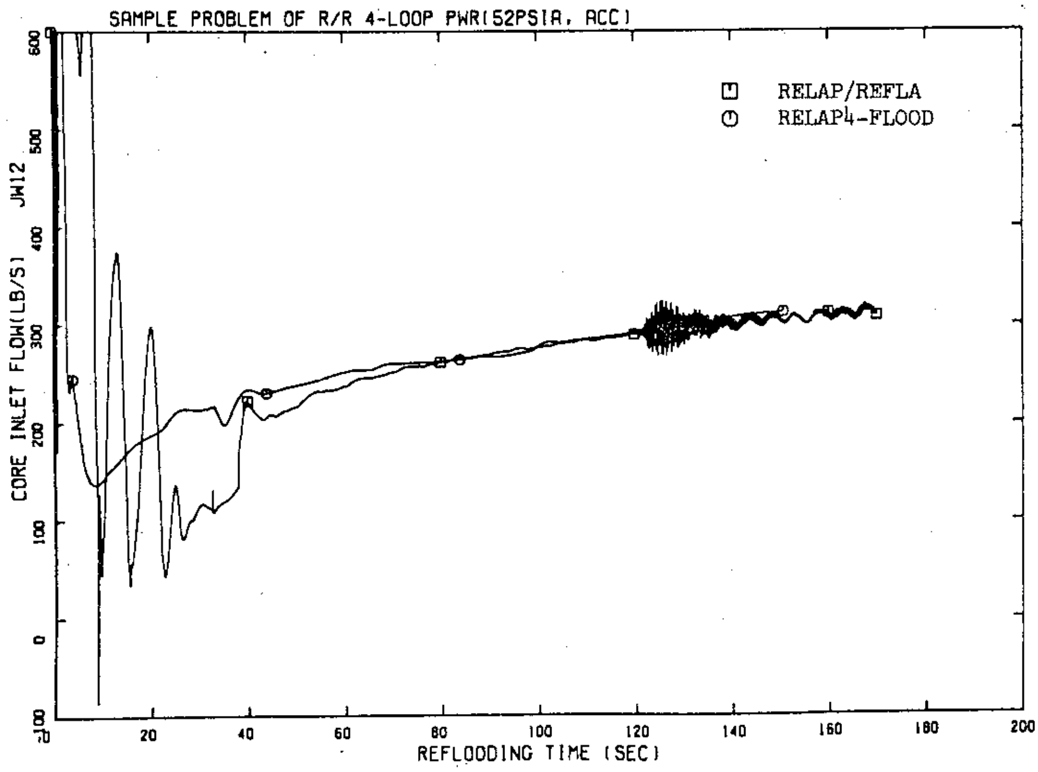


Fig. 5.10 Reflood of 4 Loop PWR, Case 2; Core Inlet Flow

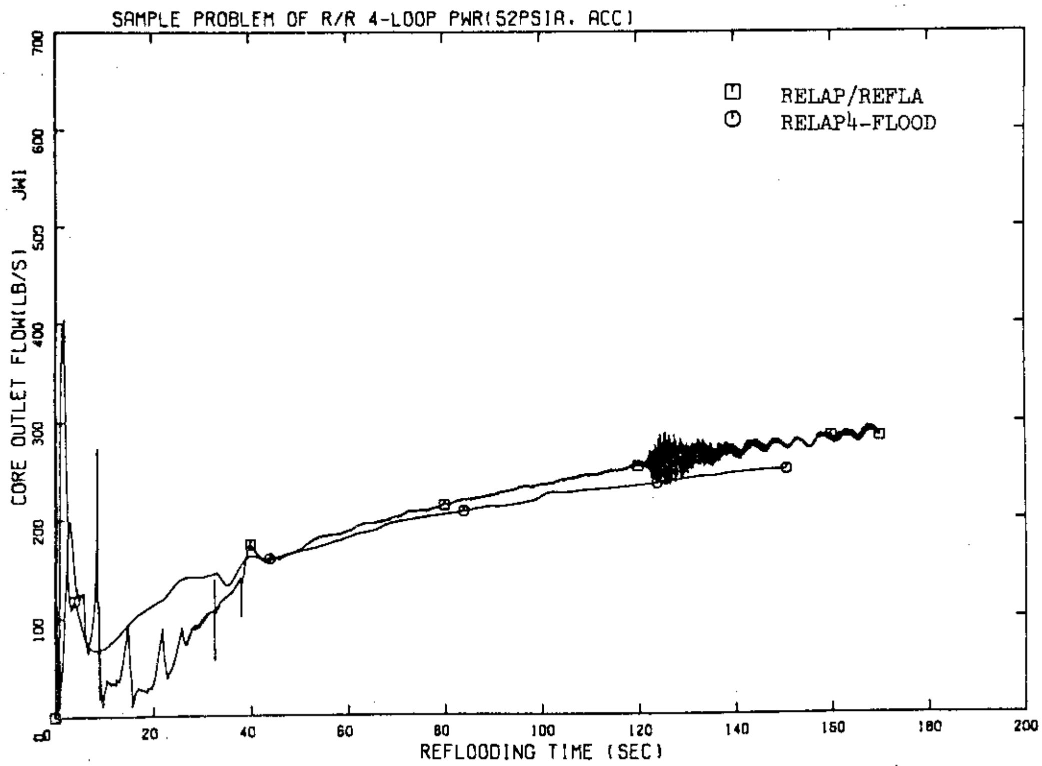


Fig. 5.11 Reflood of 4 Loop PWR, Case 2; Core Outlet Flow

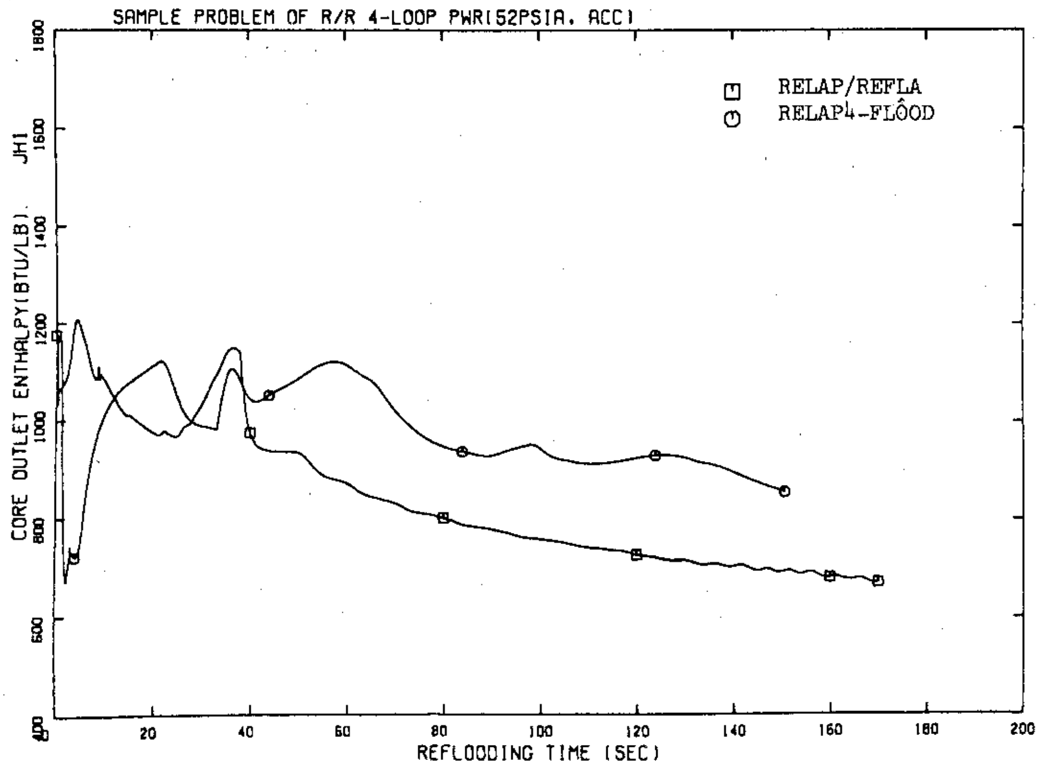


Fig. 5.12 Reflood of 4 Loop PWR, Case 2; Core Outlet Enthalpy

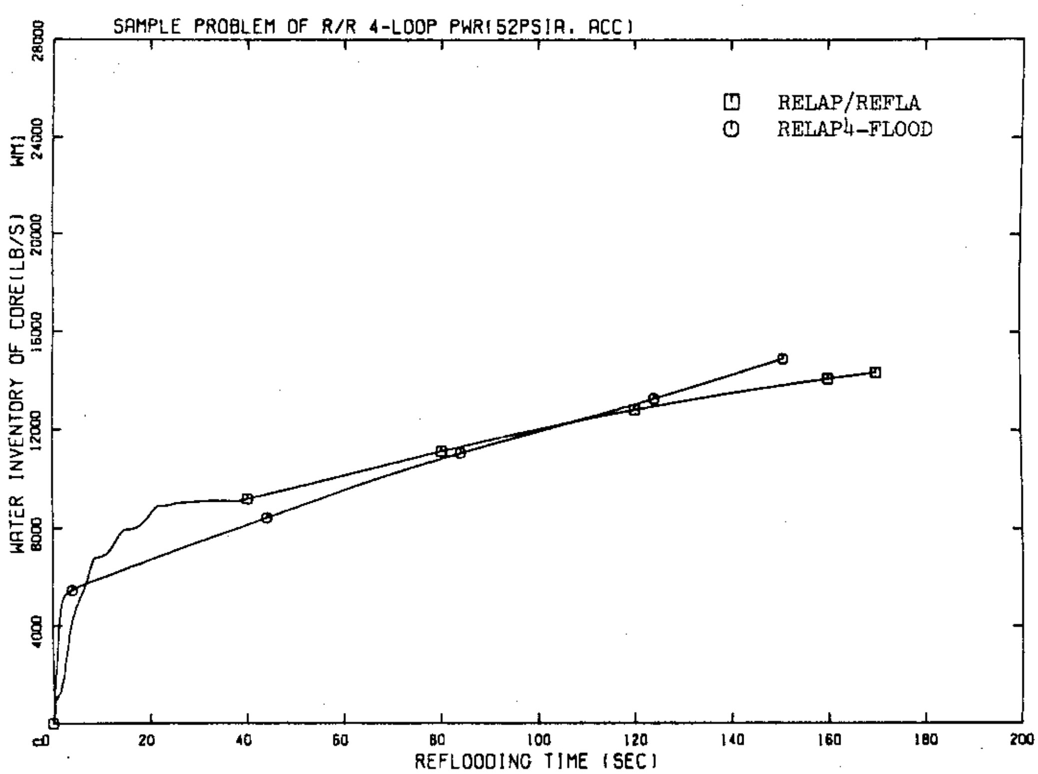


Fig. 5.13 Reflood of 4 Loop PWR, Case 2; Water Mass in the Core Volume

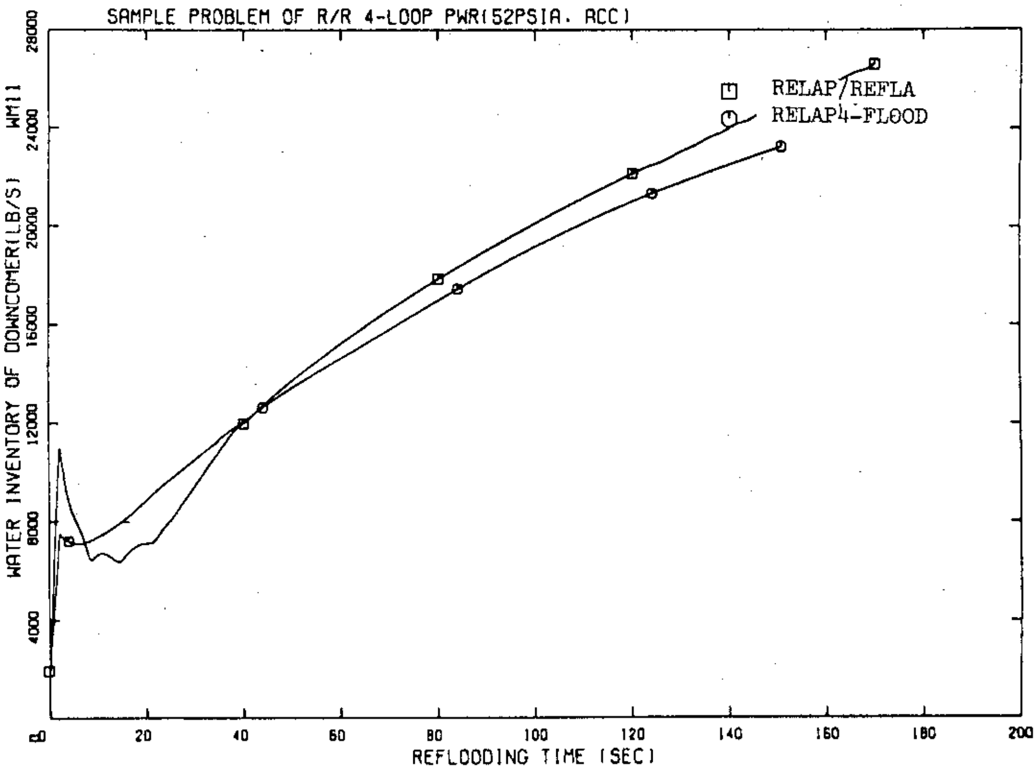


Fig. 5.14 Reflood of 4 Loop PWR, Case 2; Water Mass in the Downcomer Volume

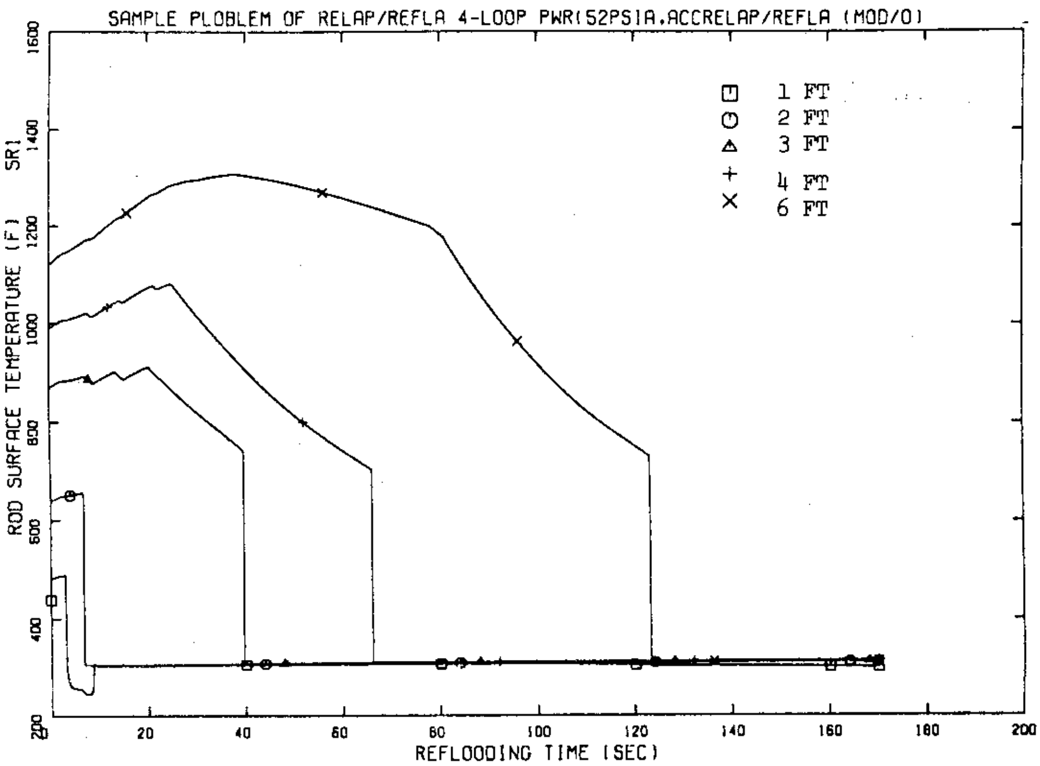


Fig. 5.15 Reflood of 4 Loop PWR, Case 2; Clad Surface Temperatures for the Lower Half of the Core

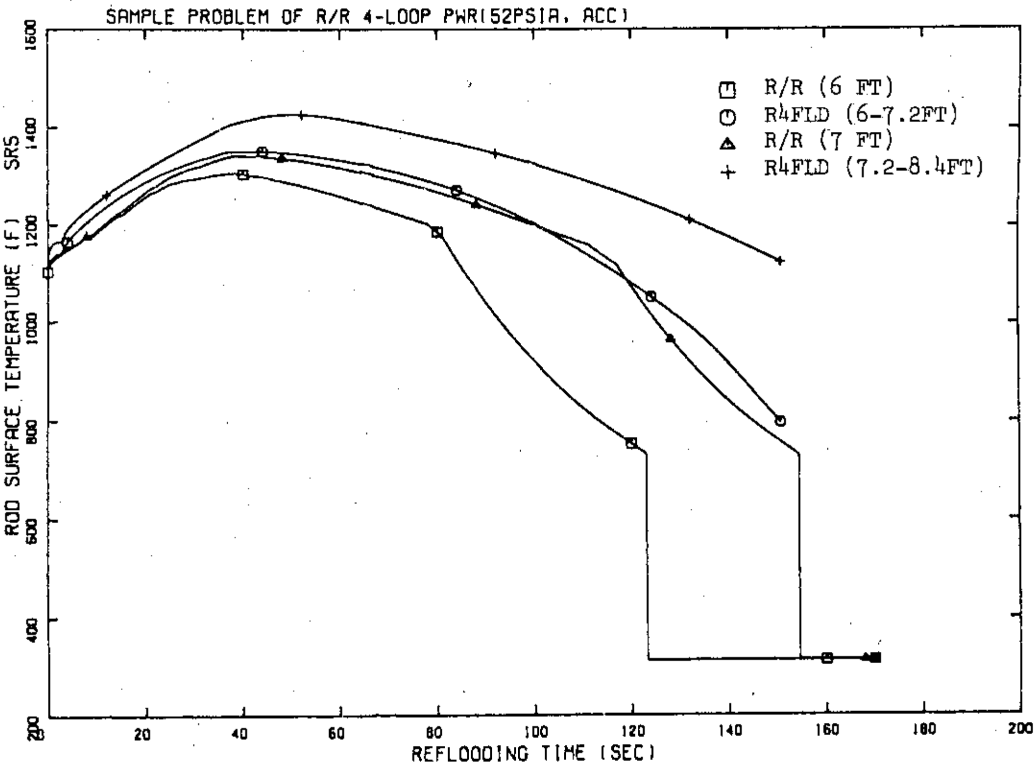


Fig. 5.16 Reflood of 4 Loop PWR, Case 2; Clad Surface Temperatures for the Middle of the Core

5.2 FLECHT-SET Experiments

PWR FLECHT-SET program was carried out by Westinghouse Electric Co. as a sponsored work of United States Government. Its objective was to provide experimental data describing the influence of system effects on emergency core cooling behavior during a loss-of-coolant accident. Accordingly, tests in FLECHT-SET program were just suitable to check RELAP/REFLA's capability by simulating the experiments. Two tests were selected among Phase-B series[25] of the program, which are Run 2714B and Run 3105B, each of them was considered as a typical case (also considered as a reference case in the evaluation report[25]) with system pressure at 20 psia and 60 psia, respectively. The tests were performed in a scaled facility which included an electrically heated 100 (10×10) rod bundle with 12 feet length, two full length loops with active steam generator simulators and proper flow resistances and full-length downcomer. (Note: The expression such as "full-scaled" or "full-length" means a dimension of test facility is nearly equal to the dimension of typical large scale PWR plant.) The vertical dimensions were carefully set equal to the typical PWR plant.

The facility was initially heated to the specified temperature for each component. The system was pressurized with steam to the nominal test pressure. The lower plenum was filled with water to the bottom of the heated length. When initial conditions of the facility met the specifications within the allowable tolerances, power was applied to the heater rods. When the rod temperature reached the specified initial value, injection of coolant began and decay of the power input started simulating the fission product decay power. In FLECHT-SET program, the decay of power was intended to simulate the values of ANS+20 % standard from 30 second after shutdown. The injection rate of coolant was large for first interval (corresponding to the water injected by accumulator) followed by continuous injection at 1 or 2 lbm/sec (corresponding to LPIS or HPIS flow). This continuous injection rate was manually controlled in some intervals to prevent the downcomer overflow because it might cause non-typical pressure transient due to steam condensation in overflow tanks.

The system model for RELAP/REFLA is shown in Figs. 5.17 and 5.18. It consists of 31 volumes, 32 junctions and 27 heat conductors. The lowest portion of downcomer (volume 1), volume 2 and lower plenum (volume 3) are filled with water at nearly saturated temperature. The secondary side of steam generator simulator is partially filled with water and kept at approximately 511 F and 750 psia. Initial temperature of each heat conductor which is attached to primary loop is set equal to the initial fluid temperature of adjacent volume, that is, saturation temperature between upper plenum and steam generator simulator, and 500 F for the downstream of steam generator simulator. Test section housing is neglected in this model because RELAP/REFLA can handle only one stack of heat conductors which is adjacent to the core volume. The axial distribution of initial clad temperature for 91 meshes is necessary for the input of RELAP/REFLA, so the thermocouple data of discrete points (14 elevations) are averaged and interpolated to obtain such axial distribution.

5.2.1 RUN 3105B Results

The results calculated by RELAP/REFLA are shown in Fig. 5.19 through 5.25. The comparisons with the experimental data are also made in some figures. We should note that some of the 'experimental data' reported[25], for example, mass flow rate at the core inlet and in the loop piping, mass storaged in the test section, were calculated value based on the experimental mass balance data of the system. Accordingly the fine structures such as rapid oscillations of the flow are eliminated.

Fig. 5.19 presents the mass flow rate at the inlet of test section. In the first interval with relatively large inlet flow, ECC injection rate was large because it simulated the flow from the accumulators. The flow rate calculated by RELAP/REFLA was about a half of the experimental value for this interval. After injection rate decreased to low (almost constant) level, data showed flow rate decreased to about 1 lbm/sec but calculated flow rate showed some oscillation and then settled down to stable level with 0.8 lbm/sec. The oscillatory interval corresponded to the transition of flow patterns in the heated channels as shown in Fig. 5.22. After that, dispersed flow had fully developed and this led the increase of loop flow upto same order to the test section inlet flow (Fig. 5.20). Calculated intact loop flow was larger than the data and its fraction to the flow entering the test section was also larger than the data. This led accumulated water mass in the test section to be small. Fig. 5.21 shows this situation.

Fig. 5.22 illustrates the movement of calculated flow regime boundaries in reflood. ZB1 to ZB5 are:

ZB1 : Single liquid phase to bulk boiling regime

ZB2 : Quench front

ZB3 : Subcooled film boiling to transition flow regime

ZB4 : Transition flow to dispersed flow regime

ZB5 : Lowest position of rewetted portion from the top

Dotted line in Fig. 5.22 shows the quench envelope which was estimated from the thermocouple data with the latest quench time for each elevation. Quench level calculated by RELAP/REFLA and the data were essentially similar for the lower half of test bundle but quench times for 7-foot to 9-foot elevation were very different. Rewetted region from the top of the bundle progressed down earlier than the data. About 140 seconds, the data showed the almost simultaneous quench had occurred from 7-foot to 10-foot elevation. This might have been caused by a kind of co-operative phenomena along the axial direction but RELAP/REFLA did not include any kind of such mechanism. Accordingly very different quench behaviors were assumed to be appeared in the last portion of quench process.

Another problem shown in Fig. 5.22 is the behavior of the boundary point ZB1 (saturation point). It sometimes moved stepwise. This might cause discontinuous change of water properties above the saturation point, so some improvement of calculational procedure must be considered in the future development.

Fig. 5.23 and 5.24 compares the calculated surface temperatures with the reported experimental data. At the elevation below 6 feet, the calculated maximum temperatures compared well with the data, but the RELAP/REFLA's quench times were delayed with respect to the data.

The calculated results for the higher elevations do not compare as well, with higher maximum temperatures and delayed quench times. This tendency is also obvious from the comparison of quench envelope in Fig. 5.22. The heat transfer in the upper elevations was in the dispersed flow region for longer period than the lower elevations, and this might be the cause of the poorer comparisons of maximum temperatures.

Quench temperatures calculated for the elevations which the quench point had reached from the top, were vary with the elevation and higher than the data. The data shows the almost constant quench temperatures for all elevations. This fact suggested the poorness of the top rewetting model.

Fig. 5.25 illustrates the change of the temperature profile calculated for the test bundle. The unit used in this figure is different (MKS) because these output come essentially from the REFLA part and the plotter routine was not fully arranged yet. This figure is helpful to understand the progress of quench, precursory cooling, variation of quench temperatures and so on.

5.2.2 RUN 2714B Results

The test-section inlet flow is presented in Fig. 5.26. As with the RUN 3105B calculation, the mass flow rate calculation was quite constant except for the first 20 seconds, with the data showing more fluctuation. The calculation reproduces the data after 20 seconds.

The mass flow rate in the intact loop is shown in Fig. 5.27. The calculated flow was greater than the data until 120 seconds, then it became smaller than the data. The data showed rather constant loop flow after 100 seconds.

These flow behaviors caused a significant difference of the mass stored in the test section. As shown in Fig. 5.28, the calculated water inventory increased monotonically after 15 seconds, but the data shows the increase of stored water in the first 50 seconds and some fluctuations after that time.

Fig. 5.29 illustrates the movement of calculated flow regime boundaries. In this case quench data were so dispersed that the quench envelope was assigned only as the broad band (two dotted line in Fig. 5.29 shows this data band). Accordingly, definite comparison between calculated quench level and the data was difficult, but roughly speaking, the calculated quench level lay in the data band.

Fig. 5.30 and 5.31 illustrate the calculated fuel temperature and the thermocouple data. Good agreement was shown about the maximum temperatures for the lower elevations, but poor agreement was about the quench temperatures (the data selected in the Fig. 5.30 are the typical ones for each elevation and the definite argument on the difference of quench time was impossible due to broad width of the data band).

The calculation was not representative for the upper elevations. The maximum temperature was overpredicted by 300 °F at the 8-foot elevation. Except near the top of the bundle, quench temperatures and quench times did not agree with the data. This strongly suggested again the poorer model on the top rewetting.

Fig. 5.32 shows the temperature profile calculated at different times. Quench temperature become too large for the top quenching as in the case of RUN 3105B.

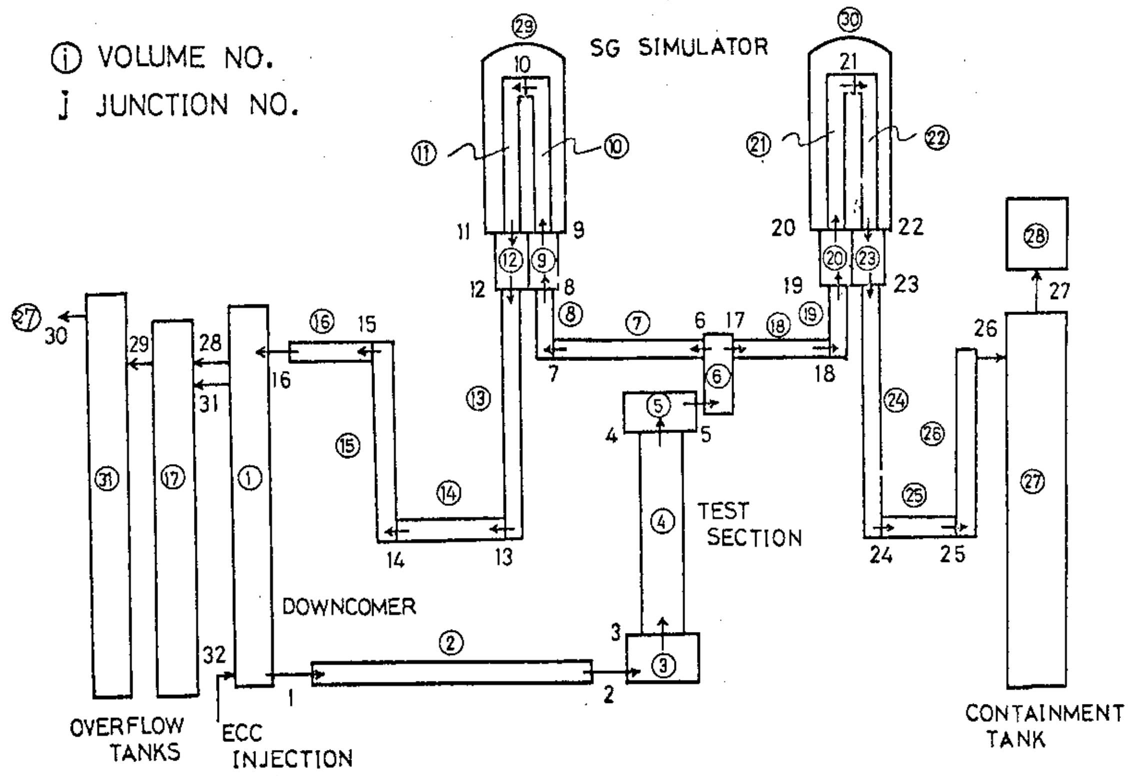


Fig. 5.17 System Model of FLECHT-SET for RELAP/REFLA
(1) Volumes and Junctions

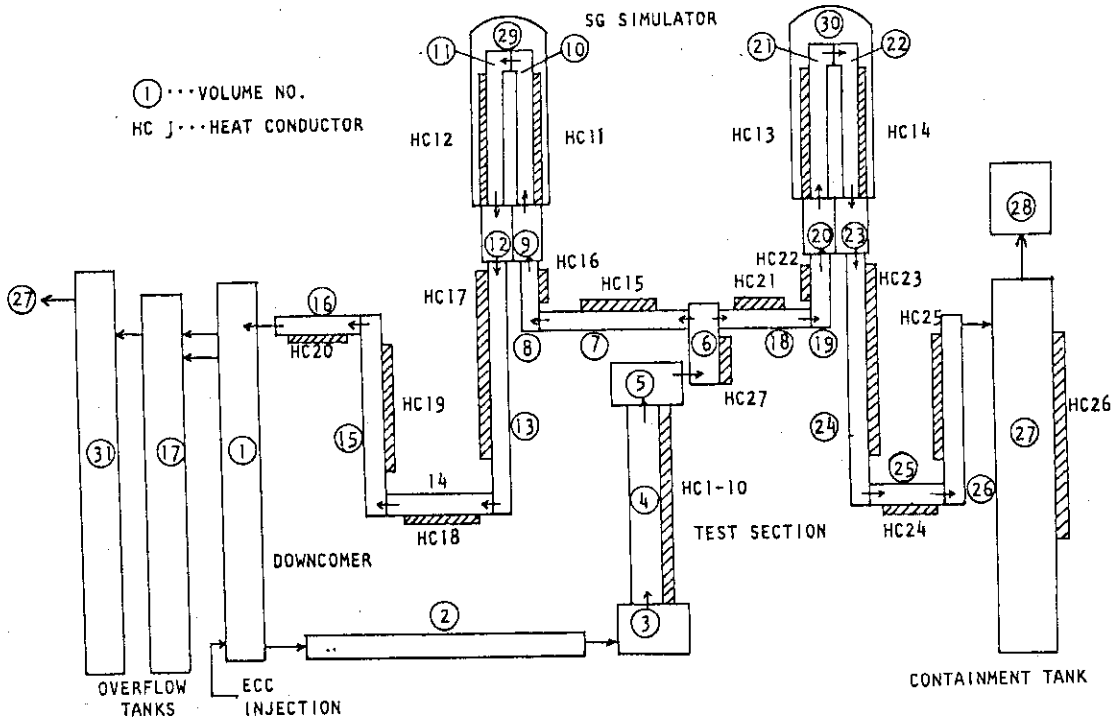


Fig. 5.18 System Model of FLECHT-SET for RELAP/REFLA
(2) Heat Conductors

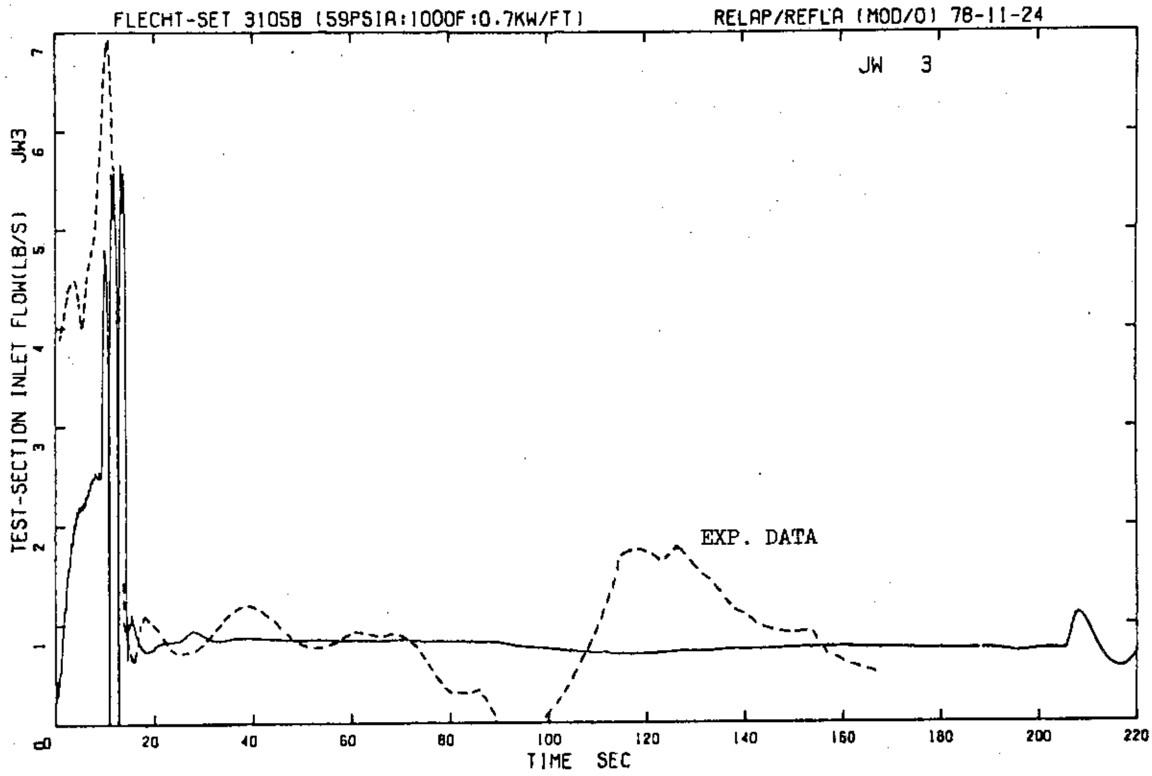


Fig. 5.19 FLECHT-SET RUN 3105B; Mass Flow Rate at the Inlet of Test-section

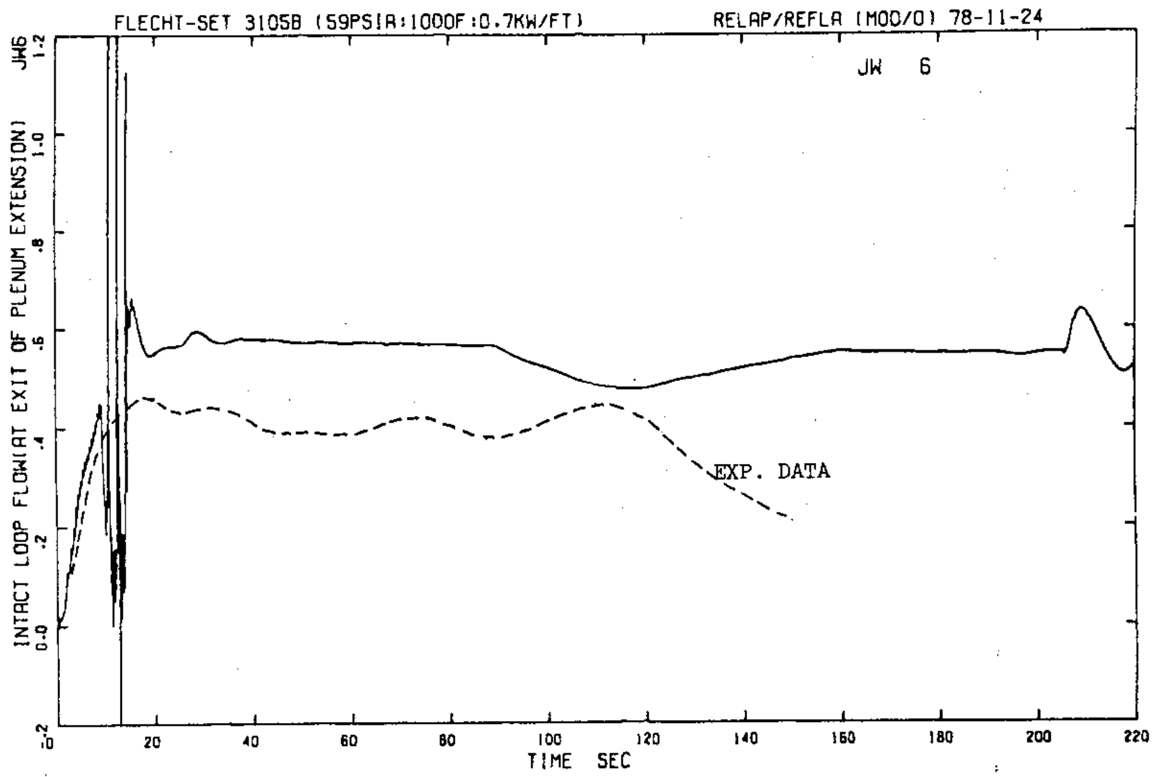


Fig. 5.20 FLECHT-SET RUN 3105B; Mass Flow Rate in the Intact Loop

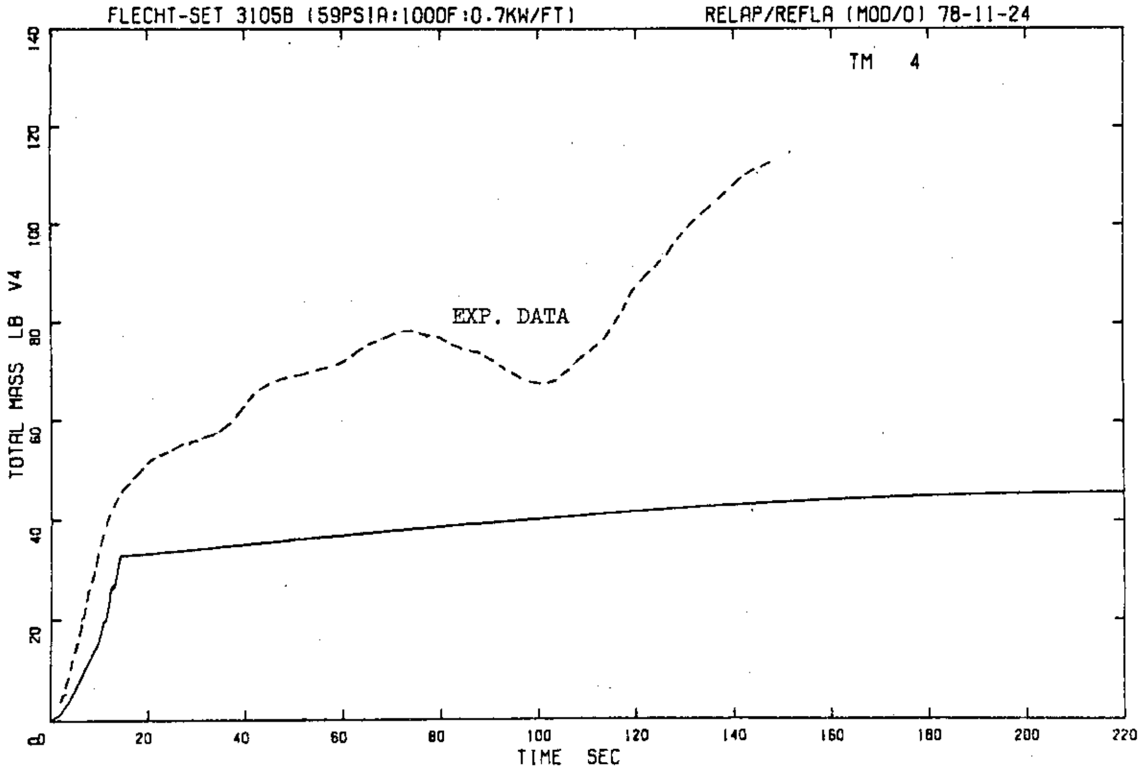


Fig. 5.21 FLECHT-SET RUN 3105B; Water Mass Accumulated in the Test-section

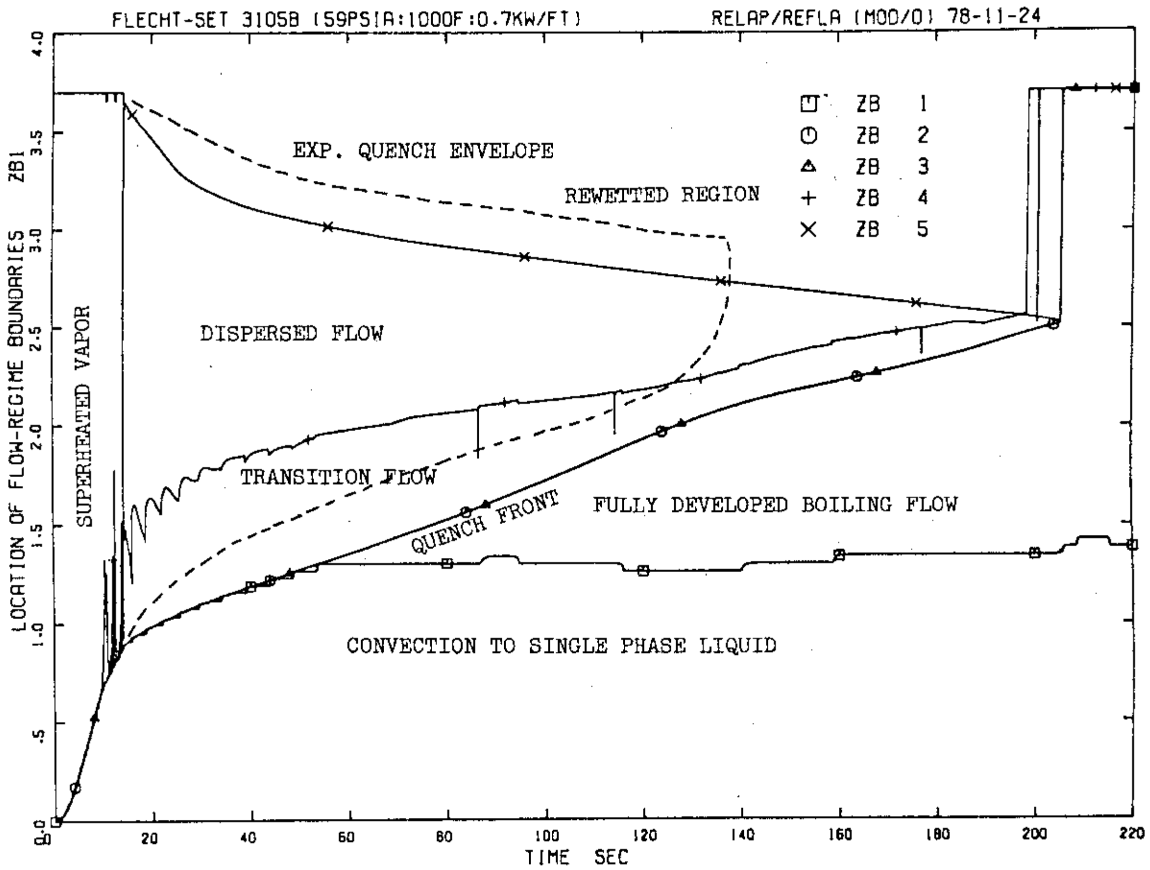


Fig. 5.22 FLECHT-SET RUN 3105B; Movements of Boundaries between Flow Region

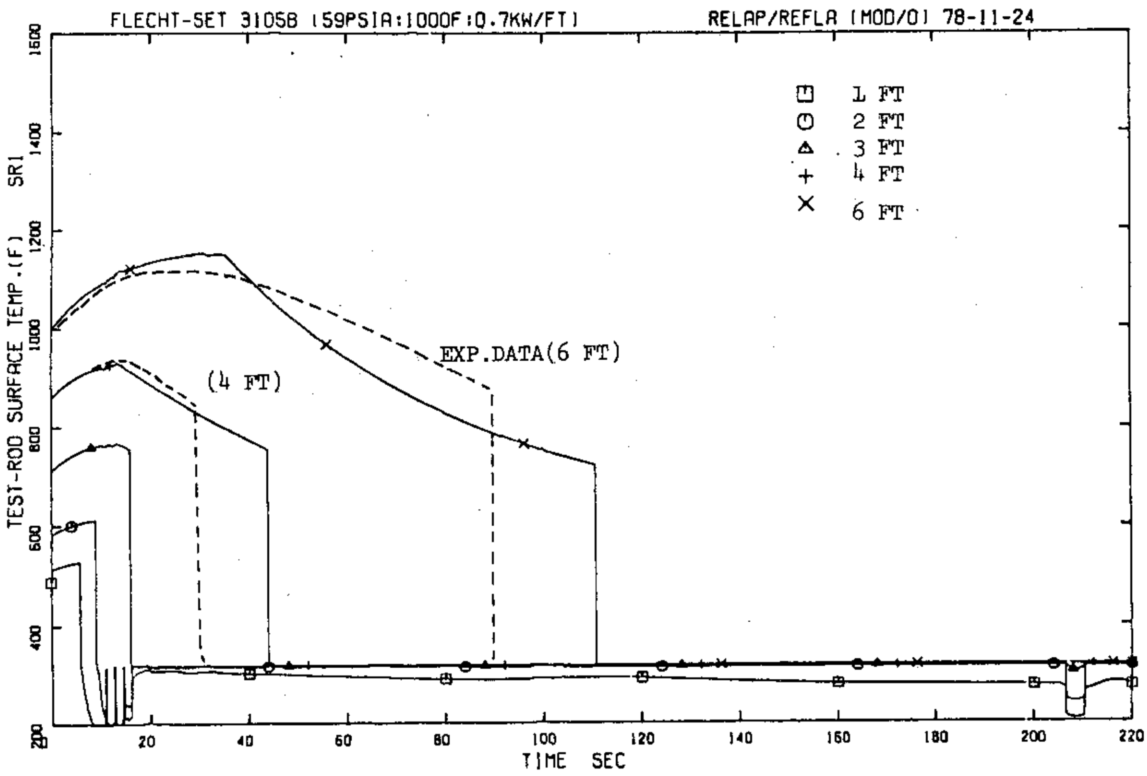


Fig. 5.23 FLECHT-SET RUN 3105B; Rod Surface Temperatures for the Lower Half of the Test Bundle

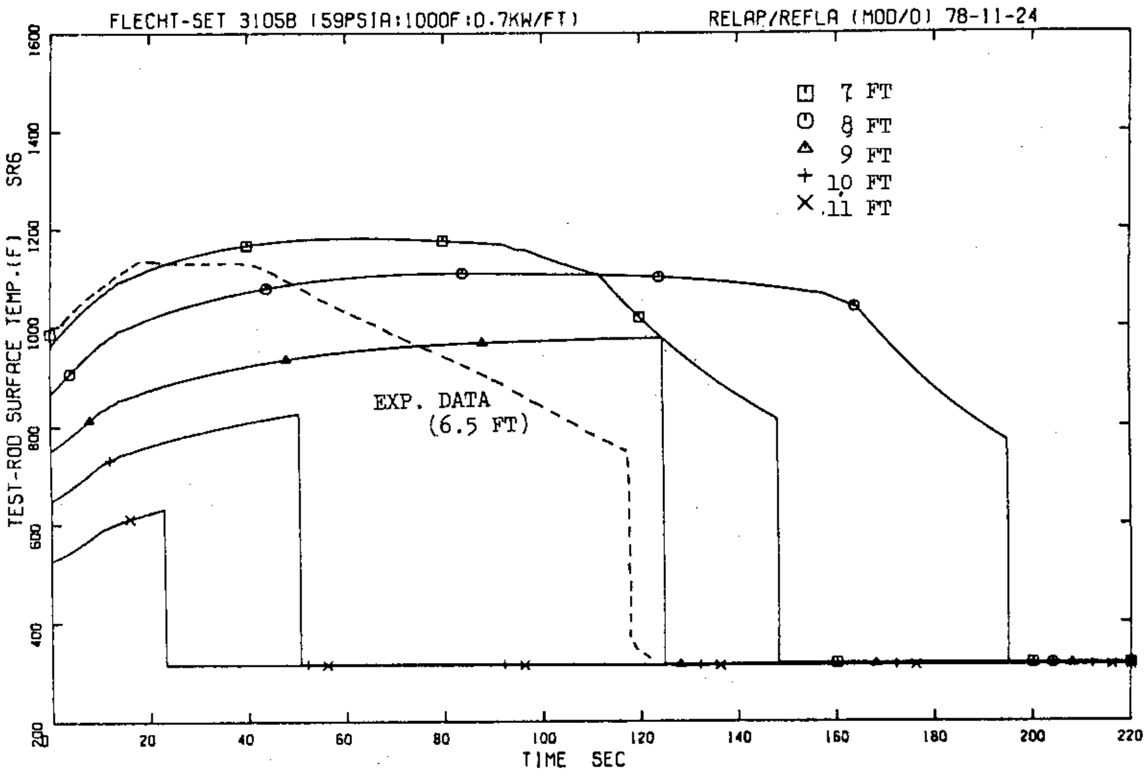


Fig. 5.24 FLECHT-SET RUN 3105B; Rod Surface Temperatures for the Upper Half of the Core

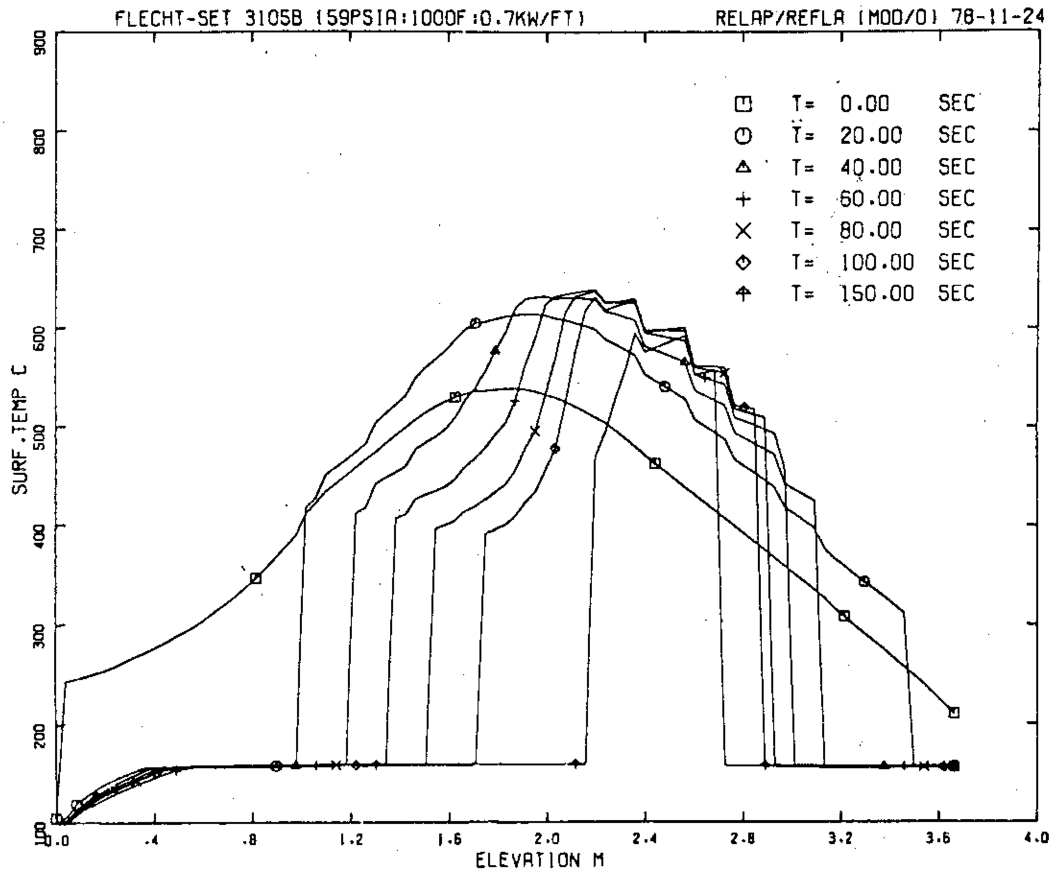


Fig. 5.25 FLECHT-SET RUN 3105B; Temperature Distrubiton in the Test Bundle

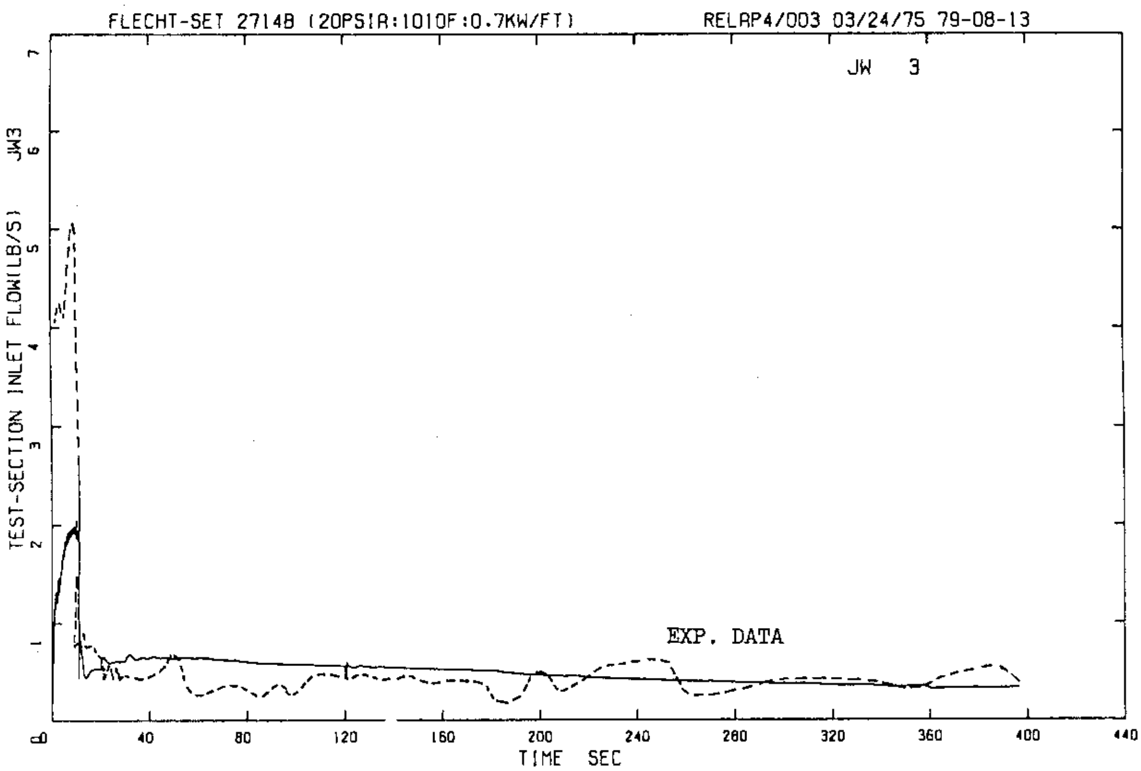


Fig. 5.26 FLECHT-SET RUN 2714B; Mass Flow Rate at the Inlet of the Test-section

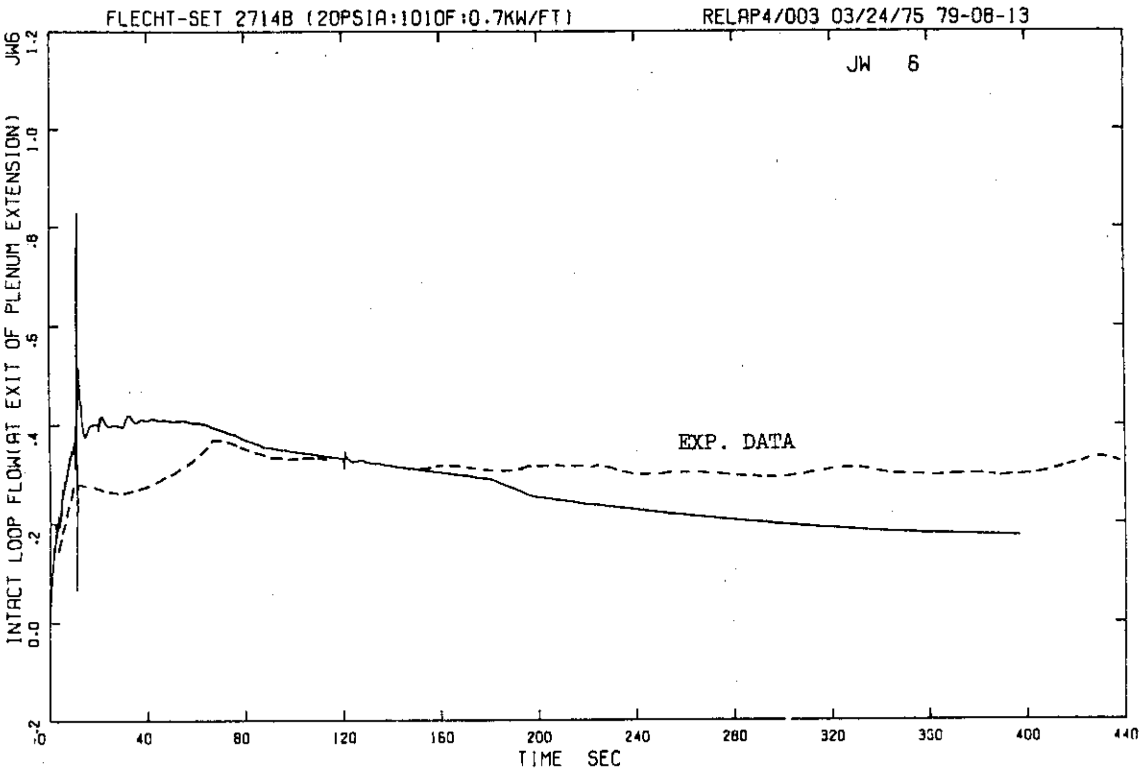


Fig. 5.27 FLECHT-SET RUN 2714B; Mass Flow Rate in the Intact Loop

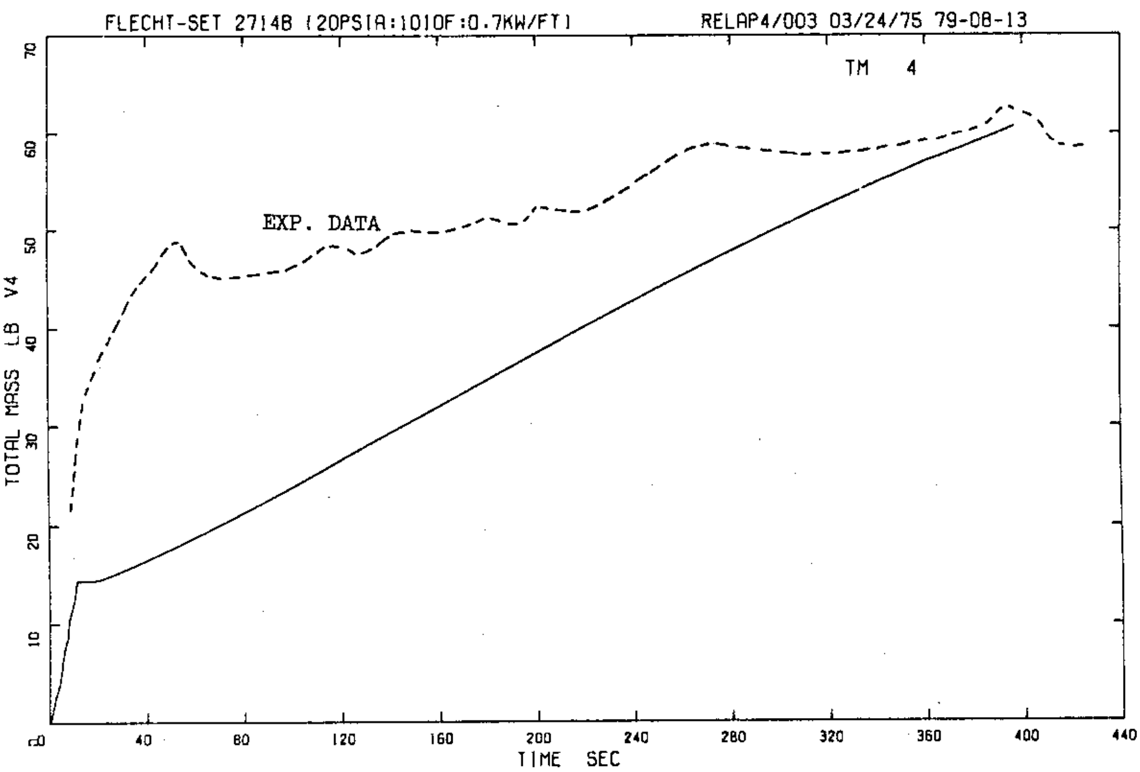


Fig. 5.28 FLECHT-SET RUN 2714B; Water Mass Accumulated in the Test-section

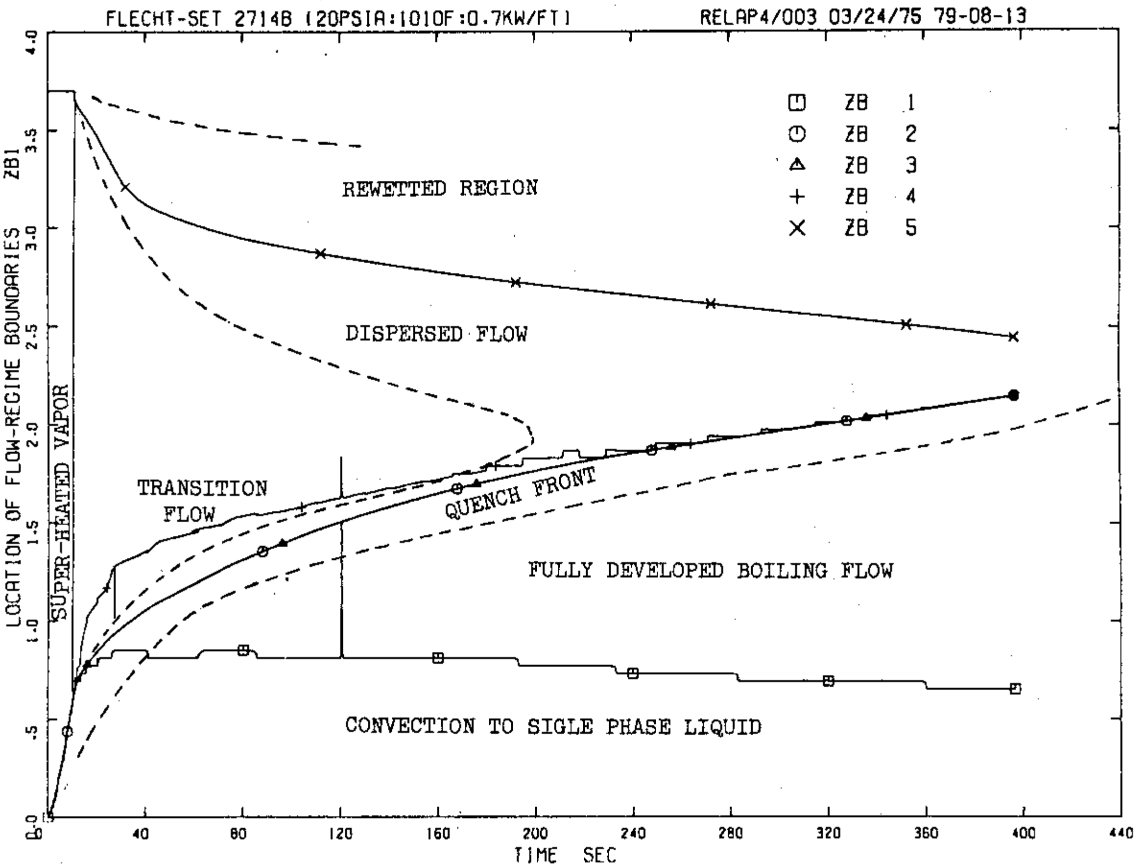


Fig. 5.29 FLECHT-SET RUN 2714B; Movements of Boundaries between Flow Regions

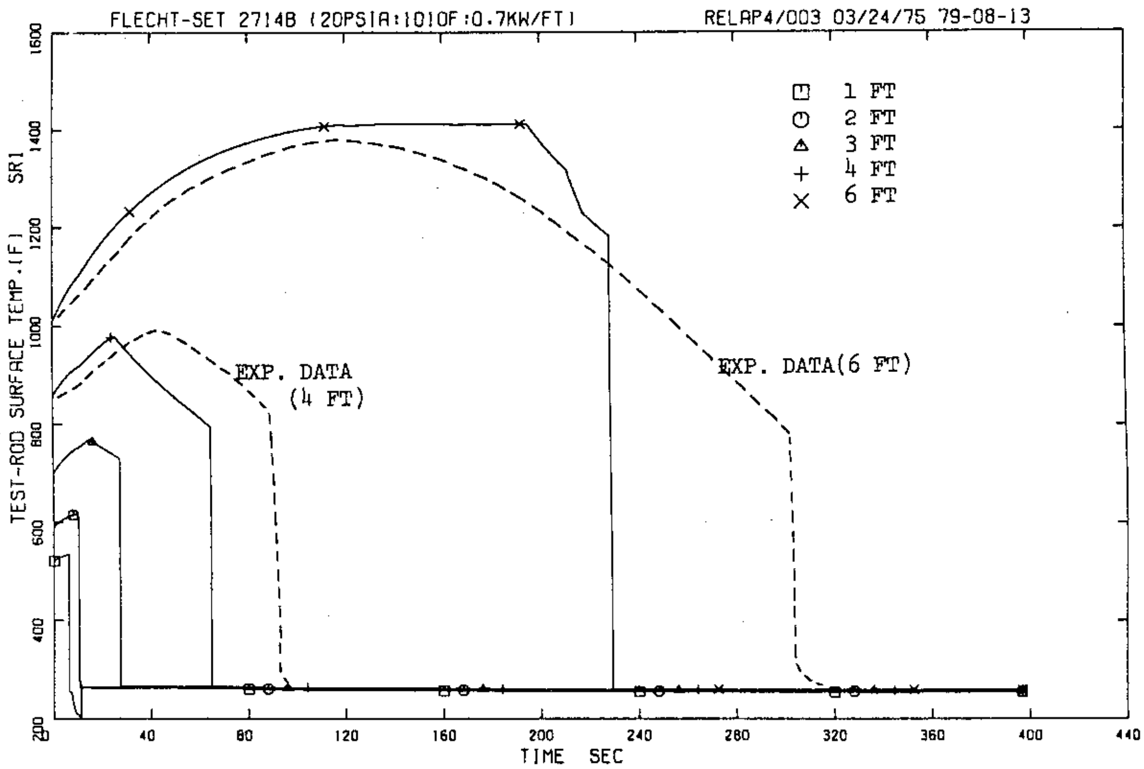


Fig. 5.30 FLECHT-SET RUN 2714B; Rod Surface Temperatures for the Lower Half of the Test Bundle

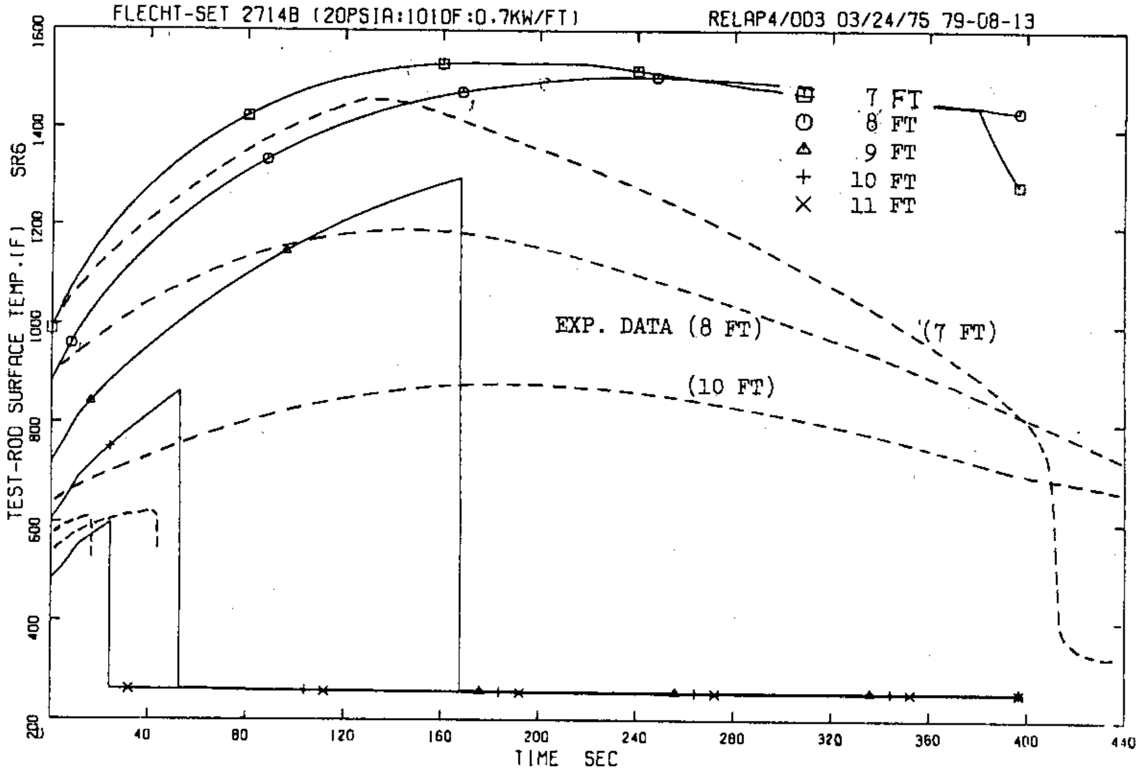


Fig. 5.31 FLECHT-SET RUN 2714B; Rod Surface Temperatures for the Upper Half of the Test Bundle

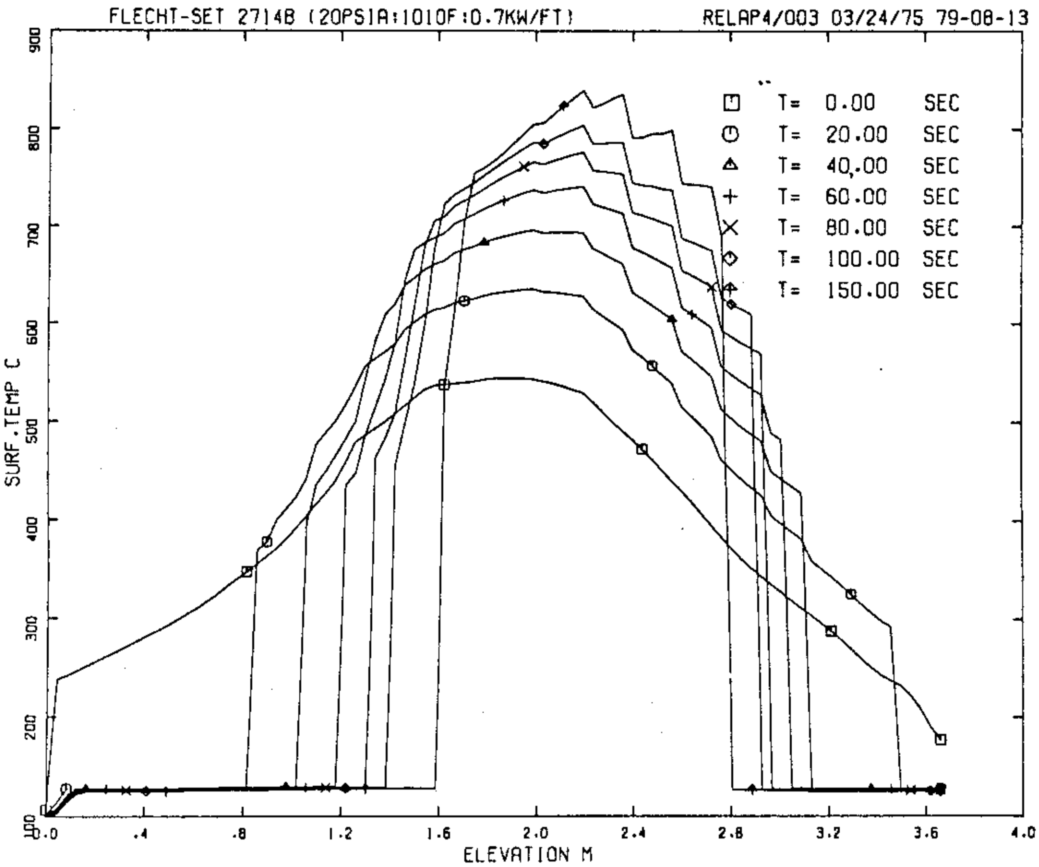


Fig. 5.32 FLECHT-SET RUN 2714B; Temperature Distribution in the Test Bundle

6. Conclusions

Based on the two distinct code, RELAP4 of the system hydraulic analysis and REFLA-ID of the detailed analysis of the reflooding core channel, system reflood analysis code "RELAP/REFLA" was developed. The code can be applied to any PWR system with different geometries in principle.

Reasonable results were obtained on the analysis of the reflood phenomena in a postulated LOCA of large PWR, in spite of rather primitive procedure on the combination between two parts of the code.

On the analysis of FLECHT-SET experiments, the behavior of the quench front was traced well for the lower elevations of the test-bundle but was not for the upper elevations especially in the case with low system pressure. It was supposed to be caused by the poorness of the model for the quenching from the top (rewetting). The evaluation of the stored mass in the test-bundle was much lower than the data. This difference was likely to cause delayed quench time but was not always the case in the analysis of FLECHT-SET. This point should be considered in the future improvement of the code.

In some cases of analysis, the code met instability which cause a flow oscillation and calculation was terminated by errors. It was supposed to come partially from the explicit numerical schemes of the code and to come from the heat transfer model. More detailed analysis will be necessary about the core model under the time-dependent boundary conditions.

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Nomenclature

A	m^2	volume flow area
C_D		drag coefficient
C_ℓ	m	wetting perimeter
C_p	kcal/kgK	specific heat
D_d	m	droplet diameter
D_e	m	equivalent diameter
F_s		shape factor defined by eq. (3.29)
f		fanning friction factor
G	kg hr/m^3	mass velocity
Gr		Grashof number
g	m/hr^2	acceleration of gravity
H	kcal/kg	enthalpy
H_{fg}	kcal/kg	latent heat
J	m^3/hr	volumetric flow rate
k	kcal/mhrK	thermal conductivity
ℓ	m	volume flow length
M	kg	mass in control volume
Nu		Nusselt number
n	1/m^2h	number flux
P	kg/m^2	pressure
Pr		Prandtl number
Q	kcal/hr	heating power into control volume
$\dot{Q}$	kghr/m^4	mass transfered from liquid phase to vapor phase in unit volume of two-phase mixture
Re		Reynolds number
S	m^2	cross section of flow channel
T	C	temperature (except for the calculational results)
ΔT_{sub}	C	subcooling temperature
U	kcal	internal energy in control volume
u	m/hr	fluid velocity
V	m^3	volume
W	kghr/m^2	mass flow rate
We		Weber number
Wec	critical Weber number	
x	quality	

X_{tt}		Lockhart-Martinelli's parameter defined by eq. (3.37)
Z	m	elevation
α		void fraction
γ		ratio surface area to the area of flow channel wall
Δu	m/hr	slip velocity
ε	$kcal/m^2hrK^4$	Stefan-Boltzmann Constant
μ	$kghr/m^2$	dynamic viscosity
ρ	kgh^2/m^4	density
σ	kg/m	surface tension
τ	kg/m^2	shearing stress
Φ_{2p}		two-phase multiplier for increased friction in eq. (3.78)
ϕ	$kcal/m^2hr$ or Btu/ft^2hr (Table 3.2)	heat flux