December 1998

SCDAP/RELAP5 Modeling of Movement of Melted Material Through Porous Debris in Lower Head

RECEIVED

JUN 30 1999

OSTI

L. J. Siefken

LOCKHEED MARTIN

NOTICE

This information was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for any third party's use, or the results of such use, of any information, apparatus, product, or process disclosed herein, or represents that its use by such third party would not infringe privately owned rights. The views expressed herein are not necessarily those of the U.S. Nuclear Regulatory Commission.

SCDAP/RELAP5 Modeling of Movement of Melted Material Through Porous Debris in Lower Head

L. J. Siefken

Published December 1998

**Idaho National Engineering and Environmental Laboratory
Lockheed Martin Idaho Technologies Company
Idaho Falls, Idaho 83415**

**Prepared for the
U.S. Nuclear Regulatory Commission
Washington, D. C. 20555**

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ABSTRACT

Designs are described for implementing models for calculating the movement of melted material through the interstices in a matrix of porous debris in the lower head of a reactor vessel. The COUPLE model in SCDAP/RELAP5 represents both the porous and nonporous debris that results from core material slumping into the lower head during a severe accident in a Light Water Reactor. Currently, the COUPLE model has no capability to model the movement of material that melts within a matrix of porous material. The COUPLE model also does not have the capability to model the movement of liquefied core plate material that slumps onto a porous debris bed in the lower head. In order to advance beyond the assumption that liquefied material always remains stationary, designs are developed for calculations of the movement of liquefied material through the interstices in a matrix of porous material. Correlations are identified for calculating the permeability of the porous debris and for calculating the rate of flow of liquefied material through the interstices in the debris bed. Correlations are also identified for calculating the relocation of solid debris that has a large amount of cavities due to the flowing away of melted material. Equations are defined for calculating the effect on the temperature distribution in the debris bed of heat transported by moving material and for changes in effective thermal conductivity and heat capacity due to the movement of material. The implementation of these models is expected to improve the calculation of the material distribution and temperature distribution of debris in the lower head for cases in which the debris is porous and liquefied material is present within the porous debris.

CONTENTS

ABSTRACT	v
1. INTRODUCTION	1
2. MODELS FOR MOVEMENT OF MATERIAL IN POROUS DEBRIS	3
3. EFFECTS OF MATERIAL MOVEMENT ON DEBRIS BED HEAT TRANSFER	8
4. BOUNDARY CONDITIONS FOR CASE OF CORE PLATE MELTING ABOVE DEBRIS BED	10
5. NUMERICAL SOLUTION	11
6. IMPLEMENTATION INTO COUPLE MODEL	20
7. TESTING AND ASSESSMENT OF IMPLEMENTED MODELS	24
8. SUMMARY	27
9. REFERENCES	28

FIGURES

Figure 1-1. Schematic of situation represented by COUPLE model (particle size of debris greatly exaggerated).	1
Figure 1-2. Current modeling of liquefied material within porous debris bed.	2
Figure 1-3. Proposed extension in modeling of liquefied material within porous debris bed.	2
Figure 4-1. Schematic of material movement occurring when core plate melts and lower head supports ceramic porous debris.	11
Figure 7-1. Description of Test Problem Number 1.	26
Figure 7-2. Description of Test Problem Number 2.	26
Figure 7-3. Description of Test Problem Number 3.	27

TABLES

Tables 5-1. Types and atomic weights of materials represented by COUPLE model.	18
Tables 6-1. Variables added to COUPLE data base for modeling of flow of liquefied material within porous debris bed.	20
Tables 6-2. User-defined variables added to data base for modeling of flow of liquefied material within porous debris bed.	23
Tables 6-3. Extensions to existing COUPLE subroutines for modeling flow of liquefied material within porous debris bed.	24
Tables 7-1. Matrix of test problems for assessing models of liquefied material moving through porous debris bed.	25

1. Introduction

In the event of a severe accident in a Light Water Reactor (LWR), core material may slump to the lower head of the reactor vessel and form a bed of porous debris with interstitial melted material. If the concentration of melted material at any location reaches a threshold value, the melted material will move downward due to gravity and other forces. The movement of the melted material influences the temperature distribution in the debris bed and in the lower head that supports the debris. Thus, the movement of liquefied material within a debris bed may have a significant influence on the damage progression that occurs during the late phase of a severe accident.

The COUPLE model in SCDAP/RELAP5⁸ is intended to calculate the heatup of the lower head and the debris that it supports. The situation that the COUPLE model is designed to analyze is shown in Figure 1-1. Currently, the COUPLE code has the capability to model the melting of material in the debris but it

Figure 1-1. Schematic of situation represented by COUPLE model (particle size of debris greatly exaggerated).

cannot model the movement of the melted material. A schematic of the current modeling capability with respect to melted material is shown in Figure 1-2. The presence of interstitial melted material is possible whenever the debris at any location is heated above its melting temperature. The presence of interstitial melted material is also possible when core plate material melts and slumps onto a debris bed below it. In order to advance the modeling of debris in the lower head to account for the movement of melted material, designs were developed for a calculation of these processes by the COUPLE model. This report describes these designs and their implementation into SCDAP/RELAP5. The schematic of modeling capability to be added to the COUPLE model is shown in Figure 1-3.

This report is organized as follows. Section 2 describes the models to be applied to calculate the movement of liquefied material through the interstices in a matrix of porous debris. This section also presents the correlation to be applied to calculate the movement of solid material. Section 3 describes the

Figure 1-2. Current modeling of liquefied material within porous debris bed.

Figure 1-3. Proposed extension in modeling of liquefied material within porous debris bed.

interface of the COUPLE model for the movement of liquefied material with models that calculate the rate of melting of metallic material above a porous debris bed. The numerics of the melt relocation model are described in Section 5 and the basic features of its implementation are described in Section 6. Section 7 presents plans for testing and assessing the implemented models. A summary of the extensions in modeling proposed for SCDAP/RELAP5 is presented in Section 8. The references are presented in Section 9.

2. Models for Movement of Material in Porous Debris

This section describes the models to be applied for calculating the movement liquefied material through the interstices in a matrix of porous material and the model for calculating the movement of solid debris that has a large amount of cavities due to the flowing away of melted material.

The situation to be modeled for liquefied material has been previously shown in Figure 1-3. The movement of the liquefied material is driven by several forces, including gravity, capillary force, and pressure gradient. Resistances to movement are caused by viscous forces and form losses due to a continuous contraction and expansion of flow areas as the liquefied material flows through the porous debris. The resistances to movement increase with the velocity of the moving material. The balancing of the forces driving the movement of the liquefied material with the forces resisting the movement results in a conservation of momentum equation for the liquefied material.

A general conservation of momentum equation for the liquefied material is given by the equation¹

$$\rho_1 \frac{\partial v_1}{\partial t} + 0.5 \rho_1 \frac{\partial v_1^2}{\partial y} = \rho_1 g - \frac{\partial P_1}{\partial y} - F_r \quad (2-1)$$

where

ρ_1	=	density of liquefied material (kg/m ³),
v_1	=	velocity of liquid material (m/s),
t	=	time (s),
y	=	spatial coordinate that defines elevation (defined in Figure 1-1) (m),
g	=	acceleration of gravity (9.8 m/s),
P_1	=	pressure of the liquefied material (N/m ²),
F_r	=	flow resistance (N/m ³).

The flow resistance term in the above equation, F_r , is calculated by the equation^{2,3,4}

$$F_r = \left[\frac{\mu_1 j_1}{k_1 k} + \frac{\rho_1 j_1^2}{m_1 m} \right] \quad (2-2)$$

where

μ_1	=	dynamic viscosity of liquefied material (kg/m · s),
---------	---	---

- j_l = superficial velocity of liquefied material ($j_l = \epsilon v_l$)(m/s),
 k = Darcy permeability (m^2),
 k_l = relative permeability (unitless),
 m = passability of debris bed (m^2),
 m_l = relative passability of debris bed (m^2).

The second set of variables in the bracket of the above equation is the turbulent counterpart to the first set of variables.

The Darcy permeability is calculated by the equation

$$k = \frac{\epsilon^3 D_p^2}{150(1 - \epsilon)^2} \quad (2-3)$$

where

- ϵ = porosity of the debris bed (unitless),
 D_p = diameter of particles in debris bed (m).

The passability of the debris bed is calculated by the equation

$$m = \frac{\epsilon^3 D_p}{1.75(1 - \epsilon)} \quad (2-4)$$

In general, the relative passability is equal to the relative permeability.² Thus,

$$m_l = k_l \quad (2-5)$$

The relative permeability is a function of the effective saturation of the debris bed and the Darcy permeability. The relative permeability is calculated by the equation⁵

$$\begin{aligned}
 k_l &= k S_e^3, S_e > 0 \\
 k_l &= 0, S_e \leq 0
 \end{aligned} \quad (2-6)$$

where

S_e = effective saturation of debris bed (unitless).

The effective saturation is calculated by the equation⁵

$$S_e = \frac{S - S_r}{1 - S_r} \quad (2-7)$$

where

S_e = effective saturation of debris bed (unitless),

S = true saturation of debris bed (unitless),

S_r = residual saturation of debris bed (unitless).

In the above equation, the true saturation of the debris bed is calculated by the equation

$$S = \frac{\alpha_l}{(1 - \alpha_s)} \quad (2-8)$$

where

α_l = volume fraction of liquefied material in debris bed (unitless),

α_s = volume fraction of solid material in debris bed (unitless).

The volume fractions of liquefied and solid material in the debris bed are related to each other by the equation

$$\alpha_s + \alpha_l + \alpha_g = 1 \quad (2-9)$$

where

α_g = volume fraction of gas (steam, hydrogen, etc.) in debris bed.

The above equation is based on the assumption that liquefied material is not present at any location where water in the liquid phase is present.

The residual saturation, S_r , is a function of the surface tension of the liquid and of the degree of wetting of the solid material by the liquefied material. Reference 5 provides an empirical equation for calculating residual saturation that is appropriate for debris resulting from the disintegration of nuclear reactor cores. This equation is

$$S_r = \begin{cases} \frac{1}{86.3} \left[\frac{\gamma \cos(\theta)}{k \rho_l g} \right]^{0.263} & ; 0 \leq \theta \leq 90^\circ \\ 0 & ; 90^\circ < \theta \leq 180^\circ \end{cases} \quad (2-10)$$

where

γ = surface tension of the liquid (N/m),

θ = wetting contact angle (degrees).

In the case of liquefied material that does not wet the solid material ($90^\circ < \theta < 180^\circ$), the residual saturation is equal to zero. An example of such a system is debris bed composed of UO_2 and stainless steel.⁵ In this case, bulk motion occurs at a relatively low values of bed saturation. In the case of liquefied material that wets the solid material ($0^\circ < \theta < 90^\circ$), bulk motion does not occur until the bed saturation has attained a relatively high value.

In Equation (2-1), the pressure of the liquefied material is a function of the gas pressure and capillary pressure. The pressure is given by the equation

$$P_l = P_g - P_c \quad (2-11)$$

where

P_g = gas pressure (N/m^2),

P_c = capillary pressure (N/m^2).

According to Reference 5, the variable P_c changes much more rapidly with respect to the spatial coordinate y than does the variable P_g . Thus,

$$\frac{\partial P_l}{\partial y} = \frac{\partial P_c}{\partial y} \quad (2-12)$$

The capillary pressure is a function of the debris bed effective saturation, surface tension of the liquid, and wetting angle. According to Reference 5, the capillary pressure is calculated by the equation

$$P_c = J \gamma \cos(\theta) \left[\frac{(1 - \alpha_s)}{k} \right]^{0.5} \quad (2-13)$$

where

J = empirical function of saturation named the "Leverett" function (unitless).

In the above equation, the Leverett function, J , is calculated by the equation

$$J = 0.38[S_e + 0.014]^{-0.27} \quad (2-14)$$

The conservation of mass equation is applied to obtain the relation of the rate of change with time of the local saturation of the debris bed to the local velocity of the liquefied debris and to the local rate of melting of the solid debris. The result is the equation

$$\frac{\partial S}{\partial t} = \frac{\alpha_s Q_s}{(1 - \alpha_s)\rho_s h_{fus}} - \frac{1}{\varepsilon} \frac{\partial j_l}{\partial y} \quad (T_{sol} < T_s < T_{liq}) \quad (2-15)$$

$$\frac{\partial S}{\partial t} = \frac{1}{\varepsilon} \frac{\partial j_l}{\partial y} \quad (T_s < T_{sol})$$

where

Q_s = volumetric heat generation in solid debris (W/m^3),

ρ_s = density of solid debris (kg/m^3),

h_{fus} = heat of fusion of solid material (J/kg),

T_s = temperature of solid material (K),

T_{sol} = solidus temperature of solid debris (K),

T_{liq} = liquidus temperature of solid debris (K).

Equations (2-1) and (2-5) are a coupled set of nonlinear equations for solving for the axial distribution through the debris bed of the bed saturation and the velocity of the liquefied material in the debris bed. In the context of severe accident analysis, a study of the order of magnitude of the terms in Equation (2-1) indicates that the first two terms in this equation are small compared to the other terms in this equation,⁵ and thus can be omitted. In addition, the importance of capillary effects and thus the pressure gradient term in Equation (2-1) has not been firmly established at this time.⁵ Also, the material properties needed to calculate capillary effects, namely the surface tension of the liquid and the wetting angle, are not firmly established. For example, the uncertainty of the wetting angle of liquefied stainless steel in contact with UO_2 is estimated to range from 60° (wetting) to 120° (nonwetting).¹⁰ Also, the possibility of a heterogeneous particle size distribution in the debris bed makes capillary effects less important.⁵ As a result, the pressure gradient term in Equation (2-1) will also be omitted. Thus, Equation (2-1) simplifies to an equation that only contains terms for velocity, gravity and flow resistance. This equation is

$$\frac{\mu_1 j_1}{k_1 k} + \frac{\rho_1 j_1^2}{m_1 m} = \rho_1 g. \quad (2-16)$$

Thus, Equations (2-15) and (2-16) are a set of two equations for solving for the variables j_1 and S . The terms k_1 and m_1 in Equation (2-15) are a function of S and thus contribute to the nonlinearity of the set of equations. Although the momentum equation in the model described in Reference 5 omits the turbulent term in Equation (2-16), a hand calculation for a possible debris bed condition indicated that for a saturated debris bed the omission of the turbulent term would result in a factor of two overprediction of the velocity of the liquefied material. So the turbulent term is being retained for the present model. If results from the testing of the model indicate that the turbulent term has only a second order effect on calculation results, then the turbulent term will be omitted from the model.

Solid debris will be assumed to collapse when its porosity has increased due to flowing away of melted material to the point that the solid material can no longer support itself. The criteria for collapse and the subsequent movement of the collapsed material will be obtained from the DEBRIS model.⁵ According to one empirical correlation in this model, the solid material at a location collapses when the porosity at that location has increased to a value of 0.9. The material slumps to the closest location below it that has a porosity greater than 0.4 after accounting for presence of the collapsed material.⁵ Liquid in the collapsed solid material is displaced along with the solid material. If the downward motion of solid material requires the displacement of liquid, the liquid is constrained to move upward into the location from which the solid material slumped.

3. Effects of Material Movement on Debris Bed Heat Transfer

The movement of liquefied material through the interstices in a porous debris bed results in the transport of energy within the debris bed. In addition, the movement of liquefied material through the debris bed, in particular the movement of metallic material through a ceramic matrix, influences the thermal conductivity and heat capacity of the debris bed. As a result, the movement of liquefied material may have a significant influence on the temperature distribution within the debris bed. This section defines the change to be made to the heat transport equations in the COUPLE model so as to account for the effect of material movement on temperature distribution.

In the context of severe accident analysis, a previous study has shown that the liquefied material moves at a slow velocity and as a result moving liquefied material is in thermal equilibrium with the matrix of solid debris that it contacts.⁵ The heat transport model is currently defined by the equation

$$(\rho c_v)_e \frac{\partial T_n}{\partial t} = \frac{\partial}{\partial x} \left(K_e \frac{\partial T_n}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_e \frac{\partial T_n}{\partial y} \right) + Q_n - Q_{cn} \quad (3-1)$$

where

$$(\rho c_v)_e = (1 - \epsilon_h)(\rho c_v)_s + \epsilon_h(\rho c_v)_g$$

ρ	=	density (kg/m^3),
C_v	=	constant volume specific heat $\text{J}/(\text{kg} \cdot \text{K})$,
K	=	thermal conductivity ($\text{W}/\text{m} \cdot \text{K}$),
Q_n	=	volumetric heat generation rate (W/m^3),
Q_{cn}	=	heat transferred from debris to gas by convective and radiative heat transfer (W/m^3),
T_n	=	temperature of debris at node n (K),
ϵ_h	=	heat conduction porosity of debris (unitless),
x	=	spatial coordinate in horizontal direction (m),
y	=	spatial coordinate in vertical direction (m),
e	=	equivalent,
g	=	gas in interstices of debris,
s	=	solid and liquefied phases of debris.

The above equation models heat transport through debris by conduction and radiation. To account for the transport of heat by the movement of liquefied material, the Q and Q_c terms in the above equation will be replaced by the term

$$Q_{nn} = Q_n - Q_{cn} + Q_{Tn} \quad (3-2)$$

where

Q_{Tn}	=	effective heat generation at node n due to movement of liquefied material (W/m^3),
Q_{nn}	=	net volumetric heat generation rate at node n (W/m^3).

The variable Q_{Tn} in the above equation is a function of the rate of flow and internal energy of the liquefied material that flows into node n during a time step. The rate of flow of liquefied material into node n is calculated by the equation

$$M_{Fi} = 0.5(j_{l,n+1} + j_{l,n}) + A\rho_l\Delta t \quad (3-3)$$

where

- M_{Fi} = mass of liquefied material that flowed into node n during time step (kg),
- $j_{l, n+1}$ = superficial velocity of liquefied material at node n+1 (m/s),
- A = average of cross sectional areas of nodes n and n+1 (m^2),
- ρ_l = density of liquefied material flowing into node n (kg/m^3),
- Δt = time step (s).

The above equation is formulated assuming that there is liquid material of only one type of composition, such as stainless steel or UO_2 . If severe accident analyses indicate that two or more types of liquid may be present at a location, then the equation can be extended to account for the flow of two or more compositions of liquid material.

The variable Q_{Tn} in Equation (3-2) is then calculated by the equation

$$Q_{Tn} = M_{Fi}([u_l(T_{Fi}) - u_l(T_{ne})]/A\Delta z_n\Delta t) \quad (3-4)$$

where

- $u_l(T_{Fi})$ = internal energy of flowing liquefied material at temperature of T_{Fi} (J/kg) (calculated by MATPRO function ZUNTH1),
- T_{ne} = equilibrium temperature of node n assumming instantaneous transfer of heat between liquid flowing into node n and stationary material in node n (K),
- A = cross sectional area (m^2),
- Δz_n = height of node n (m).

In the above equation, the variable T_{ne} is calculated by the equation

$$T_{ne} = F_{mxt}(m1_n, m2_n, \dots, T_n, M_{Fi}, T_{Fi}) \quad (3-5)$$

where

- F_{mxt} = function calculating equilibrium temperature of two mixtures of materials that are combined (subroutine MIXTMP in SCDAP/RELAP5),
- $m1_n$ = mass of first type of stationary material at node n (kg),

m_{2n} = mass of second type of stationary material at node n (kg),

T_n = temperature of node n at start of time step,

The movement of liquefied material through the interstices of a porous debris bed has an effect on the porosity, heat capacity, and effective thermal conductivity of the debris bed. The modeling of these effects is described in Section 5 of this report. The movement of solid debris also results in the transport of heat. The modeling of this heat transport process is also described in Section 5.

4. Boundary Conditions for Case of Core Plate Melting Above Debris Bed

This section describes the boundary condition applied to the model for movement of liquefied core plate material through a ceramic porous debris bed below a melting core plate. Such a case is shown in Figure 4-1. Currently, liquefied material that originates from above the debris bed, such as from melting of a core plate, is assumed to accumulate on top of the debris bed. Designs are described in this section of models that will extend the COUPLE model in SCDAP/RELAP5 so that it will calculate the behavior of liquefied material for situations such as that shown in Figure 4-1. The movement and location of liquefied

Figure 4-1. Schematic of material movement occurring when core plate melts and lower head supports ceramic porous debris.

material will be calculated as a function of time. The liquefied material will be calculated to move until either it freezes, reaches a location in the debris bed where the degree of bed saturation is less than the residual saturation, or reaches an impermeable boundary.

For nodes at the top of the debris bed, the equation based on the principles of flow of liquefied material in a porous debris bed is replaced by an equation that defines the rate of melting of a structure above the debris bed. In other words, Equation (3-3) in Section 3 is replaced by the equation

$$M_{FIT} = A \frac{dm_s}{dt} \Delta t \quad (4-1)$$

where

M_{FIT}	=	mass of liquefied material that flowed into a node at top of debris bed during time step (kg),
A	=	cross sectional area of the node (m^2),
$\frac{dm_s}{dt}$	=	rate of melting of structure above debris bed per unit of cross sectional area (kg/s) m^2 ,
Δt	=	time step (s).

5. Numerical Solution

An explicit, iterative scheme for numerical solution will be used to solve for the distribution in velocity of liquefied material and in debris bed saturation. The scheme will be based on the concept that the velocity gradient changes at a slower rate than the degree of bed saturation changes. In the first step for the first iteration, the change in bed saturation at each node will be calculated using previous time step velocities in the neighborhood of each node. Next, the end of time step velocity at each node will be calculated using the values for bed saturation calculated in the previous step. Next, the bed saturation at each node will be calculated using the velocities just calculated for the end of the time step. If at any node the difference between the last two values calculated for bed saturation is greater than the tolerance for error in bed saturation, another iteration will be performed. Subsequent iterations will be performed until convergence is obtained at each node.

The equations in the numerical solution scheme are arranged as follows. First, a guess of the end of time step bed saturation will be calculated using the equation

$$S_n^{m+1} = S_n^m - \frac{1}{\epsilon_{mn}} \left[\frac{(j_{l,n+1}^m - j_{l,n-1}^m)}{(y_{n+1} - y_{n-1})} \right] \Delta t + \frac{\alpha_{sn} Q_{sn} \Delta t}{(1 - \alpha_{sn}) \rho_{sn} h_{fus}} \quad (5-1)$$

where

m	=	time step number,
S_n^{m+1}	=	bed saturation at node n at end of time step,
S_n^m	=	same as S_n^{m+1} , but for start of time step,
$j_{l,n+1}^m$	=	superficial velocity at start of time step of liquefied material at node $n+1$ (m/s),

$j_{l,n}^m$	=	same as $j_{l,n+1}^m$, but for node n (m/s),
ϵ_{mn}	=	porosity at node n for mass transport calculations (unitless),
y_{n+1}	=	elevation of node n+1 (m),
y_n	=	elevation of node n (m),
Δt	=	time step (s),
α_{sn}	=	volume fraction of solid debris at node n,
Q_{sn}	=	volumetric heat generation rate in melting debris at node m (W/m^3) ($Q_{sn} = 0$ for no melting at node n),
ρ_{sn}	=	density of solid debris at node n (kg/m^3),
h_{fus}	=	heat of fusion of solid debris (J/kg).

If debris is not melting at node n, then the variable Q_{sn} in the above equation is equal to zero. In the above equation, heat input to node n by conduction is assumed to be negligible on the basis of a small temperature gradient in the neighborhood of melting. Also, in the above equation, the nodes are assumed to have uniform cross sectional areas and uniform spacings in the vertical direction.

The local melting of debris and the moving of liquefied material changes the local volume fraction of solid material and the local porosity. Two categories of porosity need to be calculated at each node at each time step. One category of porosity, named the mass transport porosity, will be used in the equations that calculate the flow of liquefied material. For this category, the volumes of liquid and gas are lumped together to represent the porosity. The other category of porosity, named the heat conduction porosity, will be used in the equations that calculate the heatup and conduction of heat through the debris bed. For this category, the volumes of solid material and liquefied debris will be lumped together.

The mass transport porosity will be calculated by the equation

$$\epsilon_{mn} = 1 - \alpha_{sn} \quad (5-2)$$

The value of the volume fraction of the solid debris changes with time when this material is melting. This variable is calculated by the equation

$$\alpha_{sn} = \alpha_{son} \left[1 - \frac{Q_{sn} \Delta t}{\rho_{sn} h_{fus}} \right] \quad (5-3)$$

where

α_{son} = volume fraction of solid debris at start of time step.

The heat conduction porosity will be calculated by the equation

$$\varepsilon_{hn} = 1 - \alpha_{sn} - \alpha_{ln}. \quad (5-4)$$

The volume fraction of liquefied material will be updated using the equation

$$\alpha_{ln} = S_n^{m+1} (1 - \alpha_{sn}) \quad (5-5)$$

Next, the Darcy permeability and the passability of the debris bed will be updated using the equations

$$k_n = \frac{\varepsilon_{mn}^3 D_p}{150(1 - \varepsilon_{mn})^2} \quad (5-6)$$

where

k_n = Darcy permeability of debris bed at node n (m^2).

$$m_n = \frac{\varepsilon_{mn}^3 D_p}{1.75(1 - \varepsilon_{mn})} \quad (5-7)$$

where

m_n = passability of debris bed at node n (m^2).

Next, the effective saturation of the debris bed at the end of the time step for each node will be calculated using the equation

$$S_{en}^{m+1} = \frac{S_n^{m+1} - S_r}{1 - S_r} \quad (5-8)$$

where

S_{en}^{m+1} = effective saturation at node n at end of time step.

The residual saturation, S_r , is a function of material properties, namely wetting angle, surface tension, Darcy permeability, and liquid density; it is calculated using Equation (2-10).

Next, the relative permeability of the debris bed at the end of the time step for each node will be calculated using the equation

$$k_{ln}^{m+1} = k_n [S_{en}^{m+1}]^3 \quad (5-9)$$

where

k_{ln}^{m+1} = relative permeability at node n at end of time step,

k_n = Darcy permeability at node n, which is a function of debris porosity and particle size, and is calculated using Equation (5-6) (m^2).

The relative passability of the debris bed at the end of the time step for each node will be calculated using the equation

$$m_{ln}^{m+1} = k_{ln}^{m+1} \quad (5-10)$$

where

m_{ln}^{m+1} = relative passability of debris bed at node n at end of time step.

Next, the velocity of the liquefied material at each node will be calculated using Equation (2-15). For numerical solution, terms in this equation are combined as follows

$$A[J_{ln}^{m+1}]^2 + B J_{ln}^{m+1} + C = 0 \quad (5-11)$$

where

$A = \frac{\rho_{ln}}{m_{ln}^{m+1} m_n}$

$B = \frac{\mu_{ln}}{k_{ln}^{m+1} k_n}$

$C = -\rho_{ln} g$

m_n = passability of debris at node n (m^2),

ρ_{ln} = density of liquefied debris at node n (kg/m^3),

μ_{1n} = dynamic viscosity of liquefied material at node n kg/m · s ,

g = acceleration of gravity (9.8 m/s).

Applying the quadratic equation, the superficial velocity of the liquefied material at each node at the end of the time step is calculated using the equation

$$J_{1n}^{m+1} = \frac{-B + [B^2 - 4AC]}{2A} \quad (5-12)$$

The bed saturation at each node at the end of the time step is then calculated using Equation (5-1) with the start of time step superficial velocities in this equation replaced with the end of time superficial velocities calculated by Equation (5-12).

The fractional difference in bed saturation between two successive iterations is calculated by the equation

$$f_n = \frac{|S_n^{i+1} - S_n^i|}{0.5(S_n^{i+1} + S_n^i)} \quad (5-13)$$

where

f_n = fractional difference in value of S_n^{m+1} between two successive iterations,

i = iteration number,

S_n^i = value of S_n^{m+1} at i-th iteration.

If the value of f_n at any node is greater than the tolerance in error for bed saturation, another iteration will be performed. The maximum value of the tolerance in error that results in an acceptably accurate calculation of the temperature and mass distribution in the debris bed will be determined during the testing stage of model development. If the testing stage of model development indicates that convergence to an accurate solution is not occurring efficiently, then the numerical solution will be augmented with a scheme to accelerate convergence, such as using the Newton-Raphson Method⁶ to obtain a better guess of the bed saturation based on the change in value of bed saturation during the last two iterations.

After convergence of the debris bed saturation at each node has been obtained, the effect of the movement of liquefied material during the time step on heat transport will be calculated. First, the mass of material flowing into each node during the time step will be calculated. For the top nodes in the debris bed, Equation (4-1) will be used to calculate the mass of liquefied material that moved into these nodes during the time step. Then, Equation (3-4) will be used to calculate the term added to the volumetric heat generation rate for each axial node to account for the transport of liquefied material. Then, the heat conduction porosity for each node will be updated to account for the addition or subtraction of material

from each node during the time step. Then, atomic fractions of each type of material at each node will be updated to account for the addition or subtraction of material from each node during the time step. Also, the internal heat generation (power) at each node will be updated to account for the addition or subtraction of material from each node during the time step. The effective particle size at each node is assumed to not be influenced by the presence of liquefied debris or frozen previously liquefied debris.

The mass of liquefied material added to each node will be calculated by the equation

$$m_{an} = A\rho_{ln}\left(j_{l,n+1}^{m+1} - j_{l,n-1}^{m+1}\right)\Delta t \quad (5-14)$$

where

m_{an} = mass of liquefied material added to node n during time step (kg),

A = cross sectional area of nodes (m^2).

For the top nodes in the debris bed, the mass of liquefied material flowing into these nodes will be calculated by the equation

$$m_{an} = A\frac{dm_{sn}}{dt}\Delta t \quad (5-15)$$

where

$\frac{dm_{sn}}{dt}$ = rate of melting of structure above the debris bed per unit of cross sectional area (kg/s)/ m^2 .

The mass of liquefied material that flowed into each node during a time step will be calculated by the equation

$$m_{in} = 0.5A\rho_l\left(j_{l,n+1}^{m+1} + j_{l,n}^{m+1}\right)\Delta t \quad (5-16)$$

For the top nodes, Equation (5-15) will be used in place of Equation (5-16) to calculate the mass of material that flowed into the nodes during a time step.

Next, the calculation will be made of the term to be added to the volumetric heat generation at each node to account for the thermal effect of the addition by flow of liquefied material to each node. This term is calculated by the equation

$$Q_{Tn} = m_{in}[u_i(T_{Fi}) - u_i(T_{ne})]/0.5(y_{n+1} - y_{n-1})A\Delta t \quad (5-17)$$

where

- Q_{Tn} = heat transported into node n due to movement of liquefied material (W/m^3),
- $u_i(T_{Fi})$ = internal energy of material flowing into node n at temperature of T_{Fi} (J/kg),
- T_{Fi} = T_{n+1} (Temperature at node n+1) for nodes other than top node; for top node, T_{Fi} = temperature of material slumping onto top of debris bed (K),
- T_{ne} = equilibrium temperature as calculated by Equation (3-5).

Next, the calculation will be made of the atomic fractions of each type of material at each node. This calculation will be performed in three steps. First, the mass of each type of material that flowed into or out of each node during the time step will be calculated. Second, the mass at each node of each type of material will be calculated. Third, the atomic fractions of each type of material will be calculated. The calculations will be performed based on the assumption that only one type of liquefied material exists at contiguous nodes. The mass of each type of material that flowed into or out of a node during a time step will be calculated by the equation

$$m_{bin} = \delta_i m_{an} \quad (5-18)$$

where

- m_{bin} = net balance of i-th type of material that flowed into node n during time step (kg),
- δ_i = 1 for m_{an} consisting of i-th type of material; $\delta_i = 0$; otherwise,
- m_{an} = net balance of material that flowed into node during time step, and calculated by Equation (5-14) (kg).

Since only one type of material is assumed to be liquefied at contiguous nodes, m_{bin} is always equal to zero for all material types except one.

The mass of each type of material at each node will be calculated by the equation

$$m_{in} = m_{ion} + m_{bin} \quad (5-19)$$

where

- m_{in} = mass of i-th type of material at node n at end of time step (kg),

m_{ion} = mass of i-th type of material at node n at start of time step (kg).

Finally, the end of time step atomic fractions of each type of material each node will be calculated by the equation

$$f_{in} = \left(\frac{m_{in}}{a_{wi}} \right) / \sum_i \frac{m_{in}}{a_{wi}} \quad (5-20)$$

where

f_{in} = atomic fractions of i-th type of material at node n at end of time step,

a_{wi} = atomic weight of i-th type of material.

The types of materials represented by the COUPLE model and the atomic weight of each type of material are listed in Table 5-1.

Table 5-1. Types and atomic weights of materials represented by COUPLE model .

Number identifier	Material type	Atomic weight
1	<i>Zircaloy</i>	91
2	<i>metallic uranium</i>	238
3	<i>stainless steel</i>	56
4	<i>Silver</i>	109
5	<i>Boron Carbide (B_4C)</i>	55
6	<i>Uranium Dioxide (UO_2)</i>	270
7	<i>Zircaloy Dioxide (ZrO_2)</i>	123
8	<i>Aluminum</i>	26.98
9	<i>Lithium</i>	6.94
10	<i>Cadmium</i>	60

The heat transported by solid material that collapses due to porosity increase caused by flowing away of melted material will be modeled the same as heat transport due to material relocation in the core region of a reactor. According to this modeling approach, the collapsing material and the location receiving the collapsing material come into thermal equilibrium at the instant of contact.⁸ The equilibrium temperature will be calculated by the equation

$$T_{ke} = F_{mxt}(m_{1j}, m_{2j}, \dots T_j, m_{1k}, m_{2k}, \dots T_k) \quad (5-21)$$

where

T_{ke}	=	equilibrium temperature of node k after receiving material that slumped from node j (K),
F_{mxt}	=	function calculating equilibrium temperature of two mixtures of materials that are combined (subroutine MIXTMP in SCDAP/RELAP5),
m_{1j}	=	mass of first type of material that slumped from node j (kg),
m_{2j}	=	mass of second type of material that slumped from node j (kg),
T_j	=	temperature of node j (K),
m_{1k}	=	mass of first type of material at node k (kg),
m_{2k}	=	mass of second type of material at node k (kg),
T_k	=	temperature of material at node k just before it received material from node j (K).

6. Implementation into COUPLE model

This section identifies the extensions required to the data base of the COUPLE model and to its subroutines in order to implement the numerical solution for the movement of liquefied material through a porous debris bed. The variables to be added to the COUPLE model data base are described in Table 6-1. This table also defines the Fortran name to be assigned each variable added to the COUPLE data base and identifies its corresponding name in the numerical solution section of this report. The table also identifies the subroutines that will calculate the values of the new variables. The arrays in Table 6-1 will be stored in the COUPLE bulk storage array named "a," which is stored in the common block named "alcm." The pointers in Table 6-1 will be stored in the COUPLE common block named "iparm." In order to improve computational efficiency, several variables in the numerical solution are omitted from Table 6-1, such as (1) density of liquid material, and (2) dynamic viscosity of liquid material. These variables will be stored as local variables in the subroutines that use them.

Table 6-1. Variables added to COUPLE data base for modeling of flow of liquefied material within porous debris bed .

variable definition	Fortran name	Numerical solution name	units	subroutines that calculate variable
<i>pointer to variable storing volume fraction of liquefied debris at element n</i>	<i>iptvlq</i>	-	-	<i>AUMESH</i>

Table 6-1. Variables added to COUPLE data base for modeling of flow of liquefied material within porous debris bed (continued).

variable definition	Fortran name	Numerical solution name	units	subroutines that calculate variable
volume fraction of liquefied debris at element n	$a(iptvlq+n-1)$	α_{ln}	-	ICNOSL, MOVCPPL
pointer to variable storing volume fraction of solid debris at element n	$iptvsl$	-	-	AUMESH
volume fraction of solid debris at element n	$a(iptvsl+n-1)$	α_{sn}	-	ICNOSL, MOVCPPL
pointer to variable storing bed saturation at current iteration at element n	$iptbst$	-	-	AUMESH
bed saturation at element n at current iteration	$a(iptbst+n-1)$	S_n^{m+1}	-	ICNOSL, MOVCPPL
pointer to variable storing bed saturation at previous iteration	$iptbs0$	-	-	AUMESH
bed saturation at element n at previous iteration	$a(iptbs0+n-1)$	S_n^m	-	ICNOSL, MOVCPPL
pointer to variable storing effective bed saturation at element n	$iptebs$	-	-	AUMESH
effective bed saturation at element n	$a(iptebs+n-1)$	S_{en}	-	ICNOSL, MOVCPPL
pointer to array storing Darcy permeability at element n	$iptprm$	-	-	AUMESH
Darcy permeability at element n	$a(iptprm+n-1)$	k_n	m^2	MOVCPPL
pointer to array storing passability at element n	$iptpas$	-	-	AUMESH
passability at element n	$a(iptpas+n-1)$	m_n	m^2	MOVCPPL
pointer to variable storing relative permeability at element n	$iptprpr$	-	-	AUMESH
relative permeability at element n	$a(iptprpr+n-1)$	k_{ln}	-	MOVCPPL
pointer to array storing mass of Zr in element n	$iptlzt$	-	-	AUMESH

Table 6-1. Variables added to COUPLE data base for modeling of flow of liquefied material within porous debris bed (continued).

variable definition	Fortran name	Numerical solution name	units	subroutines that calculate variable
mass of Zr in element n	$a(iptl_{Zr}+n-1)$	-	kg	MUPDAT, MOVCPPL
pointer to array storing mass of metallic U in element n	$iptl_{ur}$	-	-	AUMESH
mass of metallic U in element n	$a(iptl_{ur}+n-1)$	-	kg	MUPDAT, MOVCPPL
pointer to array storing mass of stainless steel in element n	$iptl_{ss}$	-	-	AUMESH
mass of stainless steel in element n	$a(iptl_{ss}+n-1)$	-	kg	MUPDAT, MOVCPPL
pointer to array storing mass of Ag-In-Cd in element n	$iptl_{ag}$	-	-	AUMESH
mass of Ag-In-Cd in element n	$a(iptl_{ag}+n-1)$	-	kg	MUPDAT, MOVCPPL
pointer to array storing mass of B_4C in element n	$iptl_{bc}$	-	-	AUMESH
mass of B_4C in element n	$a(iptl_{bc}+n-1)$	-	kg	MUPDAT, MOVCPPL
pointer to array storing of UO_2 in element n	$iptl_{uo}$	-	-	AUMESH
mass of UO_2 in element n	$a(iptl_{uo}+n-1)$	-	kg	MUPDAT, MOVCPPL
pointer to array storing mass of ZrO_2 in element n	$iptl_{zo}$	-	-	AUMESH
mass of ZrO_2 in element n	$a(iptl_{zo}+n-1)$	-	kg	MUPDT, MOVCPPL
pointer to array storing superficial velocity of liquefied material after current iteration at node n	$iptj_{lm}$	-	-	AUMESH
superficial velocity of liquefied material after current iteration at node n	$a(iptj_{lm}+n-1)$	j^{m+1}_{ln}	m/s	MUPDAT, MOVCPPL

Table 6-1. Variables added to COUPLE data base for modeling of flow of liquefied material within porous debris bed (continued).

variable definition	Fortran name	Numerical solution name	units	subroutines that calculate variable
<i>pointer to array storing superficial velocity of liquefied material after previous iteration at node n</i>	<i>iptjl0</i>	-	-	<i>AUMESH</i>
<i>superficial velocity of liquefied material after previous iteration at node n</i>	<i>a(iptjl0+n-1)</i>	j_{ln}^m	<i>m/s</i>	<i>MOVCPPL</i>
<i>pointer to array indicating whether solid material at node n collapsed during time step</i>	<i>iptclp</i>	-	-	<i>AUMESH</i>
<i>node number receiving material that slumped from node n due to collapse of solid material at node n; if collapse has not occurred at node n during time step, the value for that node is zero</i>	<i>a(iptclp+n-1)</i>	-	-	<i>MOVCPPL</i>

Several user-defined variables are required for the numerical solution; these variables are identified in Table 6-2. Two of the variables in Table 6-2 are material properties that are not defined in the material properties part (MATPRO)⁹ of SCDAP/RELAP5. These variables are the liquid-solid contact angle and the surface tension of the liquefied material. The latter property is defined in MATPRO, but it is defined only for a mixture of Zr-U-O and has a large amount of uncertainty. When the values of these material properties are firmly established, the values will be obtained from MATPRO instead of being user-defined. Another variable in this table, namely the rate of melting of a structure directly above a debris bed, such as particular a core plate, could be obtained from calculations performed by the core plate model in SCDAP/RELAP5. Nevertheless, it is useful to make this variable user-defined for testing and for analyses focusing on behavior of debris in the lower head of a reactor vessel instead of on behavior of an overall reactor system.

Table 6-2. User-defined variables added to data base for modeling of flow of liquefied material within porous debris bed .

Variable definition	Fortran name	Numerical solution or theory name	Units	Common block
<i>liquid-solid contact angle (wetting angle)</i>	<i>thtwet</i>	θ	<i>radians</i>	<i>tblsp</i>

Table 6-2. User-defined variables added to data base for modeling of flow of liquefied material within porous debris bed (continued).

Variable definition	Fortran name	Numerical solution or theory name	Units	Common block
<i>surface tension of liquefied material</i>	<i>gamwet</i>	γ	<i>N/m</i>	<i>tblsp</i>
<i>rate of slumping of melting structure located directly above debris bed</i>	<i>mdtstr</i>	dm_s/dt	$(kg/s)/m^2$	<i>tblsp</i>
<i>accuracy of calculated bed saturation</i>	<i>accbst</i>	-	-	<i>tblsp</i>

The model for calculating the movement of liquefied debris will be programmed in a new subroutine named MOVCP. This new subroutine will be called from subroutine COUPLE just before the call to subroutine EGEN2. The new subroutine will calculate the distribution of liquefied material within the debris bed and calculate the magnitude of the addition to be made to the volumetric heat generation term in the COUPLE model in order to account for the transport of heat by movement of liquefied material. The new subroutine will also calculate the change in effective thermal conductivity and heat capacity at each node due to movement of liquefied material. The subroutine will also calculate the change in power in each finite element due to the movement of material. The subroutine will also calculate the relocation of solid debris that slumps due to cavities caused by flowing away of melting material. The Fortran programming of the new subroutine will be based on the numerical solution scheme outlined in Section 5 of this report.

The extensions required to existing COUPLE subroutines are summarized in Table 6-3. Subroutine MATERL will be extended to define input needed for the models that calculate the movement of liquefied material. Subroutine AUMESH will be extended to reserve storage for the new variables added to the COUPLE model to calculate the movement of liquefied material and its consequences. Subroutine ICPL will be extended to initialize the new variables added to the COUPLE model. Subroutine COUPLE will be extended to call the new subroutine named MOVCP, which calculates the movement of liquefied material and its consequences, including the slumping of solid material. Subroutine TGPSET will be updated to calculate the temperature at locations which received collapsed solid material during the time step. The subroutine will also be extended to update the mass of each type of material at each node to account for the relocation of solid material. Subroutine MAJCOU will be extended to display the results calculated by subroutine MOVCP.

Table 6-3. Extensions to existing COUPLE subroutines for modeling flow of liquefied material within porous debris bed .

Subroutine	Line in subroutine	Extensions
<i>MATERL</i>	<i>read(eoin,1005)emissm</i>	<i>add to this read statement the definition of input variables listed in Table (6-3)</i>

Table 6-3. Extensions to existing COUPLE subroutines for modeling flow of liquefied material within porous debris bed (continued).

Subroutine	Line in subroutine	Extensions
<i>AUMESH</i>	<i>i111=i110+4*numel</i>	<i>after this line, define pointers listed in Table (6-2) and reserve storage for variables associated with the pointers</i>
<i>ICPL</i>	<i>do 50 i=1,numel</i>	<i>in this do loop, initialize to value of zero the variables in Table (6-2) with element number for index</i>
<i>COUPLE</i>	<i>call egen2(a(i8),....</i>	<i>before this line, add call to new subroutine named MOVCPPL to obtain movement of liquefied material and its consequences</i>
<i>TGPSET</i>	<i>390 continue</i>	<i>after this line, call subroutine MIXTMP for every node receiving collapsed material during time step and set tz for that node equal to that temperature, also update mass inventories at each to account for slumping of solid material</i>
<i>MAJCOU</i>	<i>1575 format(... end if</i>	<i>after these lines, print values of bed saturation and porosity in each element and the code number for the liquefied material in each element</i>

7. Testing and Assessment of Implemented Models

The models added to SCDAP/RELAP5 will be tested and assessed using three test problems. Two of these test problems involve calculating the flow of liquefied material for simplified conditions. The other test problem involves the analysis of an experiment that measured the displacement of liquefied material moving through the interstices of a porous debris bed. The matrix of test problems is described in Table 7-1.

Table 7-1. Matrix of test problems for assessing models of liquefied material moving through porous debris bed .

Problem no.	Problem description	Focus of assessment
<i>1</i>	<i>Liquefied stainless steel slumps onto top of hot porous debris bed composed of UO₂ and then flows through the debris bed</i>	<i>Internal consistency of modeling, including maintaining of conservation of mass and energy</i>

Table 7-1. Matrix of test problems for assessing models of liquefied material moving through porous debris bed (continued).

Problem no.	Problem description	Focus of assessment
2	<i>Melting occurs to UO_2 particles in porous debris bed composed of particles of UO_2, problem is described in Figure (7-2), two cases solved, one with spatially uniform power in debris bed and other with power increasing with elevation.</i>	<i>Internal consistency of modeling, including maintaining of conservation of mass and energy, and calculating distribution in velocity of moving material consistent with the permeability and saturation of debris bed</i>
3	<i>Porous debris part of MP-2 experiment is heated, partially melts, and material movement occurs as consequence; geometry and boundary conditions will be simplified and idealized to preclude need of major update to COUPLE model for input to define initial conditions; problem is described in Figure (7-3)</i>	<i>Compare calculated and measured movement of material through porous debris section of experiment</i>

The first problem involves the calculation of the flow of liquefied stainless steel that slumps onto the top of a porous debris bed. The test problem is described in Figure 7-1. The debris bed has an initial

Figure 7-1. Description of Test Problem Number 1.

temperature of 2500 K and the slumping liquefied stainless steel has a temperature of 1700 K just before contact with the top surface of the debris bed. The debris particles have a volumetric heat generation rate of 1 MW/m^3 . The debris particles are composed of UO_2 with a diameter of 2 mm. The initial porosity of the debris bed is 0.5. No water or steam is flowing through the debris bed. The debris is represented by two parallel stacks of COUPLE model finite elements, with twenty elements in each stack.

The second problem involves the calculation of the flow of liquefied material that originates from melting within the debris bed. The test problem is described in Figure 7-2. The debris bed is composed of

Figure 7-2. Description of Test Problem Number 2.

particles of UO_2 with a particles size of 2 mm. The initial porosity of the debris bed is 0.5. The volumetric heat generation rate in the debris particles is 1 MW/m^3 at the top surface of the debris bed and linearly decreases to a value of 0.20 MW/m^3 at the bottom surface of the debris bed. A case will also be calculated in which the volumetric power is uniform through the debris bed. No water or steam is flowing through the debris bed. The debris is represented by two parallel stacks of COUPLE model finite elements, with twenty elements in each stack.

The third problem is an analysis of the porous, ceramic debris portion of the MP-2 experiment.⁷ This experiment involved the melting and flowing of ceramic and metallic material through porous debris and rod-like structure. The test problem will only analyze the section of the experiment that initially was composed of porous, ceramic debris. This simplification of the experiment is necessary to prevent the assessment effort from exceeding its project scope. The test problem is described in Figure 7-3. The debris particles are composed of a mixture of UO_2 and ZrO_2 particles with a mass mean particle size of 2 mm. The mass fraction of UO_2 is 0.8279. The porosity of the debris is 0.5. The flow of coolant through the debris bed is assumed to not be significant. The transient power distribution in the debris bed will be obtained from previous analysis.⁷ A center cylindrical section of the experiment will be selected for

Figure 7-3. Description of Test Problem Number 3.

analysis. This cylinder will have a radius of 0.01 m and its centerline will be located at the centerline of the debris bed. The outer radius of the experiment debris bed was 0.0436 m. The cylinder will be assumed to be perfectly insulated at its outer radius. The top and bottom surfaces of the cylinder will be prescribed the temperature histories measured at these locations. The debris bed will be represented by a stack of ten to twenty finite elements. The behavior of debris will be calculated out to the experiment time of 16,500 s, which is the time at which most of the debris in this section of the experiment had melted or slumped to the bottom part of the section.

8. Summary

Designs were described for models to calculate the movement of liquefied material through the interstices of porous debris. The models are intended for implementation into the COUPLE model in SCDAP/RELAP5 so as to give it the capability to calculate the effect on lower head heatup of liquefied material moving through porous debris in the lower head. The models have been designed assuming that liquefied material originates from two sources; (1) melting of core plate above porous debris in the lower head, and (2) melting of in situ debris in the lower head. Equations and solution methods were presented for the calculation of the motion of liquefied and solid material and the heat transported by the moving material. Equations were also presented for calculating the effect of moving material on effective thermal conductivity and heat capacity. A description was presented of the extensions in COUPLE model Fortran programming required to implement these equations and solution methods. A matrix of test problems was defined for assessing these models and their implementation.

9. References

1. The RELAP5 Development Team, "RELAP5/MOD3 Code Manual, Volume 1: Code Structure, System Models, and Solution Methods," NUREG/CR-5535, INEL-95/0174, August 1995.
2. Mo Chung and Ivan Catton, "Post-Dryout Heat Transfer in a Multi-Dimensional Porous Bed," Nuclear Engineering and Design 128 (1991) pages 289-304.
3. V.X. Tung, "Hydrodynamic and Thermal Aspects of Two-Phase Flow Through Porous Media," Ph. D. Thesis, University of California, Los Angeles, 1988.
4. L. J. Siefken, E. W. Coryell, and S. Paik, "SCDAP/RELAP5 Modeling of Heat Transfer and Flow Losses in Lower Head Porous Debris," INEL/EXT-98-00820, September 1998.
5. R. C. Schmidt and R. D. Gasser, "Models and Correlations of the DEBRIS Late-Phase Melt Progression Model," SAND93-3922, September 1997.
6. W. H. Press, et. al., "Numerical Recipes," Cambridge University Press, Cambridge, 1986.
7. R. D. Gasser et. al., "Late-Phase Melt Progression Experiment: MP-2; Results and Analysis," NUREG/CR-6167, SAND93-3931, May 1997.
8. The SCDAP/RELAP5 Development Team, "SCDAP/RELAP5/MOD3.2 Code Manual, Volume 2: Damage Progression Model Theory," NUREG/CR-6150, Volume 2, Rev. 1, INEL-96/0422, July 1998.
9. The SCDAP/RELAP5 Development Team, "SCDAP/RELAP5/MOD3.2 Code Manual, Volume 4: MATPRO - A Library of Materials Properties for Light-Water-Reactor Accident Analysis," NUREG/CR-6150, Volume 4, Rev. 1, INEL-96/0422, July 1998.
10. S. S. Dosanjh, "Relocation of Metallic Constituents in Core Debris Beds," NUREG/CR-5109, SAND 88-0535, R7, September 1988.