Development and Assessment of the COBRA/RELAP5 Code

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The COBRA/RELAP5 code has been developed to combine the realistic three-dimensional reactor vessel model of COBRA-TF with RELAP5/MOD3.2, thus to produce an advanced system analysis code with a multidimensional thermal-hydraulic module. This paper provides the integration scheme of the two codes. The results of developmental assessments are also provided, which include single channel tests, manometric flow oscillation problem, THTF Test 105, and LOFT L2-3 large break loss-of-coolant experiment. From the single channel tests, the integration scheme was proven to be valid. Other simulation results showed good agreement with the experimental data. The computational speed was also satisfactory. Therefore, the assessment confirmed that the COBRA/RELAP5 code can be a promising tool for analysis of complicated, multidimensional, two-phase flow system transients.

KEYWORDS: best-estimate system codes, computer codes, COBRA-TF, RELAP5/MOD3.2, COBRA/RELAP5, code integration, three-dimensional thermal-hydraulic module, inter-process communication, parallel processing, accuracy

I. INTRODUCTION

The state-of-the-art system analysis codes, such as TRAC-PF1(1), CATHARE2(2), REFLA/TRAC(3)(4), ATHLET(5), and WCOBRA/TRAC(6), have multidimensional thermal-hydraulic modules. KAERI has developed the COBRA/RELAP5 code(7), a merged version of the COBRA-TF and RELAP5/MOD3 code, to produce an advanced system analysis code with a multidimensional module.

Several efforts to link the existing thermal-hydraulic code with others have been made, such as RELAP5/COSBWR(8), RELAP5/CONTAIN(9)(10), and RELAP5/CONTEMPT4(11). This approach—to link the existing code with others—is very reasonable and economical to use the advantage of the existing verified codes, yielding a new code system with scope of applications far beyond that of individual codes(8). The purpose of the COBRA/RELAP5 integration is to combine the excellent features of the two codes, that is, the realistic three-dimensional reactor vessel hydrodynamic model of COBRA-TF and the very useful general features of RELAP5/MOD3.2. Basic guideline of the code integration is that the inherent features of each code are not to be degraded so that the users can fully utilize the features available from both codes. The concept and linking technique of COBRA/RELAP5 are similar to examples above, but in COBRA/RELAP5, the system pressure matrix equations of the hydrodynamic models in the two codes are merged and solved simultaneously. Therefore, the COBRA/RELAP5 is a fully-coupled single code executed by two child processes, that is, the COBRA-TF and the RELAP5 processes.

To integrate the two codes on a workstation, the so-called “shared memory” and “IPC (Inter-Process Control)” technique(12) are used. A supervisory program, named COBLAP, controls the communication between the two child processes of COBRA-TF and RELAP5 to synchronize the integrated calculations. The integrated code runs in a parallel mode on workstations equipped with multiple CPUs (Central Processing Units).

This paper provides the COBRA/RELAP5 code integration scheme and the results of developmental assessments including single channel tests, manometric flow oscillation problem, THTF (Thermal-Hydraulic Test Facility) Test 105, and LOFT (Loss-Of-Fluid Test) L2-3 large break loss-of-coolant experiment. This paper also addresses the area of the future improvements in the COBRA/RELAP5 code.

II. COBRA/RELAP5 CODE INTEGRATION

The RELAP5 code(13) is a general, one-dimensional system analysis code. This code has a number of special features that have proven to be very useful in thermal-hydraulic analysis of PWRs (Pressurized Water Reactors), such as an accumulator component, a centrifugal pump model, choked flow, control systems, reactor kinetics with reactivity feedback, various valves, a trip system,
and others. One of the limitations in the RELAP5 fluid model is the restriction of one liquid field; during the reflood phase of a LOCA (Loss-Of-Coolant Accident), liquid film and liquid droplets show quite different behaviors. Whereas, the COBRA-TF code was developed for realistic simulations of the reactor vessel thermal-hydraulics during a LOCA. Its hydrodynamic model employs a three-dimensional, two-fluid, three-field representation of two-phase flow. The three-dimensional feature of COBRA-TF allows extremely flexible noding of the reactor vessel and, thus, more efficient, realistic simulations. The heat transfer models of COBRA-TF were focused on the reflood phase of a LOCA.

The flow system simulated with COBRA/RELAP5 is divided into a three-dimensional COBRA-TF region and several one-dimensional RELAP5 regions. For instance, the reactor vessel of a PWR can be a COBRA-TF region, and the primary loops and the secondary systems become RELAP5 regions. In COBRA/RELAP5, the thermal-hydraulic behavior of each region is modeled by either COBRA-TF or RELAP5/MOD3.2, however, the system pressure equations of the hydrodynamic models in two codes are merged and solved simultaneously. Thus, the integration of the two codes is focused on the hydrodynamic model and its numerical solution scheme.

1. Hydrodynamic Models

The RELAP5 (hereinafter, RELAP5 means RELAP5/MOD3.2) code employs a one-dimensional, transient, 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-TF adopts a three-dimensional, two-fluid, three-field model on rectangular Cartesian or sub-channel coordinates. 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 model, the RELAP5 does not model the entrained liquid droplet field, however, the nonvolatile component such as boron is added. Thus, the following assumptions apply for the COBRA/RELAP5 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 the two regions are treated as continuum across the regions.

2. Numerical Solution Schemes

The numerical solution schemes for the hydrodynamic models of the two codes are basically the same but slightly different in calculational sequence. 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 $L$:

$$V_{k,j}^{n+1} = \alpha_j + \beta_j (\delta P_K - \delta P_L),$$

where the coefficients $\alpha$ and $\beta$ are explicitly obtained from old time-step values, and

<table>
<thead>
<tr>
<th>Code</th>
<th>COBRA-TF</th>
<th>RELAP5/MOD3.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>FDEs</td>
<td>Continuity equation of noncondensable gases (CN)</td>
<td>Density equation of noncondensable gases</td>
</tr>
<tr>
<td></td>
<td>Continuity equation of continuous liquid (CL)</td>
<td>Energy equation of vapor</td>
</tr>
<tr>
<td></td>
<td>Energy equation of vapor (EV)</td>
<td>Energy equation of liquid</td>
</tr>
<tr>
<td></td>
<td>Energy equation of continuous and entrained liquid (EL)</td>
<td>Difference density equation</td>
</tr>
<tr>
<td></td>
<td>Continuity equation of entrained liquid (CE)</td>
<td>Sum density equation</td>
</tr>
<tr>
<td></td>
<td>Continuity equation of vapor (CV)</td>
<td></td>
</tr>
<tr>
<td>Independent variables</td>
<td>$\alpha_v, P_g, \alpha_v, \alpha_v h_v, (1 - \alpha_v) h_i, \alpha_e,$ and $P$</td>
<td>$X_n, U_g, U_f, \alpha_g,$ and $P$</td>
</tr>
<tr>
<td></td>
<td>$(\alpha_v + \alpha_v + \alpha_e = 1)$</td>
<td>$(\alpha_f + \alpha_e = 1)$</td>
</tr>
</tbody>
</table>
δP = P^{n+1} - P^n, \\
k = \begin{cases} 
\text{f or g in RELAP5} \\
\text{l, v or e in COBRA-TF.}
\end{cases}

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 as follows:

RELAP5 (Ref. 13, vol. 1, p. 3.32),

\begin{equation} \tag{2a} 
\begin{bmatrix} 
\tau_{11} & \tau_{12} & \cdots & \tau_{15} \\
\tau_{21} & \cdots & \tau_{25} \\
\tau_{31} & \cdots & \tau_{35} \\
\vdots & \cdots & \vdots \\
\tau_{51} & \cdots & \tau_{55} \\
\end{bmatrix} \begin{bmatrix} 
\delta X_n \\
\delta U_g \\
\delta U_f \\
\delta \alpha_g \\
\delta \alpha_f \\
\end{bmatrix} = \frac{g^1}{g_{j+1}} + \frac{f^1}{f_{j+1}} + \frac{g^2}{g_j} + \frac{f^2}{f_j}, \tag{2a}
\end{equation}

where \( g^1 = \frac{f^1}{f_j} = \frac{g^2}{g_j} = \frac{f^2}{f_j} \) are coefficient vectors.

-COBRA-TF (Ref. 14, vol. 2, p. 4.4),

\begin{equation} \tag{2b} 
\begin{bmatrix} 
E_{CN} \\
E_{CL} \\
E_{EV} \\
E_{EL} \\
E_{EB} \\
E_{CV} \\
\end{bmatrix} \begin{bmatrix} 
\delta(\alpha_v P_g) \\
\delta \alpha_v \\
\delta(\alpha_v h_v) \\
\delta((1 - \alpha_v) h_j) \\
\delta P_j \\
\delta P_{j,1} \\
\delta P_{j,NC} \\
\end{bmatrix} = \begin{bmatrix} 
\delta \alpha_v \\
\delta \alpha_v \\
\delta \alpha_v \\
\delta \alpha_v \\
\delta \alpha_v \\
\delta \alpha_v \\
\end{bmatrix}
\end{equation}

where \( NC \) is the number of adjoining cells to cell \( J \). In Eq. (2b), the unknown phasic mass flow rates are already substituted with Eq. (1). Multiplying Eq. (2a) by the inverse of the cell Jacobian matrix, the bottom row results in a single equation involving just pressures, where the unknown velocities in the RHS (Right-Hand Side) are replaced with Eq. (1). Equation (2b) also can be reduced using the Gaussian elimination, of which the bottom row results in an equation involving just pressures. This is done for each cell and, finally, one can set up the so called system pressure matrix equation:

\[ \Delta P = b. \] \tag{3}

where \( \Delta \) is an \( N \times N \) matrix (\( N \) is the number of computational cells). The pressure variations are obtained by solving Eq. (3), 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. After that, the remaining numerical procedures are performed in each code until the completion of a time-step calculation. However, because these parts are not affected during the integration process, further descriptions are not provided.

3. Integration of the System Pressure Matrices and Reduction

Consider a flow system that is divided into a COBRA-TF and several RELAP5 regions with \( NR \) interface junctions. For convenience, let us define \( Ci \) and \( Ri \) 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 \( Ci \) is treated as a pseudo "time-dependent volume (tmdpvol)" of which scalar variables are updated every time-step by COBRA-TF. The momentum equations at the interface junction are solved in RELAP5. Here, positive flow at the interface is defined as the flow from cell \( Ci \) to cell \( Ri \). 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 \( Ri \) is implicitly regarded as a sink. When fluid enters cell \( Ci \) from cell \( Ri \), 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 (For computational efficiency, the coupled matrix is solved in a reduced form).

The modeling of the momentum balance at the interface junction from the cell \( Ci \) and \( Ri \) is performed in RELAP5, where the old time-step variables of cell \( Ci \) are transferred from COBRA-TF. Then, the phasic velocity at the \( i \)-th interface junction is given by

\[ V_{ki,i}^{n+1} = \alpha_{ki,i} + \beta_{ki,i}(\delta P_{Ci} - \delta P_{Ri}). \tag{4} \]

When RELAP5 establishes the FDEs of momentum equations for a junction that connects a tmdpvol and a normal cell, the momentum balance at the tmdpvol side is neglected. Therefore, the treatment of cell \( Ci \) as a tmdpvol evokes a momentum error at the interface, which will be discussed later.

Effects of the connections should be taken into account for the conservation of momentum in the COBRA-TF region. For simplicity, it is assumed that cell \( Ri \) is normal to the interface surface and that the connection is either vertical or transverse. When cell \( Ci \) is a full three-dimensional cell, the five momentum cells adjacent to the interface are influenced by the connection of cell \( Ri \).

Normally, the new time-step pressure at "tmdpvol" is known in RELAP5. However, in COBRA/RELAP5, it is still an unknown variable and, thus, the RELAP5 source program should be modified appropriately when solving the mass and energy equations. Consider that the junction \( j \) in Eq. (2a) is a \( i \)-th interfacing junction from cell \( Ci \) to \( Ri \), and the junction \( j + 1 \) is a normal RELAP5 junction from cell \( Ri \) to \( K \). Then, Eq. (2a) for cell \( Ri \) is represented by
Rearranging the terms including \( \delta P_{Ri} \) in the RHS of Eq. (5) to the left-hand side gives

\[
\begin{bmatrix}
    r_{11} & r_{12} & \cdots & r_{15} \\
    r_{21} & \cdots & r_{25} \\
    r_{31} & \cdots & r_{35} \\
    r_{41} & \cdots & r_{45} \\
    r_{51} & \cdots & r_{55}
\end{bmatrix}
\begin{bmatrix}
    \delta X_n \\
    \delta U_g \\
    \delta U_f \\
    \delta \alpha \\
    \delta P
\end{bmatrix}_R = \delta P_{Ri} + \frac{g^2_{Ri}}{L_{Ri}} \{ \alpha_{g,j+1} + \beta_{g,j+1}(\delta P_{Ri} - \delta P_K) \} \\
+ \frac{f^2_{Ri}}{L_{Ri}} \{ \alpha_{f,j} + \beta_{f,i}(\delta P_{Ci} - \delta P_{Ri}) \} \\
+ \frac{g^2_{Ri}}{L_{Ri}} \{ \alpha_{g,i} + \beta_{g,i}(\delta P_{Ci} - \delta P_{Ri}) \} \\
+ \frac{f^2_{Ri}}{L_{Ri}} \{ \alpha_{f,i} + \beta_{f,i}(\delta P_{Ci} - \delta P_{Ri}) \}. \tag{5}
\]

Multiplying Eq. (6) by the inverse of the cell Jacobian matrix, the bottom row results in a single equation involving just pressures at cell \( K, Ri, \) and \( Ci \). This procedure is done for all the RELAP5 cells connected with the COBRA-TF region. The resulting pressure equations are replaced with the corresponding rows of the RELAP5 system pressure equation. Then, the system pressure equation comes into additional terms related with \( \delta P_{Ci} \):

\[
\Delta_R \delta P = b_R + \sum_{i=1}^{NR} \gamma_i \delta P_{Ci}, \tag{7}
\]

where \( \gamma_i \) is a coefficient vector, of which all elements except one are zeros. Figure 1 illustrates an example of the COBRA/RELAP5 nodalization and its system pressure matrices. In that case, the coefficient vectors \( \gamma_i \) are given by

\[
\gamma_1 = (0, 0, 0, 0, 0, 0, 0, x)^T, \\
\gamma_2 = (x, 0, 0, 0, 0, 0, 0, 0)^T,
\]

where \( x \) is a nonzero element. Multiplying Eq. (7) by the inverse of \( \Delta_R \) yields

\[
\delta P = \Delta^{-1}_R \delta P_R + \sum_{i=1}^{NR} (\Delta^{-1}_R \gamma_i) \delta P_{Ci}.
\]

Since \( \delta P_{Ri} \) is also an element of \( \delta P \), \( \delta P_{Ri} \) can be written as

\[
\delta P_{Ri} = \xi_i + \sum_{j=1}^{NR} \eta_{ij} \delta P_{Cj}.
\]
where the second term in the RHS indicates the convection terms (from cell \( C_i \) to cell \( R_i \)) and \( D_{Ci} \) is a diagonal matrix. The diagonal elements \( d_i \) of \( D_{Ci} \) are obtained by the donor cell scheme as follows:

\[
\begin{align*}
  d_1 &= \left\{ \begin{array}{ll}
    (\alpha_e \rho g h_{i+C1})_{C1} & \text{if } V_{g,i}^n \geq 0 \\
    (X_{n} \alpha_e \rho g)_{R1} & \text{if } V_{g,i}^n < 0
  \end{array} \right.
  \\
  d_2 &= \left\{ \begin{array}{ll}
    (\alpha_f \rho)_{C1} & \text{if } V_{f,i}^n \geq 0 \\
    (\alpha_f \rho f)_{R1} & \text{if } V_{f,i}^n < 0
  \end{array} \right.
  \\
  d_3 &= \left\{ \begin{array}{ll}
    (\alpha_c (\rho g h_{i+C2} + \rho u_{i+C2} h_{i+C2}))_{C1} & \text{if } V_{g,i}^n \geq 0 \\
    (\alpha_g (\rho g U_f + P))_{R1} & \text{if } V_{g,i}^n < 0
  \end{array} \right.
  \\
  d_4 &= \left\{ \begin{array}{ll}
    (\alpha_c \rho h_{i+C3})_{C1} & \text{if } V_{g,i}^n \geq 0 \\
    (\alpha_g \rho g)_{R1} & \text{if } V_{g,i}^n < 0
  \end{array} \right.
  \\
  d_5 &= \left\{ \begin{array}{ll}
    (\alpha_g \rho)_{C1} & \text{if } V_{g,i}^n \geq 0 \\
    (\alpha_g \rho f)_{R1} & \text{if } V_{g,i}^n < 0
  \end{array} \right.
  \\
  d_6 &= \left\{ \begin{array}{ll}
    \left( \alpha_c \rho h_{i+C4} \right)_{C1} & \text{if } V_{g,i}^n \geq 0 \\
    0 & \text{if } V_{g,i}^n < 0
  \end{array} \right.
\end{align*}
\]

The last term in Eq. (10) represents the energy convection by entrained liquid droplet phase, where the coefficient \( d_e \) is given by

\[
d_e = \left\{ \begin{array}{ll}
    (\alpha_c \rho h_{i+C1})_{C1} & \text{if } V_{g,i}^n \geq 0 \\
    0 & \text{if } V_{g,i}^n < 0
  \end{array} \right.
\]

Inserting Eq. (9) into Eq. (10) and rearranging yields

\[
\begin{align*}
  \begin{bmatrix}
    c_{11} & c_{21} & \cdots & c_{16+NC} & \cdots & c_{16+NC+N+NR} \\
    c_{21} & c_{26} & \cdots & c_{26+NC} & \cdots & c_{26+NC+N+NR} \\
    c_{31} & c_{36} & \cdots & c_{36+NC} & \cdots & c_{36+NC+N+NR} \\
    c_{41} & c_{46} & \cdots & c_{46+NC} & \cdots & c_{46+NC+N+NR} \\
    c_{51} & c_{56} & \cdots & c_{56+NC} & \cdots & c_{56+NC+N+NR} \\
    c_{61} & c_{66} & \cdots & c_{66+NC} & \cdots & c_{66+NC+N+NR}
  \end{bmatrix}
  \begin{bmatrix}
    \delta (\alpha_e P_g) \\
    \delta (\alpha_v) \\
    \delta (\alpha_e h_e) \\
    \delta \{1 - (1 - \alpha_v) h_i\} \\
    \delta P_{C1} \\
    \delta P_{C1,1} \\
    \cdots \\
    \delta P_{C1,NC} \\
    \delta P_{C1,NC+1} \\
    \cdots \\
    \delta P_{C1,NC+N+NR}
  \end{bmatrix}
  =
  \begin{bmatrix}
    E_{CN} \\
    E_{CL} \\
    E_{EV} \\
    E_{EL} \\
    E_{CE} \\
    E_{CV}
  \end{bmatrix}
  \begin{bmatrix}
    d_1 (\alpha - \beta \xi)_{g,i} \\
    d_2 (\alpha - \beta \xi)_{f,i} \\
    d_3 (\alpha - \beta \xi)_{g,i} \\
    d_4 (\alpha - \beta \xi)_{f,i} \\
    d_5 (\alpha - \beta \xi)_{g,i} \\
    d_6 (\alpha - \beta \xi)_{g,i}
  \end{bmatrix}
  -
  \begin{bmatrix}
    d_1 (\alpha - \beta \xi)_{g,i} \\
    d_2 (\alpha - \beta \xi)_{f,i} \\
    d_3 (\alpha - \beta \xi)_{g,i} \\
    d_4 (\alpha - \beta \xi)_{f,i} \\
    d_5 (\alpha - \beta \xi)_{g,i} \\
    d_6 (\alpha - \beta \xi)_{g,i}
  \end{bmatrix}
  =
  \begin{bmatrix}
    0 \\
    0 \\
    0 \\
    0 \\
    0 \\
    0
  \end{bmatrix}
  -
  \begin{bmatrix}
    d_e (\alpha - \beta \xi)_{g,i}
  \end{bmatrix}
\end{align*}
\]

where

\[
\begin{align*}
  c_{16} &= c_{16} + d_3 \beta_{g,i} (1 - \eta_i) \\
  c_{26} &= c_{26} + d_3 \beta_{g,i} (1 - \eta_i) \\
  c_{36} &= c_{36} + d_3 \beta_{g,i} (1 - \eta_i) \\
  c_{46} &= c_{46} + (d_4 \beta_{f,i} + d_6 \beta_{g,i}) (1 - \eta_i) \\
  c_{56} &= c_{56} + d_3 \beta_{g,i} (1 - \eta_i) \\
  c_{66} &= c_{66} + d_6 \beta_{g,i} (1 - \eta_i) \\
  c_{16+NC+j} &= -d_1 \beta_{g,i} \eta_j \\
  c_{26+NC+j} &= -d_2 \beta_{f,i} \eta_j \\
  c_{36+NC+j} &= -d_3 \beta_{g,i} \eta_j \\
  c_{46+NC+j} &= -(d_4 \beta_{f,i} + d_6 \beta_{g,i}) \eta_j \\
  c_{56+NC+j} &= -d_5 \beta_{g,i} \eta_j \\
  c_{66+NC+j} &= -d_6 \beta_{g,i} \eta_j \\
  j &= 1, 2, \cdots, N_R, \text{ and } j \neq i.
\end{align*}
\]

Using the Gaussian elimination method, we can obtain a single equation involving just pressures from the bottom row of Eq. (11). Like this procedure, the pressure equations for all the cell \( C_i \)'s are obtained. These are replaced in the original COBRA-TF system pressure matrix equation, resulting in a reduced, integrated system pressure
matrix equation. The new time-step pressures in the COBRA-TF region are obtained by solving this system pressure matrix equation. Figure 1 shows an example of the reduced matrix.

The phasic velocities at the interface junctions are then obtained by back-substitutions of Eq. (9). The new time-step pressures in the RELAP5 regions are obtained from Eq. (7). The remaining numerical sequences are performed in parallel by each code.

4. Inter-Process Communication

All the FORTRAN variables defined for the COBRA/RELAP5 integration are stored on a “shared memory” created in the COBLAP supervisory program. Both the COBRA-TF and RELAP5 processes can access the shared memory, by which the data transfer between the two codes is established.

To control the data transfer and the time advancement of each code, the IPC function provided by the UNIX system is used. Several IPC schemes are available in the UNIX system, but the so-called semaphore type of IPC(12) was adopted. Four basic IPC functions are used as follows:

-ec2.$init("filename", ec_a): initialize the semaphore ec_a (set to zero).
-ec2.$read(ec_a): read the current value of ec_a.
-ec2.$advance(ec_a): increase ec_a to ec_a + 1.
-ec2.$wait(ec_a, ec_b): wait until the value of ec_a increases to ec_b.

Using these IPC functions, the COBLAP program synchronizes the data transfer and the advancement of the two codes. In case of the calculation failure in one of the two codes, COBLAP reduces time-step size and lets the two codes recalculate the time step.

III. DEVELOPMENTAL ASSESSMENT

The following code assessment strategy has been established to evaluate the integrity of the COBRA/RELAP5 code as a merged version of the existing verified codes.

1. Assessment Strategy

First of all, it should be confirmed whether the code integration scheme and its implementation are valid. Then, general code assessment activities are required. The COBRA/RELAP5 code assessment against SETs (Separate Effect Tests) can be performed using COBRA-TF and RELAP5 independently. This implies that the SET assessment results of the two codes can be taken as a part of the COBRA/RELAP5 assessment. However, for some separate effect phenomena, such as multidimensional two-phase flows within downcomer and asymmetric upper plenum thermal-hydraulics in PWRs, the COBRA-TF code has not been sufficiently assessed, thus further assessment is needed. Overall performance of the COBRA/RELAP5 code should be evaluated by the IETs (Integral Effect Tests) assessment.

Near-term assessment activities aim at the improvement of the predictive capability of large-break LOCA. In the long term, the assessment will be extended to best-estimate simulations of a wide range of transients, including both operational transients and design basis accidents of the existing PWRs as well as advanced light water reactors. Presently, the assessment matrix of COBRA/RELAP5 has not been completely established, however, a preliminary assessment program is under progress as follows:

-Phenomenological Assessment:
Using very simple flow problems such as single/two-phase flow in a single channel and manometric flow oscillations, the integration scheme can be validated.

-SET Assessment:
The assessment against SETs will focus on blowdown/reflood heat transfer, entrained liquid droplet behaviors, and multidimensional flow effects. The SETs to be used are FLECHT SEASET(15), THTF(16), experiments for droplet model assessments(17), and some multidimensional tests for the PWR downcomer and the upper plenum thermal-hydraulics.

-IET Assessment:
Large-break LOCA experiments in the ENCOUNTER data bank(18) will be used. These include the LOFT, LSTF (Large Scale Test Facility), Semiscale, and others.

The results of the developmental assessments, which have been conducted to verify the code integration scheme as well as to evaluate the overall performance of the COBRA/RELAP5 code, are presented below.

2. 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 and performed. Consider a vertical channel, of which inner diameter and length are 0.1 and 4.8 m, respectively. As shown in Fig. 2, 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 COBRA/RELAP5 input data for the models R/C and R/C/R consist of three input data. First, the RELAP5 input is prepared like a normal RELAP5 for the RELAP5 region, where cell Ci (cell 13 in the model R/C) is modeled as a tmdpvol and the interface junction should connect from cell Ci to Ri. If a flow system is divided into several unconnected flow systems due to the existence of the COBRA-TF region (e.g., the model R/C/R), they should be connected by a “trip valve” which is always closed. Otherwise, RELAP5 regards them as several independent flow systems. Second, the COBRA-TF input is prepared like a normal COBRA-TF for the COBRA-TF region. The interface junction should be blocked using the flow boundary conditions, if the junctions are on the top or at the bottom of a channel. Third, the COBLAP input includes total number of COBRA-TF to RELAP5 junctions, the RELAP5 index numbers of cell Ci and Ri, and the COBRA-TF
The inlet flow and the exit pressure are specified as boundary conditions for the single channel. The following four boundary conditions are applied:

- Case A: \( P_{\text{exit}} = 0.2 \text{ MPa}, \ W_{\text{inlet}} = 0 \text{ kg/s}, \ U_{\text{inlet}} = 418.2 \text{ kJ/kg} \) (subcooled water)
- Case B: \( P_{\text{exit}} = 0.2 \text{ MPa}, \ W_{\text{inlet}} = 10 \text{ kg/s}, \ U_{\text{inlet}} = 418.2 \text{ kJ/kg} \) (subcooled water)
- Case C: \( P_{\text{exit}} = 12 \text{ MPa}, \ W_{\text{inlet}} = 5 \text{ kg/s} \) (sat. water 4.5 kg/s; sat. steam 0.5 kg/s)
- Case D: \( P_{\text{exit}} = 15 \text{ MPa}, \ W_{\text{inlet}} = 2 \text{ kg/s}, \ U_{\text{inlet}} = 2,490.4 \text{ kJ/kg} \) (superheated steam)

The steady-state calculation results are summarized in Table 2. In an ideal case, the results of the four models must be exactly the same. Mass conservation can be easily confirmed by comparing the mass flow rates at the inlet and the exit. Table 2 shows that the mass error is zero in case of Model C and R, but very small errors (maximum 0.065%) appear in the results of Model R/C and R/C/R. This inconsistency is due to different EOSs (Equations Of States) used in the COBRA-TF and RELAP5 of the COBRA/RELAP5. Because the mass error in a closed system can accumulate continuously, this should be corrected. Currently, it is planned that the COBRA-TF EOSs are replaced with those of RELAP5. Table 2 also shows the energy error through the COBRA-TF to RELAP5 interface, which is also caused by the different EOSs.

The momentum conservation is assured by single- and two-phase pressure drops across the interface. In Case A, zero flow boundary condition is applied and, thus, the pressure drop along the channel is solely determined by hydrostatic head. The pressure drop of each mesh is \( \sim 1.875 \text{ kPa} \), but Model R/C predicts \( dP_{12,13} \) as 0.936 kPa, which is half of the mesh pressure drop. It is noted that, in Model R/C, cell 12 and 13 are the top mesh in the RELAP5 region and the bottom mesh in the COBRA-TF region, respectively. This error occurs due to the fact that, when RELAP5 of the COBRA/RELAP5 solves the momentum equations at the interface, cell 13 is replaced with a tmdpvol, where gravity and wall friction terms are ignored. In case of Model R/C/R, because two COBRA-TF to RELAP5 interface junctions exist, this pressure drop error occurs twice. Thus, \( dP_{1,24} \) of Model R/C/R is always the most small among the four models. Cases B through D show similar pressure drop.
errors.

It is shown, through the single channel tests, that the COBRA/RELAP5 integration scheme works well. Two deficiencies and their effects calculated are negligible.

3. Manometric Flow Oscillations

The manometric flow oscillation problem was simulated by both COBRA/RELAP5 and RELAP5. Figure 3 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. For the COBRA/RELAP5 simulation, the right channel (component 200) is replaced with a COBRA-TF channel, which consists of 25 equal-length cells. To compensate for the pressure drop error previously described, a cell was inserted in the COBRA-TF channel.

At \( t = 0 \) s, a transient calculation begins, which results in manometric flow oscillations. As shown in Fig. 3, 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.

4. One-dimensional Loop Test: THTF Test 105 Simulation

For a one-dimensional loop test of the COBRA/RELAP5, the THTF Test 105 was simulated. The Test 105 was performed to test heat transfer and local fluid properties under blowdown conditions.

1. THTF System Nodalization

The THTF is a large non-nuclear experimental loop with a test section that contains a 7 x 7 array of 12-ft heater rods. The rod power is 5.987 MW. The system operates at the pressure of 15.28 MPa, and the coolant temperatures are 558 K at the core inlet and 607 K at the outlet.

The COBRA/RELAP5 input model is shown in Fig. 4. The reactor vessel is simulated by COBRA-TF and others by RELAP5. The reactor vessel is modeled with 2 channels. Each of the channels consists of 22 uniform cells. The outer channel in Fig. 4 represents the downcomer, and the inner channel represents the core. Zero flow conditions are applied on the bottom of the two channels, the top of the outer channel, and the gap between the two channels except between the bottom cells. Connections between the COBRA-TF and RELAP5 region are (a) a vertical connection from the top of the inner channel to the upper plenum (component 390) and (b) a transverse connection from cell 22 of the outer channel to component 340.

2. THTF Test 105 Transient Simulation

To attain a steady state, a null transient was calculated starting from rough guess of initial conditions. This calculation was repeated with slightly different initial conditions until satisfactory results are obtained. A steady state was attained after \( \sim 40 \) s of the null transient. However, the pressurizer level increased very slowly and steadily because the mass error accumulated. Since the
mass error effects were not significant, restart files written at 100s were used as the initial, steady-state conditions for the transient calculation.

The blowdown transient begins by simultaneous opening of the trip valves 510 and 130 in Fig. 4. Figure 5 shows that COBRA/RELAP5 predicts the pressurizer pressure well. In this test, the rod power experiences an exponential decay from full power at 2s until 5.8s with a time constant of 0.45. After 5.8s, the rod power becomes zero. The rod surface temperature behaviors at 1.01 and 1.92m above the bottom of the rods are illustrated in Fig. 6. The results show good agreements with the experiment data, however, the peak clad temperature was slightly underpredicted by COBRA/RELAP5. Accumulated mass error due to the different EOSs was ~0.635 kg at 20s, which seems to have negligible effect on the transient results.

The calculation results also show that the integration scheme is working well in case of one-dimensional loop system application.

### 5. Three-dimensional Test: The LOFT L2-3 Test Simulation

The LOFT L2-3 large-break LOCA experiment was simulated. To evaluate the overall accuracy, computational speed, and robustness of the COBRA/RELAP5, relatively fine three-dimensional meshing for the reactor vessel was used, although multidimensional flow effects were not much significant in this test comparing with those in full-scale facilities or commercial reactors.

(1) LOFT Facility and System Nodalization

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\(^{(19)}\). The reactor system included a 1.68 m long nuclear core arranged in nine fuel rod bundles.

The major objective of L2-3 large-break experiment\(^{(20)}\) was to investigate the thermal-hydraulic phenomena and the effects on fuel rod cladding response. Initial conditions are listed in Table 3. The experiment was initiated by opening the quick-opening blowdown valves. Reactor scram was completed 1.7s later, HPSI (high pressure safety injection) was initiated at 14s, accumulator injection at 17s at 4.18 MPa system pressure, and LPSI (low pressure safety injection) at 29s. The whole core was reflooded at 55s and the primary coolant pumps operated throughout the experiment.

The COBRA/RELAP5 input consists of a COBRA-TF input for the reactor vessel, a RELAP5 input for the other systems and control logic, and a COBLOP input for the connection data transfer.

Figure 7 shows the RELAP5 input model. It consists of 92 hydrodynamic cells, 93 junctions, and heat structures. The HPSI, the LPSI, and the feed water are modeled by “tmdpvol” and “time dependent junctions”.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Measured value</th>
<th>COBRA/RELAP5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressurizer Pressure (MPa)</td>
<td>15.06±0.03</td>
<td>15.06</td>
</tr>
<tr>
<td>Water volume (m³)</td>
<td>0.670±0.008</td>
<td>0.664</td>
</tr>
<tr>
<td>Water temp. (K)</td>
<td>615.3±3.0</td>
<td>615.3</td>
</tr>
<tr>
<td>Reactor vessel Power level (MW)</td>
<td>36±1.0</td>
<td>36.7</td>
</tr>
<tr>
<td>Maximum linear heat generation rate (kW/m)</td>
<td>39±3.0</td>
<td>39.4</td>
</tr>
<tr>
<td>Intact loop Mass flow rate (kg/s)</td>
<td>199±6.3</td>
<td>195.6</td>
</tr>
<tr>
<td>Cold leg temp. (K)</td>
<td>560.7±1.8</td>
<td>560.8</td>
</tr>
<tr>
<td>Hot leg temp. (K)</td>
<td>592.9±1.8</td>
<td>594.1</td>
</tr>
<tr>
<td>Broken loop Hot leg temp. near vessel (K)</td>
<td>565.5±1.8</td>
<td>566.4</td>
</tr>
<tr>
<td>Cold leg temp. near vessel (K)</td>
<td>554.5±1.8</td>
<td>554.6</td>
</tr>
<tr>
<td>Steam generator secondary side Water level (m)</td>
<td>3.11±0.025</td>
<td>3.139</td>
</tr>
<tr>
<td>Water temp. (K)</td>
<td>482.1±3.0</td>
<td>482.2</td>
</tr>
<tr>
<td>Pressure (MPa)</td>
<td>6.18±0.08</td>
<td>6.183</td>
</tr>
<tr>
<td>Mass flow rate (kg/s)</td>
<td>19.5±0.4</td>
<td>19.5</td>
</tr>
</tbody>
</table>

![Figure 5: Pressurizer pressure behavior](image)

![Figure 6: Rod surface temperature behaviors](image)
The break valves are represented by "trip valves". There are four COBRA-TF to RELAP5 junctions. A fictitious "trip valve" component (not shown in Fig. 7) connecting the intact and the broken loops is provided in the RELAP5 input to combine the two loops into a single hydrodynamic system with the COBRA-TF reactor vessel. The valve is always closed.

For the COBRA-TF vessel input model, three "sections" are used with section boundaries at the top and bottom of the nuclear core as shown in Fig. 8. The outer shells in the three sections, consisted of eight channels, represent the downcomer. The core regions is modeled by 9 channels, each of which represents the flow channel with a fuel bundle. The annulus bypass region is represented by 8 channels like the downcomer. The dotted lines in Fig. 8 indicate "gaps" (junctions). Each of channels 18 through 26 contains a "rod" component, which represents the average of each fuel bundle. However, channel 22 contains additional "rod" to simulate the hot rods. To simulate the fuel-to-clad gap heat transfer, the "dynamic gap heat transfer model" is used. The core power is given as a function of time. Because thermal interaction between the structure and fluid is important, most of the structures are modeled using the "unheated conductor" components.

(2) Steady-State Calculations

Since it is very tedious to correctly give initial conditions of all the three-dimensional vessel cells, the following three steps were used for a steady-state calculation:
- The RELAP5 components 120 through 170, including the pressurizer, steam generator, and pumps, are eliminated. Instead, time-dependent flow and constant pressure boundary conditions are given to the components 180 and 110, respectively, to establish the normal flow condition (started from 0 kg/s).
- The LOFT system except for the reactor vessel is simulated using RELAP5 only, where the flow conditions at the reactor vessel are replaced with boundary conditions obtained from the above step.
- A restart, null-transient calculation of COBRA/RELAP5 for the whole system is performed using the restart files of the above two steps. The null-transient calculation is continued until a satisfactory steady state is achieved.

Table 3 shows that the calculated steady-state conditions agree well with the experimental data.

(3) Transient Calculation

By simultaneous opening of the valves 335 and 355 in Fig. 7, the L2-3 transient begins. Figure 9 shows the pressure behaviors at the pressurizer and the intact loop hot leg. COBRA/RELAP5 reasonably predicts the pressure transient, but tends to slightly underpredict the intact loop hot leg pressure. This difference is caused by two factors. The first one is the higher cold-side break flow during the first 4 s. The second is the feedback between system pressure and accumulator injection.

![Fig. 7 RELAP5/MOD3 nodalization for the LOFT system](image)

![Fig. 8 COBRA-TF nodalization for the LOFT reactor vessel](image)

![Fig. 9 Comparison of the pressure behaviors](image)
The rapider the depressurization is, the earlier the accumulator injection begins. This effect evoked rapider depressurization from 15 to 30 s in the COBRA/RELAP5 results.

In the L2-3 experiment, an early cladding rewet was observed which was caused by the continuous pump operation, i.e., the transition from subcooled to saturated critical flow in the broken loop cold leg occurred about 2 s earlier than the fluid saturation in the cold leg of the operating loop, which resulted in more coolant being delivered to the downcomer than removed through the broken cold leg. This additional coolant traversed the core from bottom to top and caused core wide bottom-up quenching at ~7 s. The phenomena is well illustrated in Figs. 10 and 11. In general, COBRA/RELAP5 predicts the cladding temperatures well, but the blowdown quenching is predicted later at 0.64 m above the bottom of the core as shown in Fig. 10. One of the reasons is that the later transition to two-phase critical flow at the cold-side break, which yields relatively less amount of water being delivered to the core at ~4.5 s. Another reason is that the fuel-to-clad gap heat transfer coefficients in COBRA/RELAP5 at 5 s is believed to be too great. However, since this calculation was run to check the general performance of COBRA/RELAP5, no further efforts were made to improve the results.

Figure 12 shows the liquid droplet volume fractions above the top of active core. Entrainment of liquid droplets can occur under variety of conditions. The droplets formed during the first 15 s are mainly due to entrainment from liquid film and, after ~30 s, entrainment from quench front. It can be seen from Figs. 11 and 12 that the latter significantly contributed to cooling of the upper part of the fuel rods; a part of the droplets accumulated in the upper plenum fell back into the core causing top-down quenching.

The accumulated mass error in the COBRA-TF reactor vessel was ~6.9 kg at 60 s. This error seems to be negligible comparing with the initial inventory of ~1,948 kg and the net flow of the vessel, but should be improved. The accumulated mass error in the RELAP5 region was 0.815 kg at 60 s, which is also negligible.

It is apparently shown that the COBRA/RELAP5 integration scheme is still working well in a three-dimensional application, where the system pressure matrix structure is quite different from that of one-dimensional cases.

6. Computational Speed

The calculations were performed on the Hewlett Packard HC110 workstation equipped with a CPU. Thus, the COBRA/RELAP5 code ran in a serial mode. Table 4 summarizes the run time statistics. The COBRA/RELAP5 code did not fail during all the steady-state and transient calculations. These features shows the robustness of COBRA/RELAP5. The CPU times of COBRA/RELAP5 are 1.54 and 0.25% of total CPU time in the THTF and LOFT simulations, respectively. This indicates the code integration requires negligible overhead in terms of CPU time. To reduce total CPU time, it is necessary to reduce the COBRA-TF grind time and to increase the maximum time step of COBRA-TF.

IV. CONCLUSIONS

The COBRA/RELAP5 code was integrated to combine the excellent features of the RELAP5/MOD3.2 and COBRA-TF codes. The developmental assessments have been conducted to verify the code integration scheme as well as to evaluate the overall performance of the COBRA/RELAP5 code. The results can be summarized as follows:
From the single channel tests, the integration scheme using the IPC functions was proven to be valid. Problems identified are (a) mass and energy error due to the different EOSs and (b) momentum error due to the “time-dependent volume” treatment of cell Ci in the RELAP5 side. The root causes of the problems were clearly addressed.

Typical one- and three-dimensional loop tests have been assessed. It was shown that the code integration scheme is still working well in complicated applications. In general, the simulation results showed good agreement with the experimental data and the computational speed was satisfactory. Therefore, the COBRA/RELAP5 code can be a promising tool for analysis of multidimensional, two-phase flow transients in PWRS.

For further improvement of the COBRA/RELAP5 code, the problems identified should be resolved and, then, a systematic assessment should be performed including multidimensional effect test.

### Table 4 Run time statistics of the COBRA/RELAP5 code

<table>
<thead>
<tr>
<th></th>
<th>THTF Test 105</th>
<th>LOFT L2-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of hydrodynamic cells</td>
<td>96 (44(^{11}), 52(^{12}))</td>
<td>446 (354(^{11}), 92(^{12}))</td>
</tr>
<tr>
<td>Problem time (s)</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>Maximum time step (ms)</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>No. of time steps</td>
<td>20,639</td>
<td>60,910</td>
</tr>
<tr>
<td>Average time step (ms)</td>
<td>0.969</td>
<td>0.985</td>
</tr>
<tr>
<td>CPU time (s)</td>
<td>1,104 (751(^{11}), 336(^{12}), 171(^{13}))</td>
<td>22,352 (20,506(^{11}), 1,788(^{12}), 58(^{13}))</td>
</tr>
<tr>
<td>Grind time (CPU time/step/cell, ms)</td>
<td>0.5572 (0.8270(^{11}), 0.3131(^{12}))</td>
<td>0.8228 (0.9510(^{11}), 0.3190(^{12}))</td>
</tr>
</tbody>
</table>

### REFERENCES


### NOMENCLATURE

- **A**: Matrix
- **b**: Vector
- **h**: Enthalpy
- **NR**: Number of COBRA-TF to RELAP5 junctions
- **P**: Pressure
- **U**: Internal energy
- **V**: Velocity
- **W**: Mass flow rate
- **Xn**: Ratio of the noncondensable gas mass to the total gaseous phase mass

- **(Greek)**
  - **a**: Volume fraction or coefficient
  - **dp**: \( \phi^{n+1} - \phi^n \)
  - **ρ**: Density

- **(Subscripts)**
  - **e**: Entrained liquid droplet phase
  - **f**: Liquid phase
  - **g, v**: Vapor or gas phase
  - **gas**: Noncondensable gas phase
  - **l**: Continuous liquid phase

\(^{11}\)COBRA-TF, \(^{12}\)RELAP5, \(^{13}\)COBLOP

**n**: Old time-step
**n + 1**: New time-step
**T**: Transpose