

Development of the Unified Version of COBRA/RELAP5

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Abstract

The COBRA/RELAP5 code, an integrated version of the COBRA-TF and RELAP5/MOD3 codes, has been developed for the realistic simulations of complicated, multi-dimensional, two-phase, thermal-hydraulic system transients in light water reactors. Recently, KAERI developed an unified version of the COBRA/RELAP5 code, which can run in serial mode on both workstations and personal computers. This paper provides the brief overview of the code integration scheme, the recent code modifications, the developmental assessments, and the future development plan.

I. Introduction

The state-of-the-art system analysis codes¹⁻⁶ have multidimensional thermal-hydraulic modules. KAERI also has developed a multidimensional system analysis code COBRA/RELAP5⁷⁻⁹, which is an integrated version of the COBRA-TF and RELAP5/MOD3 codes.

The purpose of the COBRA/RELAP5 code integration was to develop a new code that combines the excellent features of each code, i.e., the realistic three-dimensional reactor vessel hydrodynamic module of COBRA-TF and the very useful, general features of RELAP5/MOD3. This approach - to link the existing codes - is very reasonable and economical to take advantage of the existing verified codes, yielding a new code with scope of applications far beyond each of individual codes¹⁰.

The earlier version^{7,8} of COBRA/RELAP5 runs in process-level parallel computation (PLPC) mode on workstations using the so-called "shared memory" and "IPC (Inter-Process Control)" technique⁹. This linking technique utilizes machine-dependent functions and, thus, limits the code portability to some workstations (WSs). To overcome the problem, we have developed a unified version of COBRA/RELAP5, running in serial mode, and converted the code language into the standard Fortran 90 to have portability on both WSs and personal computers (PCs). In addition to these, the input processing subroutines have been unified so that the code can be used more user-friendly and consistently.

This paper provides the brief overview of the COBRA/RELAP5 code integration scheme, the recent code modifications, and the developmental assessments. This paper also addresses the area of future improvement in the COBRA/RELAP5 code.

II. Integration of the RELAP5 and COBRA-TF Codes

The COBRA/RELAP5 code simulates a flow system with a three-dimensional COBRA-TF region and several one-dimensional RELAP5 regions. For instance, the reactor vessel of a pressurized water reactor (PWR) can be a three-dimensional region, and the primary loops and the secondary systems become one-dimensional regions. The thermal-hydraulic behavior of each region is modeled by either COBRA-TF or RELAP5/MOD3.2, however, the system pressure matrix equations of the hydrodynamic models in the two codes are integrated and solved simultaneously. Thus, the code unification is focused on the integration of the hydrodynamic models.

II.1. Hydrodynamic Models of the Two Codes

The RELAP5⁵ (hereinafter, RELAP5 means RELAP5/MOD3.2) code employs a *one-*

dimensional, two-fluid model for two-phase flows. The two-fluid equations consist of (a) two phasic continuity equations, (b) two phasic momentum equations, (c) two phasic energy equations, and (d) a continuity equation of noncondensable gases. The COBRA-TF⁶ adopts a *three-dimensional, two-fluid, three-field model*. The field equations are (a) four continuity equations for vapor, continuous liquid, entrained liquid droplets, and noncondensable gases, (b) three momentum equations for continuous liquid, entrained liquid, and the mixture of vapor and noncondensable gases (it is assumed that vapor and noncondensable gases are in thermal and mechanical equilibrium), (c) two energy equations for the mixture of vapor and noncondensable gases, and the mixture of continuous and entrained liquid (it is assumed that continuous and entrained liquid are in thermal equilibrium).

For closure of the system of equations in the two codes, constitutive relations are incorporated. These include the state-of-the-art physical models for the interfacial mass transfer, the interfacial forces, the wall drag, the wall and interfacial heat transfer, and the thermodynamic properties of water. In COBRA-TF, the rate of entrainment/deposition and a vapor/droplet interfacial area transport equation are also included.

Comparing with the COBRA-TF hydrodynamic field equations, the RELAP5 does not have the entrained liquid droplet field, however, the nonvolatile component such as boron is added. Thus, the following assumptions apply for the COBRA/RELAP5 code integration:

- Nonvolatile components do not exist in the flow system.
- The entrained liquid and continuous liquid flowed from the COBRA-TF to RELAP5 region are agglomerated into the liquid phase in the RELAP5 region. The liquid phase flowed from the RELAP5 to COBRA-TF region is treated as the continuous liquid phase in the COBRA-TF region.

The vapor phase and noncondensable gases of each region are treated as continuum across the regions.

II.2. Numerical Solution Schemes of the Two Codes

The numerical solution schemes for the hydrodynamic models of the two codes are basically the same but slightly different in calculational sequence^{5,6}. Both codes use a semi-implicit, finite-difference method based on a staggered-grid mesh and donor cell scheme.

In both COBRA-TF and RELAP5, the phasic momentum equations are solved first to represent the phasic velocity (phasic mass flow rate in COBRA-TF) at junction j in terms of pressures of the adjoining cells K and L :

$$V_{k,j}^{n+1} = \alpha_{k,j} + \beta_{k,j} (\delta P_K - \delta P_L), \quad (1)$$

where the coefficients α and β are explicitly obtained from old time-step values, and

$$\delta P = P^{n+1} - P^n, \quad k = \begin{cases} f \text{ or } g \text{ in RELAP5} \\ l, v \text{ or } e \text{ in COBRA-TF} \end{cases}$$

Table 1. The FDEs and independent scalar variables of the two codes

Code	COBRA-TF	RELAP5/MOD3.2
FDEs	Continuity eq. of noncondensable gases Continuity eq. of continuous liquid Energy eq. of vapor Energy eq. of continuous and entrained liquid Continuity eq. of entrained liquid Continuity eq. of vapor	Density eq. of noncondensable gases Energy eq. of vapor Energy eq. of liquid Difference density eq. Sum density eq.
Independent scalar variables	$\alpha_v P_g, \alpha_v, \alpha_v h_v, (1 - \alpha_v) h_l, \alpha_e, \text{ and } P$ ($\alpha_l + \alpha_v + \alpha_e = 1$)	$X_n, U_g, U_f, \alpha_g, \text{ and } P$ ($\alpha_f + \alpha_g = 1$)

Next, the FDEs (Finite Difference Equations) of the mass and energy equations for a hydrodynamic cell are linearized with respect to the independent scalar variables. The FDEs are ordered in the sequence shown in Table 1 and are rearranged to establish the so-called "cell Jacobian matrix" equation, where the unknown velocities are replaced with Eq. (1). Multiplying the cell Jacobian matrix equation by its inverse matrix, the bottom row of the matrix equation results in a single equation involving just pressures. This is done for each cell and, finally, one can set up the "system pressure matrix" equation:

$$\underline{A} \delta \underline{P} = \underline{b}, \quad (2)$$

where \underline{A} is an $N \times N$ matrix (N is the number of computational cells). The pressure variations are obtained by solving Eq. (2), and are substituted into Eq. (1) to obtain the new time-step velocities (or mass flow rates). Further back-substitutions are done to obtain the variations of other independent variables. The remaining numerical procedures are then followed until the completion of a time-step calculation.

II.3. Integration of the System Pressure Matrices in COBRA/RELAP5

Consider a flow system that is divided into a COBRA-TF and several RELAP5 regions with NC interface junctions. For convenience, let us define C_i and R_i as the index numbers of i -th interfacing cells in the COBRA-TF and RELAP5 regions, respectively. Basic concepts of the integration are

- In RELAP5, cell C_i is treated as a pseudo "time-dependent volume (*tm dpvol*)", of which scalar variables are updated every time-step by COBRA-TF. The momentum equations at the interface junction are solved in RELAP5. It is assumed that vapor and entrained droplets at the interface are in mechanical equilibrium (*i.e.*, $V_e = V_g$).
- In COBRA-TF, cell R_i is implicitly regarded as a sink. When fluid enters cell C_i from cell R_i , donor quantities through the interface are provided by RELAP5.
- The system pressure matrices, which are set up in each code, are coupled via the momentum modeling at the interfaces and solved simultaneously.

The modeling of the momentum balance at the interface junction between cell C_i and R_i is performed in RELAP5, where the old time-step variables of cell C_i are transferred every time-step from COBRA-TF. Then, the phasic velocity at the i -th interface junction is given by

$$V_{k,i}^{n+1} = \alpha_{k,i} + \beta_{k,i} (\delta P_{C_i} - \delta P_{R_i}). \quad (3)$$

Effects of the connections should be taken into account for the conservation of momentum in the COBRA-TF region. For simplicity, it was assumed that cell R_i is normal to the interface surface and that the connection is either vertical or transverse.

Normally, the new time-step pressure at a "*tm dpvol*" is known in RELAP5. However, in COBRA/RELAP5, it is still a unknown variable. Thus, the RELAP5 source program should be modified appropriately when solving the mass and energy equations of a cell connected to the COBRA-TF region. This results in a modified system pressure matrix equation:

$$\underline{A}_R \delta \underline{P} = \underline{b}_R + \sum_{j=1}^{NC} [\underline{r}_{f,j} V_{f,j}^{n+1} + \underline{r}_{g,j} V_{g,j}^{n+1}] \quad (4)$$

where \underline{r}_f and \underline{r}_g are element vectors, of which all elements are zero except one. Likewise, the COBRA-TF system pressure equation also changes as follows:

$$\underline{A}_C \delta \underline{P} = \underline{b}_C + \sum_{j=1}^{NC} [\underline{c}_{f,j} V_{f,j}^{n+1} + \underline{c}_{g,j} V_{g,j}^{n+1}] \quad (5)$$

where \underline{c}_f and \underline{c}_g are element vectors. By substituting the unknown velocities in the RHS of

Eqs. (4) and (5) with Eq. (3), equations (4) and (5) are coupled; that is, the system pressure matrix equations are integrated^{7,9}. New time-step pressures are obtained by solving this coupled system pressure matrix equation. The phasic velocities at the interfaces are then obtained by back-substitutions of Eq. (3). The remaining numerical sequences are performed in each code.

II.4. Time Advancement Control and Other Modifications for Code Unification

In the previous PLPC version of COBRA/RELAP5^{7,9}, a supervisory program COBLAP was used to synchronize time advancement and data transfer between COBRA-TF and RELAP5 processors. But, as mentioned earlier, this scheme has been replaced with a serial processing scheme; (a) COBLAP program was removed, (b) the RELAP5 subroutines were modified to sequentially call COBRA-TF subroutines. So, three processors are replaced by single processor (RELAP5). This modification eliminates the machine-dependent IPC functions and, as a result, greatly improves the code portability.

In parallel with the above modification, the input processing subroutines have been changed. In the previous version, the COBRA-TF and RELAP5 input data are separately prepared and processed in each code. Furthermore, an additional interface input data is needed for the COBLAP processor. This feature, three input data and three processors, makes the users somewhat cumbersome. To enhance the user-friendliness of COBRA/RELAP5, the input processing subroutines of COBRA-TF (and COBLAP) have been unified with those of RELAP5 using the INP package¹¹ so that three input files can be put into single file, where all input forms are similar to those of RELAP5. As a result, one input file and one processor are needed for a COBRA/RELAP5 execution.

To implement the above modifications, 29 existing subroutines were modified and 16 subroutines were created. All the programs are written/compiled in Fortran 90.

III. Developmental Assessments

The assessment strategy of COBRA/RELAP5 may be different from those of other best-estimate codes, because this code is an integrated version of the existing verified codes. First, the code should be numerically benchmarked whether the integration scheme and its implementation are valid. Then, the code performance should be physically assessed using various separate- and integral-effect tests.

Since both COBRA-TF and RELAP5 are respectively verified codes for separate-effect phenomena, their results can be deserved as applicable to COBRA/RELAP5. However, for some separate-effect phenomena, such as multidimensional two-phase flows within the PWR downcomer and upper plenum, further assessments of COBRA-TF are required. At present, a full assessment matrix is under development.

Near-term objective of the COBRA/RELAP5 code development is to have the improved predictive capability of multi-dimensional phenomena of large-break LOCA so that the code assessment will focus on this area. The code development and assessment will be extended to the realistic simulations of a wide range of system transients, including operational transients, design basis accidents, and beyond design basis events of advanced reactors as well as the existing commercial nuclear power plants.

In the following sections, single channel tests and manometric flow oscillation problem are tested as numerical benchmark problems. Then, the simulation results (on Hewlett Packard HC110 WS) of the LOFT L2-3 large-break loss-of-coolant experiment are briefly introduced.

III.1. Single Channel Tests

To check whether mass, energy, and momentum at the interface cells of the COBRA-TF and RELAP5 regions are conserved, several single channel tests are performed. Consider a

vertical channel, of which inner diameter and length are 0.1 and 4.8 m, respectively. As shown in Fig. 1, the flow in the channel is simulated using four models C, R/C, R/C/R, and R. In all the models, the length of a cell is 0.2 m.

The inlet flow and the exit pressure are specified as boundary conditions (BCs). Table 2 summarizes the BCs and the steady-state calculation results. It can be seen that the mass,

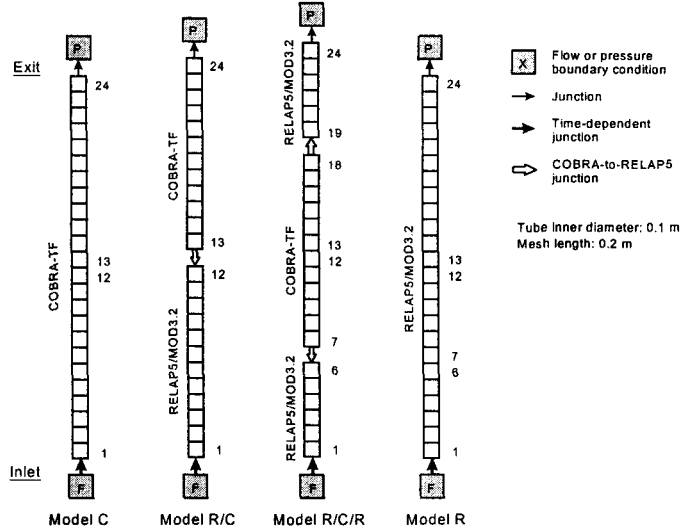


Fig. 1. Schematic of the COBRA/RELAP5 single channel tests

Table 2. The BCs and calculation results of the single channel tests

(a) Case A: $P_{exit} = 0.2 \text{ MPa}$, $W_{inlet} = 0 \text{ kg/s}$, $U_{inlet} = 418.2 \text{ kJ/kg}$ (subcooled water)

Model ^a		C	R/C	R/C/R	R
Mass flow error (%) ^b		0.0	0.0	0.0	0.0
Internal energy increase (%) ^c		0.0	0.0024	0.0024	0.0
Differential pressure (kPa) ^d	$dP_{1,24}$	43.13	42.23	41.35	43.17
	$dP_{12,13}$	1.875	0.936	1.875	1.875

(b) Case B: $P_{exit} = 0.2 \text{ MPa}$, $W_{inlet} = 10 \text{ kg/s}$, $U_{inlet} = 418.2 \text{ kJ/kg}$ (subcooled water)

Model ^a		C	R/C	R/C/R	R
Mass flow error (%) ^b		0.0	0.001	-0.015	0.0
Internal energy increase (%) ^c		0.0	0.092	0.0072	0.0
Differential pressure (kPa) ^d	$dP_{1,24}$	43.98	43.08	42.12	44.09
	$dP_{12,13}$	1.917	0.959	1.916	1.917

(c) Case C: $P_{exit} = 12 \text{ MPa}$, $W_{inlet} = 5 \text{ kg/s}$ (sat. water 4.5 kg/s; sat. steam 0.5 kg/s)

Model ^a		C	R/C	R/C/R	R
Mass flow error (%) ^b		0.0	0.002	-0.018	0.0
Internal energy increase (%) ^c		0.0	0.078	0.0065	0.0
Differential pressure (kPa) ^d	$dP_{1,24}$	17.857	18.03	17.60	19.2
	$dP_{12,13}$	0.779	0.443	0.765	0.835

(d) Case D: $P_{exit} = 15 \text{ MPa}$, $W_{inlet} = 2 \text{ kg/s}$, $U_{inlet} = 2490.4 \text{ kJ/kg}$ (superheated steam)

Model ^a		C	R/C	R/C/R	R
Mass flow error (%) ^b		0.0	0.001	0.065	0.0
Internal energy increase (%) ^c		0.0	-0.0102	0.008	0.0
Differential pressure (kPa) ^d	$dP_{1,24}$	4.40	4.357	4.20	4.50
	$dP_{12,13}$	0.192	0.053	0.193	0.20

^aSee Fig.1, ^b $(W_{exit} - W_{inlet})/W_{inlet}$, ^c $(U_{exit} - U_{inlet})/U_{inlet}$, ^d $dP_{i,j} = P_i - P_j$.

energy, and momentum are conserved the interfaces. Very small errors in mass and energy (maximum 0.092 %) appear in the results of Model R/C and R/C/R. This inconsistency is due to different equations of state (EOSs) used in the COBRA-TF and RELAP5 of the COBRA/RELAP5. Momentum error also occurs across the interfaces. This occurs due to the fact that, when RELAP5 of the COBRA/RELAP5 solves the momentum equations at the interface, cell C_i (e.g., Cell 13 in Model R/C in Fig. 1) is replaced with a *tm dpvol*, where gravity and wall friction terms are ignored. These deficiencies are currently being corrected. Nevertheless, it is shown that the COBRA/RELAP5 integration scheme works well.

III.2. Manometric Flow Oscillations

This problem was simulated by both COBRA/RELAP5 and RELAP5/MOD3.2. Figure 2(a) shows the nodalizations. Each of the two vertical channels is divided into 24 uniform-length cells (0.1 m dia., 0.2 m length). Initially, 70 % of the left channel (component 100) is filled with saturated water at 15 MPa and others with saturated steam.

At $t=0$ s, a transient calculation begins, which results in manometric flow oscillations. As shown in Fig. 2(b), the results show good agreements with each other. Especially, the frequencies of the flow and collapsed water level oscillations are exactly the same. However the amplitudes are a little different due to the different EOSs and pressure drop characteristics in the two codes.

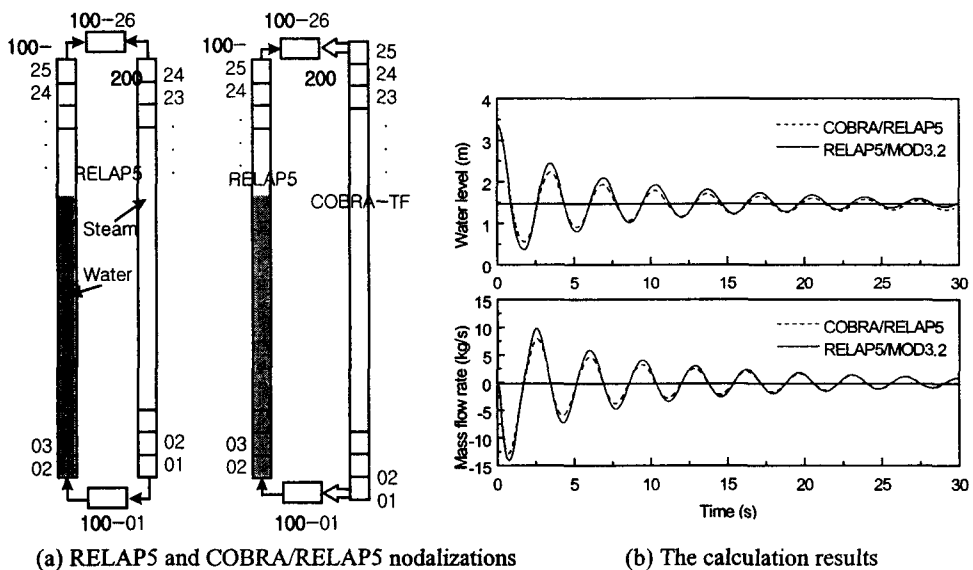


Fig. 2. Manometric flow oscillation problem

III.3. The LOFT L2-3 Large-Break Loss-of-Coolant Experiment

The LOFT facility was a 50 MWt PWR to simulate the major components and system responses of a four-loop commercial PWR during a LOCA^{12,13}. The reactor system included a 1.68 m long nuclear core arranged in nine fuel rod bundles.

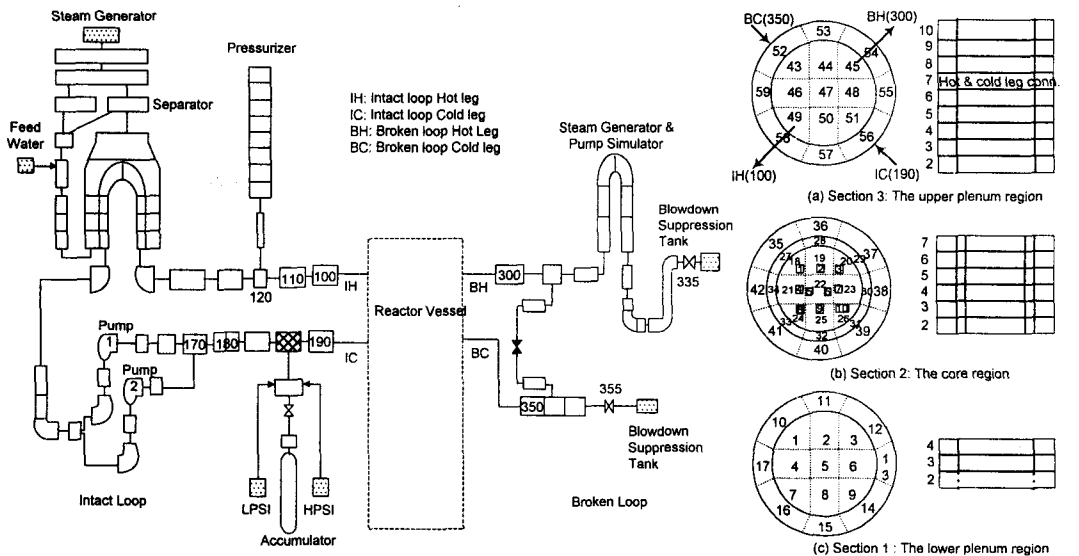
Figure 3(a) shows the RELAP5 region input model, consisting of 92 hydrodynamic cells, 93 junctions, and heat structures. There are four COBRA-TF to RELAP5 junctions. For the COBRA-TF vessel input model, relatively fine three-dimensional mesh was used in order to evaluate the overall accuracy and computational speed. The outer shells of the three sections in Fig. 3(b), consisted of eight channels, represent the downcomer. The core region is modeled by 9 channels, each of which represents the flow channel with a fuel bundle. The annular bypass region is represented by 8 channels like the downcomer. Each of channels 18

through 26 contains a "rod" component, which represents the average rod of each fuel bundle. But, channel 22 contains additional "rod" to simulate the hot rods. The core power is given as a function of time.

The transient simulation begins by simultaneous opening of valves 335 and 355 in Fig. 3(a). Figure 4 shows the pressurizer pressure behaviors. COBRA/RELAP5 reasonably predicts the pressure transient, but tends to slightly underpredict later.

In the experiment, an early clad rewet was observed which was caused by the continuous pump operation¹³. This phenomena is described well as shown in Fig. 5. In general, COBRA/RELAP5 predicts the cladding temperature behaviors reasonably well, but the blowdown quenching at 0.64 m above the bottom of the core is predicted a little later and, after then, the heatup is also delayed, which affects the consequent reflood heat transfer. Further works are planned to investigate these findings, and the details of the results are provided in Ref. 9.

It is apparently shown from the results that the COBRA/RELAP5 integration scheme is working well in a three-dimensional loop application, where the system pressure matrix structure is quite different from that of one-dimensional cases. Furthermore, it is shown that the results of COBRA/RELAP5 are in good agreement with the experimental data.



(a) RELAP5 nodalization for the system (b) COBRA-TF nodalization for the vessel
 Fig. 3. COBRA/RELAP5 nodalization for the LOFT L2-3 simulation

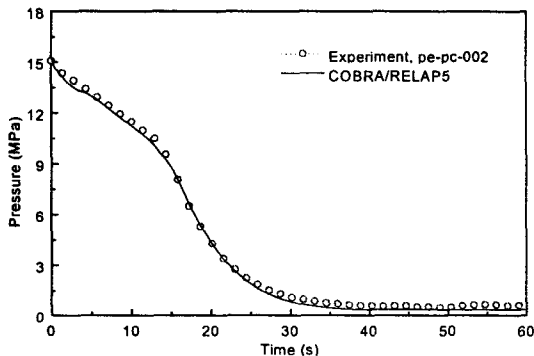


Fig. 4. Pressurizer pressure behaviors

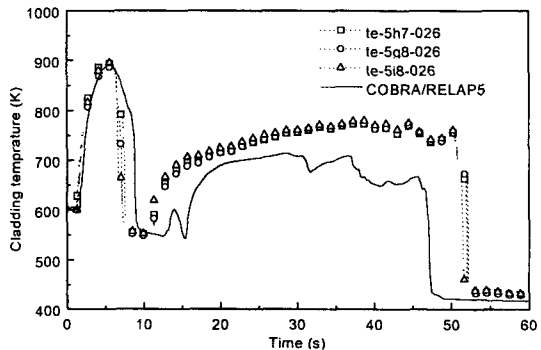


Fig. 5. Hot rod cladding temperature behaviors at $z=0.64$ m.

III.4. Computational Speed

The calculations were performed on both a Hewlett Packard HC110 WS and a PC with 166 MHz Pentium processor. For the LOFT L2-3 (45 s) transient simulation, the computation times on the WS and PC were ~16,700 s and ~82,000 s, respectively.

IV. Conclusions

The unified version of COBRA/RELAP5 code that can run in serial mode on both PC and WS has been developed by modularizing COBRA-TF into RELAP5/MOD3.2. Comparing with the previous PLPC version, the unified version has been greatly improved in terms of the code portability and user-friendliness.

To verify the code integration scheme as well as to evaluate the overall performance of the unified code, the developmental assessments have been conducted. The results can be summarized as follows:

- From the single channel tests, the integration scheme was proven to be valid. Minor problems were identified; mass and energy error due to the different EOSs, and momentum error due to the "time-dependent volume" treatment of cell C_i in the RELAP5 side. The root causes were clearly addressed.
 - It was shown, from the manometric flow oscillation and LOFT L2-3 simulations, that the code integration scheme is working even for the complicated applications.
 - In general, the simulation results showed good agreement with the experimental data.
- Therefore, the COBRA/RELAP5 code can be a promising tool for the analysis of multi-dimensional, two-phase flow system transients.

For further improvements of the COBRA/RELAP5 code, a systematic unification and assessment programs are planned. The EOSs, output/restart, heat structure, fuel and kinetics models are the candidate area of the code unification. And, various code assessment programs are scheduled using KAERI thermal-hydraulic data bank.

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