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SCDAP/RELAP5/MOD3.1
코드구조 및 노심 열수력 모델 검토

Review of the SCDAP/RELAP5/MOD3.1 Code Structure and Core T/H Model before Core Damage

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제 출 문

한국 원자력 연구소장 귀하

본 보고서를 다음과제의 기술보고서로 제출합니다.

과제명 : 중대사고 위해도 완화전략 분석 종합전산코드 개발

보고서명 : SCDAP/RELAP5/MOD3.1 코드구조 및 노심 열수력 모델 검토
(Review of the SCDAP/RELAP5/MOD3.1 Code Structure and
Core T/H Model before Core Damage)

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요 약 문

SCDAP/RELAP5 전산코드는 중대사고시 원자로 냉각재 계통내에서의 열수력 현상과 핵분열 생성물간의 상호작용을 모의할 수 있도록 USNRC의 후원아래 INEL(Idaho National Engineering Laboratory) 이 개발한 최적 평가용 코드로 최신판인 SCDAP/RELAP5/MOD3.1 코드는 기존의 RELAP5/MOD3 코드와 SCDAP 코드를 결합하여 개발된 종합 코드이다. 이 코드는 대형 및 소형 파단 냉각재 상실사고와 ATWS, 전원상실사고, 급수상실 및 유동상실 사고와 같은 가동 중 과도상태로 인한 중대노심 손상사고를 모의할 수 있다.

본 보고서의 주 목적은 현재 중.장기과제의 하나로 수행되고 있는 중대사고 종합코드 개발에 활용할 수 있도록 SCDAP/RELAP5/MOD3.1 노심 열수력 모델특성에 관한 정보를 효과적으로 제공하는 데 있다. 코드의 입력을 다루는 INPUTD 프로그램과 과도사고를 다루는 TRNCTL 그리고 Plot File을 다루는 STRIPF등 프로그램의 전체적인 구조를 분석하였고, 1차 계통에서의 열수력을 모사하기 위한 기본 방정식을 정리하였다. 특별히 노심 안에서의 사고진행과 관련하여 건전노심 및 노심손상을 모사하는 프로그램을 기능별로 요약하였고, 노심 Nodalization 변수를 정리하였으며 열전도 모델의 수치 해석 방법과 열대류 관계식을 조사함으로 앞으로의 입력 마련 및 모델 개선에 기초를 마련하였다.

SUMMARY

The SCDAP/RELAP5 code has been developed for best estimate transient simulation of light water reactor coolant systems during a severe accident. The code is being developed at the Idaho National Engineering Laboratory (INEL) under the primary sponsorship of the Office of Nuclear Regulatory Research of the U.S. Nuclear Regulatory Commission (NRC). Currently, the SCDAP/RELAP5/MOD3.1 code is the result of merging the RELAP5/MOD3 and SCDAP models. The code models the coupled behavior of the reactor coolant system, core, fission product released during a severe accident transient as well as large and small break loss of coolant accidents, operational transients such as anticipated transient without SCRAM, loss of offsite power, loss of feedwater, and loss of flow.

Major purpose of the report is to provide information about the characteristics of SCDAP/RELAP5/MOD3.1 core T/H models for an integrated severe accident computer code being developed under the mid/long-term project. This report analyzes the overall code structure which consists of the input processor (INPUTD), transient controller (TRNCTL), and plot file handler (STRIPF). The basic governing equations to simulate the thermohydraulics of the primary system are also described. As the focus is currently concentrated in the core, core nodalization parameters of the intact geometry and the phenomenological subroutines for the damaged core are summarized for the future usage. In addition, the numerical approach for the heat conduction model is investigated along with heat convection model. These studies could provide a foundation for input preparation and model improvement.

CONTENTS

FIGURES

TABLES

1. INTRODUCTION

The SCDAP/RELAP5/MOD3.1[1] computer code is designed to describe the overall reactor coolant system (RCS) thermal-hydraulic response, core damage progression, and in combination with VICTORIA[2], fission product release and transport during severe accidents. The code is being developed at the Idaho National Engineering Laboratory (INEL) under the primary sponsorship of the Office of Nuclear Regulatory Research of the U.S. Nuclear Regulatory Commission (NRC).

The code is the result of merging the RELAP5/MOD3[3] and SCDAP[4] models. The RELAP5 models calculate the overall RCS thermal hydraulics, control system interactions, reactor kinetics, and the transport of noncondensable gases.

The SCDAP code models the core behavior during a severe accident. Treatment of the core includes fuel rod heatup, ballooning and rupture, fission product release, rapid oxidation, zircaloy melting, UO_2 dissolution, ZrO_2 breach, flow and freezing of molten fuel and cladding, and debris formation and behavior. The code also models control rod and flow shroud behavior.

The RELAP5 code is based on a nonhomogeneous and nonequilibrium model for the two-phase system that is solved by a fast, partially implicit numerical scheme to permit economical calculation of system transients. The objective of the RELAP5 development effort from the outset was to produce a code that includes important first order effects necessary for accurate prediction of system transients but is sufficiently simple and cost effective such that parametric or sensitivity studies are possible. The development of SCDAP/RELAP5 has this same focus.

The code includes many generic component models from which general systems can be simulated. The component models include fuel rods, control rods, pumps, valves, pipes, heat structures, electric heaters, jet pumps, turbines, separators, accumulators, and control system components. In addition, special process models are included for effects such as form loss, flow at an abrupt area change, branching, choked flow, boron tracking, and noncondensable gas transport.

In addition to the overall code structure, this report includes PWR core-related module and phenomenology before core melt relocation in the lower head under severe accident condition.

2. CODE STRUCTURE ANALYSIS

2.1 OVERALL STRUCTURE

SCDAP/RELAP5 is coded in a modular fashion using top-down structuring. The various models and procedures are isolated in separate subroutines. Figure 1 shows an overview of the code architecture.

Input processing is performed in INPUTD and associated subroutines. Transient control is performed by TRNCTL and associated subroutines. The STRIPF routine extracts data from the restart plot file for use in other computer programs. Because of their complexity, the input processing and transient control routines are described in more detail in Sections 2.1.1 and 2.1.2.

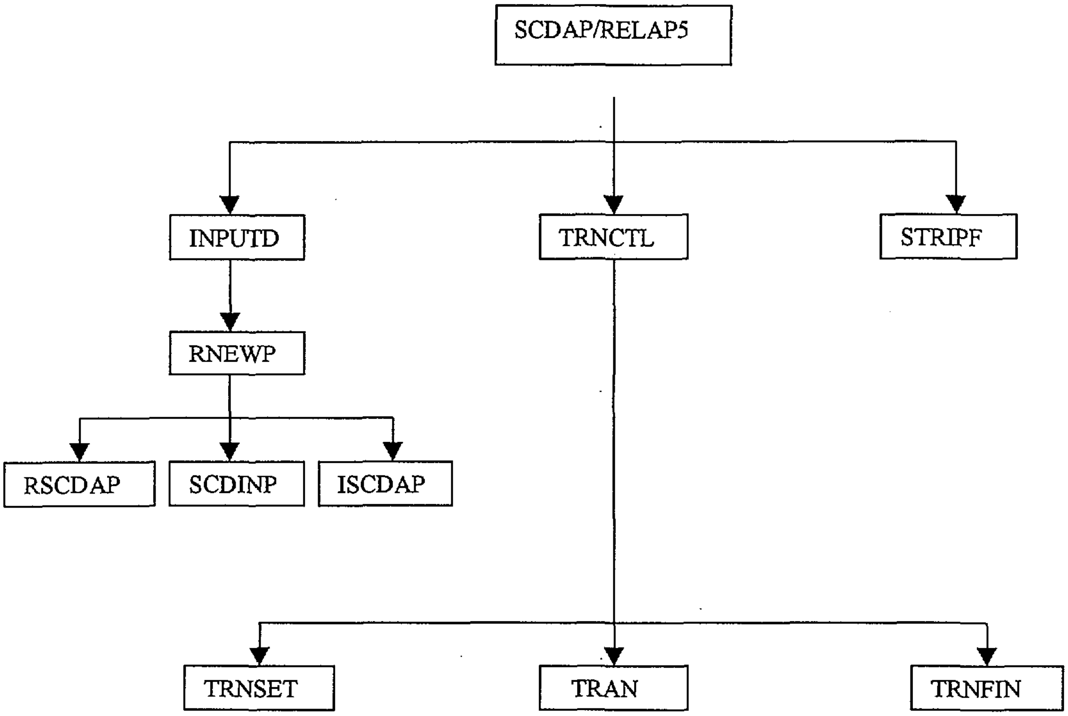

Figure 1. SCDAP/RELAP5 General Architecture

2.1.1 Input Processing Overview

The input processing is performed in three phases. In the first phase, the input data is read and checks are made for typing and punctuation errors (such as multiple decimal points and letters in numerical fields), and stores the data keyed by card number so that the data are easily retrieved. A listing of the input data is provided, and punctuation errors are noted.

During the second phase, restart data from a previous simulation are read if the problem is a RESTART type, and all input data are processed. Some processed input is stored in fixed common blocks, but the majority of the data are stored in dynamic data blocks that are created only if needed by a problem and sized to the particular problem. In a NEW-type problem, dynamic blocks must be created. In RESTART problems, dynamic blocks may be created, deleted, added to, partially deleted, or modified as modeling features and components within models are added, deleted, or modified. Extensive input checking is done, but at this level checking is limited to new data from the cards being processed. Relationships with other data cannot be checked because the latter may not yet be processed.

The third phase of processing begins after all input data have been processed. Because all data have been placed in common or dynamic data blocks during the second phase, complete checking of interrelationships can proceed. Examples of cross-checking are existence of hydrodynamic volumes referenced in junctions and boundary conditions; entry or existence of material property data; and validity of variables selected for minor edits, plotting, or used in trips and control systems. As the cross-checking proceeds, cross-linking of the data blocks is done so that it needs not be repeated at every time step. The initialization required to prepare the model for start of transient advancement is done at this level.

Input data editing and diagnostic messages can be generated during the second and/or third phases. Input processing for most models generates output and diagnostic messages during both phases.

As errors are detected, various recovery procedures are used so that input processing can be continued and a maximum amount of diagnostic information can be furnished. Recovery procedures include supplying default or replacement data, marking the data as erroneous so that other models do not attempt use of the data, or deleting the bad data. The recovery procedures sometimes generate additional diagnostic messages. Often after attempted correction of input, different diagnostic messages appear. These can be due to continued incorrect preparation of data, but the diagnostics may result from the more extensive testing permitted as previous errors are eliminated.

The input processing for the SCDAP portion of the code is performed in three main subroutines as shown in Figure 1, RSCDAP, SCDINP, and ISCDAP. These subroutines perform the following functions:

RSCDAP	Processes the new style of input based upon the RELAP5 approach. This is the preferred input option.
SCDINP	Processes the old style input which allows for backward compatibility. However, this routine will gradually be phased out.
ISCDAP	Initializes the SCDAP related variables in the code, maps fuel element locations into thermal-hydraulic volumes, and performs input consistency checks once all input data has been read in .

As was shown in Figure 1, the first phase of input processing for the SCDAP portion of the code is performed in subroutine RSCDAP. Details of this subroutine are shown in Figure 2. These subroutines perform as follows. First, the severe core damage sections of the code are initialized with calls to SCDCON and PREINT. Second, the general bundle information is read within RSCDAP. This information includes general bundle geometry information, as well as grid spacer information. The third step is to read the component specific information. This is accomplished by calls to the component specific input routines, RFUEL (fuel rod), RCYLIN (Ag/In/Cd control rod), RSHROD (shroud), RBWR (B_4C control rod), RFUELE (fuel element), and RBLA (Control Blade/ Channel Box). If the component specific information is read successfully, RSCDAP then calls a component specific initialization routine. Finally, the radiation heat transfer information, such as view factors and path lengths are read in routine RRADIA.

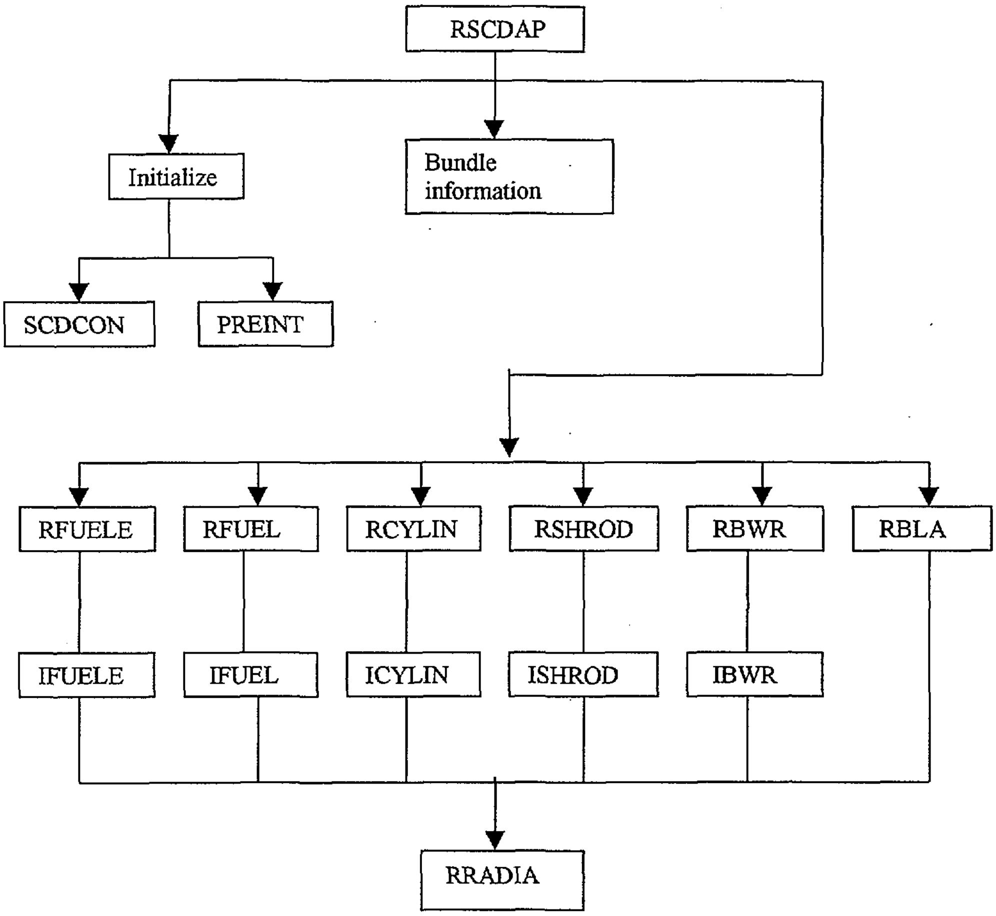

Figure 2. SCDAP/RELAP5 Input Architecture

2.1.2 Transient Overview

Subroutine TRNCTL, shown in the center branch of Figure 1, consists only of the logic to call the next lower level routines. Subroutine TRNSET brings dynamic blocks required for transient execution from disk into computer central memory, performs final cross-linking of information between data blocks, sets up arrays to control the sparse matrix solution, establishes scratch work space, and returns unneeded computer memory. The subroutine TRNFIN releases space for the dynamic data blocks that are no longer needed and prints the transient timing summary. Subroutine TRAN, the driver, controls the transient advancement of the solution. Nearly all the execution time is spent in this subroutine, and TRAN is also the most demanding of memory. TRAN consists of three modules shown in Figure 3 : thermal advancement, SCDAP advancement, and hydrodynamic advancement.

2.1.2.1 Thermal Advancement

The control of the time step advancement, the trip logic models, the calculation of the thermodynamic state of each hydrodynamic volume in the system, and the heat conduction solution for reactor heat structures are performed within this block of subroutines.

The following description is presented for selected transient subroutines (refer to Figure 3):

DTSTEP	Determines the time step size, controls output editing, and determines whether transient advancements should be terminated. During program execution, this module displays such information as CPU time, problem time, and the maximum cladding temperature on a terminal screen.
TRIP	Evaluates logical statements. Each trip statement is a simple logical statement which has a true or false result. The decision of what action is needed resides within the components in other modules. For example, valve components open or close the valve based on trip values; pump

	components test trip status to determine whether a pump electrical breaker has tripped.
TSTATE	Calculates the thermodynamic state of the fluid in each hydrodynamic user-defined time- dependent volume.
HTADV	Advances heat conduction/transfer solutions using previous-time-step reactor kinetics power and previous-time-step hydrodynamic conditions for computing heat transfer coefficients. It calculates heat transferred across solid boundaries of hydrodynamic volumes.

2.1.2.2 SCDAP Advancement

The advancement of the severe core damage models are controlled within the SCDAP advancement block. The entry point for this block of models is the SCDPRH subroutine. The SCDPRH subroutine advances the heat conduction solution (for core components only), the mechanical response models (including changes in geometry), and fission gas release models using previous-time-step hydrodynamic conditions. The SCDPRH routine drives four basic blocks of modeling, consisting of the heat transfer block, the intact geometry models, the in-core debris models, and the core slumping model.

The first block of modeling driven by SCDPRH consists of calls to the heat transfer models within RADCC2, HTRC1 and HTRC3A. RADCC2 calculates the radiation heat transfer in a fuel bundle, and is only made difficult by the interface to the MINERVA mathematics library for the solution of the system of differential equations. HTRC1 computes heat transfer from the intact geometry routines to the coolant. It computes heat transfer coefficients for air-water mixtures, single phase liquids, subcooled nucleate boiling, saturated nucleate boiling, subcooled transition film boiling, saturated transition film boiling, subcooled film boiling, saturated film boiling, and single phase vapor convection. HTRC3A calculates heat transfer from debris to coolant.

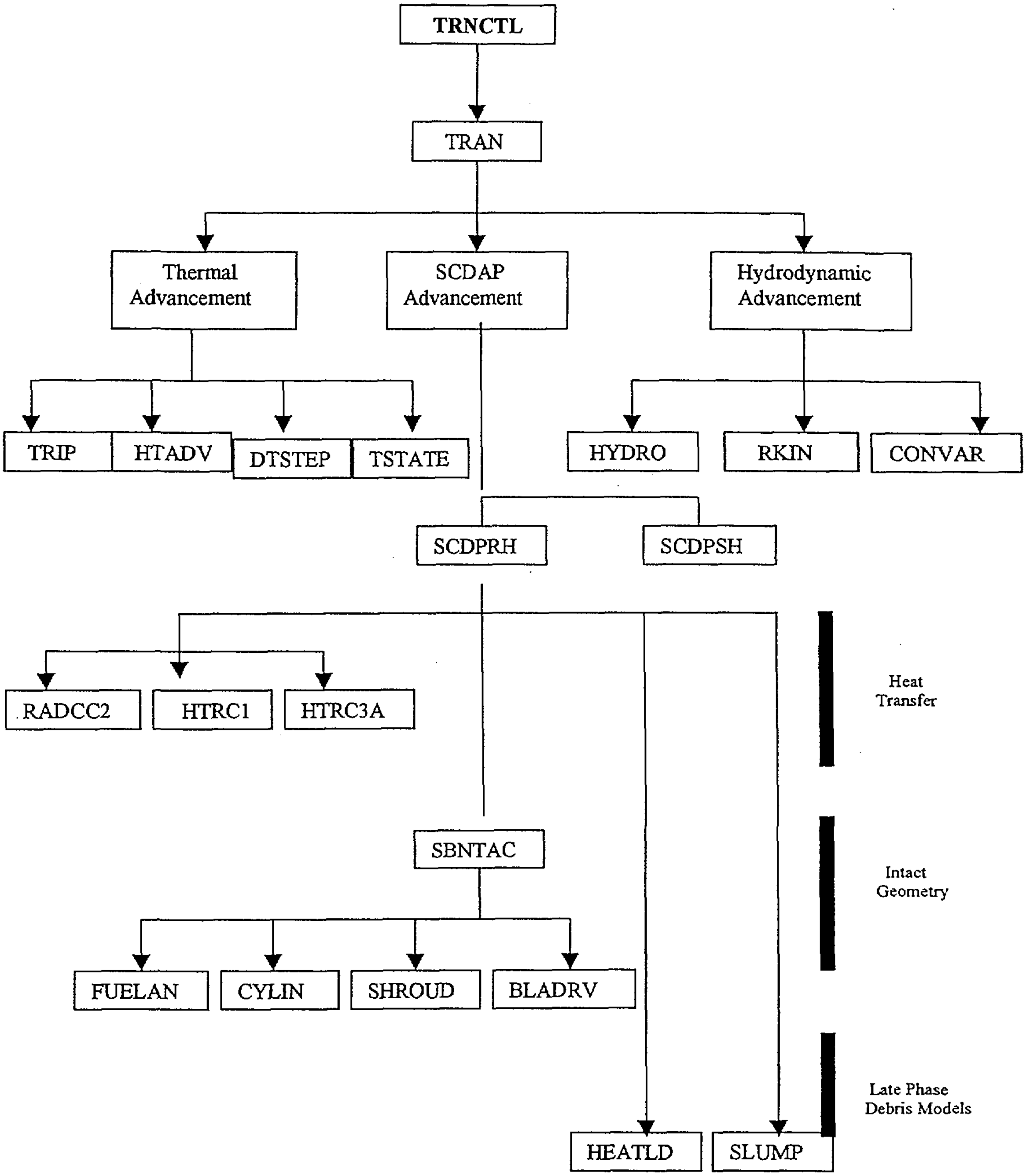

Figure 3. SCDAP/RELAP5 Transient Architecture

The second significant block of coding within SCDPRH is the call to SBNTAC, which drives all the intact geometry routines, including the rubble debris bed models. The core component routines calculate the response of inclusion FUELAN (LWR fuel rod), CYLIN (Ag/In/Cd control rod), SHROUD (shroud), and BLADRV (control blade/channel box component).

The third significant block of coding is the call to HEATLD, the routine which controls the in-core debris bed models. This routine calculates the heatup of circulating liquefied debris contained by hardpan, as well as the thickness of the hardpan and spreading of the molten pool.

Finally SCDPRH calls SLUMP, which controls the transfer of material to the COUPLE sub-code. This routine determines whether a new unique slumping of core material into the lower vessel region occurred during the time step. If slumping occurs, it calculates the total mass of material that will end up eventually falling into the lower vessel region due to this slumping. This falling may be spread out over many time steps, or occur instantaneously.

The advancement of the detailed COUPLE model for lower plenum debris heating and melting is controlled by SCDPSH, which is exercised after the hydrodynamic solution has been achieved.

2.1.2.3 Hydrodynamic Advancement

The top-level organization of SCDAP/RELAP5 allows advancement of the severe accident block prior to the hydrodynamic calculation, and allows the severe accident block to have significantly greater control of the decision as to whether a specified set of conditions are acceptable, thereby influencing the time step control.

HYDRO	Advances the hydrodynamic solution.

RKIN	Advances the reactor kinetics of the code. It computes the power behavior in a nuclear reactor using the space-independent or point kinetics approximation which assumes that power can be separated into space and time functions.
CONVAR	Provides the capability of simulating control systems typically used in hydrodynamic systems. It consists of several types of control components. Each component defines a control variable as a specific function of time advanced quantities. The time advanced quantities include quantities from hydrodynamic volumes, junctions, pumps, valves, heat structures, reactor kinetics, trip quantities, and the control variables themselves. This permits control variables to be developed from components that perform simple, basic operations.

2.2 FUNDAMENTAL FIELD EQUATIONS FOR HYDRODYNAMICS

SCDAP/RELAP5 has six dependent variables (seven if a noncondensible component is present, i.e., P, U_g, U_f, α_g, X_n, v_g, and v_f). The noncondensible quality is defined as the ratio of the noncondensible gas mass to the total gaseous phase mass [i.e., $X_n = M_n/(M_n + M_s)$, where M_n = mass of noncondensible in the gaseous phase and M_s = mass of steam in the gaseous phase].

The basic field equations for the two-fluid nonequilibrium model consist of two-phasic continuity equations, two-phasic momentum equations, and two-phasic energy equations.

The phasic continuity equations are

$$\frac{1}{V}\frac{\partial}{\partial t}(V\alpha_g \rho_g) + \frac{1}{A}\frac{\partial}{\partial x}(\alpha_g \rho_g v_g A) = \Gamma_g + \sum_{ni=1}^{N} \Gamma_{ni} - 9\Gamma_h \qquad (2.2\text{-}1)$$

$$\frac{1}{V}\frac{\partial}{\partial t}(V\alpha_f\rho_f) + \frac{1}{A}\frac{\partial}{\partial x}(\alpha_f\ \rho_f\ v_f\ A) = -\Gamma_g + \Gamma_{si}\ . \tag{2.2-2}$$

where N is the total number of noncondensible species in the gas phase, and Γ_h is the hydrogen generation rate per unit volume due to metal/water reaction.

The phasic conservation of momentum equations are used, and recorded here, in the so-called nonconservative form. For the vapor phase, it is

$$\alpha_g\ \rho_g\ A\frac{\partial v_g}{\partial t} + \frac{1}{2}\alpha_g\ \rho_g\ A\frac{\partial v_g^2}{\partial x} = -\alpha_g\ A\frac{\partial P}{\partial x} + \alpha_g\ \rho_g\ B_x\ A - (\alpha_g\ \rho_g A)\ FWG(v_g)$$

$$+ \Gamma_g\ A(v_{gI} - v_g) - (\alpha_g\ \rho_g A)\ FIG(v_g - v_f)$$

$$- C\alpha_g\ \alpha_f\ \rho A\left[\frac{\partial(v_g - v_f)}{\partial t} + v_f\frac{\partial v_g}{\partial x} - v_g\frac{\partial v_f}{\partial x}\right]$$

$$- \sum_{ni=1}^{N}\Gamma_{ni}A\ v_g + 9\Gamma_h\ A_{vg}\ . \tag{2.2-3}$$

and for the liquid phase, it is,

$$\alpha_f\ \rho_f\ A\frac{\partial v_f}{\partial t} + \frac{1}{2}\alpha_f\ \rho_f\ A\frac{\partial v_f^2}{\partial x} = -\alpha_f\ A\frac{\partial P}{\partial x} + \alpha_f\ \rho_f\ B_x A - (\alpha_f\ \rho_f\ A)\ FWF(v_f)$$

$$- \Gamma_g\ A(v_{fI} - v_f) - (\alpha_f\ p_f\ A)\ FIF(v_f - v_g)$$

$$- C\alpha_f\ \alpha_g\rho\ A\left[\frac{\partial(v_f - v_g)}{\partial t} + vg\frac{dv_f}{\partial x} - V_f\frac{\partial v_g}{\partial x}\right]$$

$$-\Gamma_{si}\ A_{vf}\ . \tag{2.2-4}$$

The phasic energy equations are

$$\frac{1}{V}\frac{\partial}{\partial t}(V\ \alpha_g\ \rho_g\ U_g) + \frac{1}{A}\frac{\partial}{\partial x}(\alpha_g\ \rho_g\ U_g\ v_g\ A) = -P\frac{\partial \alpha_g}{\partial t} - \frac{P}{A}\frac{\partial}{\partial x}(\alpha_g\ v_g\ A)$$

$$+Q_{wg} + Q_{ig} + \Gamma_{ig} h_g^{*} + \Gamma_w h_g^{s} + DISS_g + \sum_{ni=1}^{N} \Gamma_{ni} h_{ni} - 9\Gamma_h h_g \qquad (2.2\text{-}5)$$

where

h_{ni} = enthalpy of ni-th noncondensible source.

$$\frac{1}{V}\frac{\partial}{\partial t}(V\alpha_f\ \rho_f\ U_f) + \frac{1}{A}\frac{\partial}{\partial x}(\alpha_f\ \rho_f\ U_f\ v_f\ A) = -P\frac{\partial \alpha_f}{\partial t} - \frac{P}{A}\frac{\partial}{\partial x}(\alpha_f\ v_f\ A)$$

$$+Q_{wf} + Q_{if} - \Gamma_{ig} h_f^{*} - \Gamma_w h_f^{s} - DISS_f + \Gamma_{si} h_{si} \qquad (2.2\text{-}6)$$

where

Γ_{si} = solute generation rate per unit volume

h_{is} = enthalpy of the solute source.

In the phasic energy equations, Q_{wg} and Q_{wf} are the phasic wall heat transfer rates per unit volume. These phasic wall heat transfer rates satisfy the equation

$$Q = Q_{wg} + Q_{wf} \qquad (2.2\text{-}7)$$

where Q is the total wall heat transfer rate to the fluid per unit volume. The detailed explanation is given in ref[3].

2.3 CORE RELATED SUBROUTINES

Among the several modules in SBNTAC, FUELAN and CYLIN subroutines are related with intact core for PWRs. Subroutine FUELAN (drive the SCDAP fuel rod analysis) is called by subroutine SBNTAC (Drives all SCDAP components) and, calls several phenomenological and property routines. Subroutine CYLIN (drive the SCDAP control rod analysis) is called by subroutine DBNTAC and, calls several phenomenological and property routines . The description of subroutines called by these two routines are summarized in Table 1 and Table 2, respectively.

Table 1 Description for Subroutine FUELAN (1/2)

Subroutine	Description	Calling Subroutine	Subroutines called
FUELAN	drive the scdap fuel rod analysis	sbntac	ctime ,cfdata, oxidiz, liqsol, brchsw, mxarea, clddfm, freloc, shufl , fgrelh, fgrelg, fpress, fstate, nheat , rlockf,meshgn, heatcn, trate , mxctmp, gridsc, cfdamg, cfaver, fragmt
ctime	controls the time step used in the component analysis	fuelan, cylin , slabc	
cfdata	move previous time step information into input arrays for the component models	fuelan	
oxidiz	computes zircaloy cladding oxidation	fuelan, simuan, slabc	avfunc, oxcrst, oxstat, oxydef,qlimit, snfunc,vfunc
liqsol	this subroutine calculates the change in fuel rod configuration due to meltdown and the oxidation and heat transfer occurring at the locations in a fuel rod at which liquefied cladding is slumping	fuelan	disuo2,hamsub , maxrad, pliq, slgflo,trickl, volrad, zofail
brchsw	set the breach switch if liqsol indicates a breach	fuelan	
mxarea	determine when 90 percent flow blockage occurs and to set flag which will prevent entry into deformation model	fuelan	
clddfm	drive the cladding deformation models and initialize necessary input variables	fuelan, simuan	cladf , driveb
cfdata	move previous time step information into input arrays for the component models	fuelan	
freloc	this subroutine calculates the axial relocation of fuel taking place during cladding ballooning this subroutine also calculates the void fraction of fuel	fuelan	

Table 1 Description for Subroutine FUELAN (2/2)

Subroutine	Description	Calling Subroutine	Subroutines called
shufl	accounts for the effect of fuel axial movement on gas storage and release	fuelan	
fgrelg	determine the release of gap gases to the coolant	fuelan	
fstate	define the component state based upon the separate descriptions given by individual component behavioral models	fuelan	
nheat	supply nuclear heat to an intact component at user supplied elevations	fuelan, cylin,slabc	fdecay
rlockf	calculate a conductivity correction factor due to axial fuel relocation	fuelan	
meshgn	generate the radial heat conduction mesh	fuelan, cylin,slabc	
heatcn	define the heat conduction in fuel rods, cylinder, and slab	fuelan, cylin,slabc	effht,solv
trate	locate the node with that fastest changing surface temperature	fuelan, cylin,slabc	
mxctmp	set flag indicating that some nodal average cladding temperature is greater than 2098k and that the cladding deformation model should not be executed. mxctmp also turns flag on if no temperature > 600 k	fuelan	
gridsc	remove grid spacers as obstructions when melting temperature is ex	fuelan	
cfdamg	summarize any solid debris accumulated from fuel component due to liq'n. and solid'n., frag'n. and fuel relocation	fuelan	

Table 2 Description for Subroutine CYLIN

Subroutine	Description	Calling Subroutine	Subroutines called
CYLIN	drive the scdap control rod analysis	dbntac	ctime , ccdata, nheat , oxdcon, liqcon,press, cstate, meshgn, heatcn,caver, fragmt
ccdata	move previous time step information into input arrays for the component models	fuelan	
oxdcon	computes control rod oxidation	cylin	avfunc,coxwts, oxmass, oxstat, oxtran, oxydef, snfunc,soxwtk, vfunc, vsfunc
liqcon	liquefied condition	slabc	floab,solab,sol ss,solgt,matpro
cpress	calculation of general cylindrical component (control rod) internal gas pressure	cylin	
cstate	define the component state based upon the separate descriptions given by individual component behavioral models	cylin	
nheati	read user input, perform initial decay heat calculations, build power-time array for a single component	fulinp, cylinp, slbinp	actdkp,gfunc, qdtfn,pol8

3. CORE MODEL ANALYSIS

3.1 CORE NODALIZATION

The core is divided into concentric radial nodes and axial nodes. Users can specify their numbers and length, respectively. The upper limit for the number of axial nodes in a SCDAP component is set in the code at compile time by the parameter ndax. Major input variables for core are listed in Table 3.

3.2 CORE HEAT TRANSFER MODEL

3.2.1 Conduction Model

This section describes the heat conduction model used to calculate the temperature response for the fuel rod, Ag-In-Cd control rod, B_4C control rod, and shroud components.

3.2.1.1 Two-Dimensional Heat Conduction Governing Equation

In the cylindrical coordinate system, the integral form of the heat conduction equation for an isotropic solid continuum is:

$$\int_V \rho c_p \frac{\partial T}{\partial t}\, dV = \int_V \frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right)dV + \int_{Vr} \frac{1}{2}\frac{\partial}{\partial \theta}\left(k\frac{\partial T}{\partial \theta}\right)dV + \int_V \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)dV + \int_V Q_V dV + \int_B Q_S ds_B \qquad (3.2\text{-}1)$$

where

Q v = volumetric heat source (nuclear, oxidation, W/ m^3)

Q s = surface heat flux (convective, radiative, W/$m.^2$)

T = temperature at location (r, z) at time t where r and z are the radial and axial coordinates respectively (K)

ρc_p = volumetric heat capacitance (J/m^3•K)

k = thermal conductivity (W/m •K).

Table 3 Core Geometry Input Variables (1/6)

Card Number	Descriptions
40000100,	SCDAP Control -Number of Axial Nodes. The range is $2 \leq x \leq 10$. -Heat Conduction Flag. Always input the integer 1. -Reactor Environment. 1= PWR. 2= BWR -Power History Type. 1= Generic PWR 2= TMI(3,250 MWD/tU) 3= PBF Severe Fuel Damage Test Series 4= PBF(Other Test Series) 5= Full Decay Power. 6= No Decay Power
40000201 - 40000299,	Axial Node Height -Axial Node Height (m, ft). :There must be a one-to-one correspondence between axial node heights and connected RELAP5 volume heights. The default is 0.1m and the range is $0.0\text{m} \leq x \leq 2.0\text{m}$ -Axial Node. :Node number used for sequential expansion.
40000300,	Meltdown Parameters -ZrO_2 Failure Temperature. :The temperature at which a ZrO_2 shell will fail. The default is 2,600 K, and the range is $2{,}200\text{K} \leq x \leq 2{,}963\text{K}$. -Stable Oxide Shell Fraction. :The fraction of oxide thickness (oxide thickness/clad thickness) beyond which the oxide shell will not fail. The default is 0.6, and the range is $0.0 \leq x \leq 1.0$.

The presence of these cards activates the SCDAP (Severe Core Damage Analysis) portion of the code and are required only when performing analysis of a severe accident scenario. Each card number begins with the digits '40', followed by a unique two-digit component number, followed by a four-digit card number, as in '40ccttnn', where cc represents the component number, tt represents the card type, and nn represents the card count.

Table 3 Core Geometry Input Variables (2/6)

Card Number	Descriptions
40000300,	Meltdown Parameters -Double Sided Oxidation Limit. The cladding strain above which double-sided oxidation will occur. The default is 0.02, and the range is $0.0 \leq x \leq W3$ Card 40000500. -Vapor Void Fraction for Initiating Rod-to-Rod Radiation Heat Transfer. :The default is 0.5, and the range is $0.0 \leq x \leq 1.0$. Reactor Environment.
40000400,	Gamma Heating -Gamma Heat Fraction. : The fraction of power used to directly heat the coolant by gamma heating. The default is 0.026, and the range is $0.0 \leq x \leq 0.057$.
40000500 ,	Cladding Deformation Parameters -Rupture Strain. :The strain at which the cladding will rupture. The default is 0.8 and the range is $0.0 \leq x \leq W3$. -Transition Strain. :Strain for transition from sausage type deformation to localized deformation. The default is 0.15 and the range is $0.0 \leq x \leq W3$. -Limit Strain. :Strain limit for rod-to-rod contact. The default is 0.18 and the range is $0.0 < x \leq (p-2r)/p$ where p is pitch of the fuel rods and r is the fuel rod radius. -Pressure Drop Flag. : Flag for modeling pressure drop due to ballooning 0= Pressure drop caused by ballooning is modeled 1= Pressure drop caused by ballooning is not modeled. The default is 0.

Table 3 Core Geometry Input Variables (3/6)

Card Number	Descriptions
40000900,	Time Smoothing This card has been added to allow the severe accident code user to perform parametric studies on significant parameters. It should be emphasized that this card is considered optional, and is not required for a best-estimate calculation. -Time Constant for Time Smoothing of Radiation Heat Transfer to Fluid(s). The default is 0.01 s. -Time Constant for Time Smoothing of Debris Quenching(s). : If the value is 0.0, then no time smoothing is applied. The default is 1.0s.
40001000,	Grid Spacer Elevation If this card is not used, then no grid spacers will be modeled. -Elevation (m,ft). : Elevation of the first grid spacer. The bottom of the core is at elevation zero. -Elevation (m,ft). : Elevation of the grid spacer n. The bottom of the core is at elevation zero. The range is $0.0<x\leq$(top of fuel).
40001001 - 40001099,	Grid Spacer Description If grid spacer elevation has not been specified, then this card is not required. Sequential expansion format is used. -Grid Spacer Material. Input one word per spacer. 0= Zircaloy. 1= Inconel. -Mass of Grid Spacer(kg, lb_m). Mass per rod. : Total mass of spacer divided by number of rods in array. The range is $0.0kg<x\leq 0.004kg$ -Height of Grid Spacer(m, ft). :The range is $0.0m<x\leq 0.125m$

Table 3 Core Geometry Input Variables (4/6)

Card Number	Descriptions
40001001 - 40001099,	Grid Spacer Description
	-Plate Thickness of Grid Spacer(m, ft). :The range is 0.0m<x≤ 0.01m
	-Radius of Contact(m,ft). The radius of a circle which will have the same area as the contact area between the grid spacer and the fuel rod cladding. The range is 0.0m<x≤ 0.002m.
	-Grid Spacer Number. : Sequential expansion applies.
40001101 - 40001199,	Core Bypass Volume Identification - RELAP5 Hydrodynamic Volume.
40001201 - 40001299,	Core Bypass Volume Elevations
	These cards are used to specify the elevations of the core bypass volumes identified on cards 40001101 through 40001199. The elevations are referenced from the bottom of the core to the top of each RELAP5 control volume.
	- Elevation of Bypass Volum 1 or N (m,ft). :Distance from bottom of core to top of bypass volume 1 or N.
40002000,	Core Slumping Control Card
40002001 - 40002020,	Debris Time
40002021 - 40002040,	Debris Porosity
40002041 - 40002060,	Debris Particle Diameter
40002061 - 40002080,	Debris Stainless Steel Mass
40002081 - 40002099,	Debris Zircaloy Mass
40002100,	Core Debris Control Card
40002200,	Core Slumping Parameters
40009nn1,40009nn2, and 40009nn3 :	Material Property[1]
	where nn is the material number whose properties are being specified.

Table 3 Core Geometry Input Variables (5/6)

Card Number	Descriptions
40cc0000,	Fuel Rod Component Specification -Component Name, Component Keyword.
40cc0100,	Number of Rods -Number of Rods, Fuel Rod Pitch, -Average Burnup of Fuel.
40cc0200,	Fuel Rod Plenum Geometry -Plenum Length, Plenum Void Volume, -Lower Plenum Void Volume.
40cc0301 - 40cc0399,	Fuel Rod Dimensions -Fuel Pellet Radius, Inner Cladding Radius,, -Outer Cladding Radius, Axial Node.
40cc0400,	Upper and Lower Hydraulic Volumes -RELAP5 Hydraulic Volume Located above or below Fuel Rod
40cc0401 - 40cc0499,	Hydraulic Volumes
40cc0501 - 40cc0599,	Radial Mesh Spacing This card specifies the radial nodalization.
40cc0601 - 40cc0699,	Initial Temperature Initial temperature at Radial Node.
40cc1000,	Power Data
40cc1100,	Power Multiplier
40cc1200,	Power Fractions for Reactor Kinetics Option
40cc13p0,	Axial Power Profile Time
40cc13p1 - 40cc13p9,	Axial Power Profile Data
40cc1401 - 40cc1499,	Radial Power Profile
40cc1500,	Shutdown Time and Fuel Density
40cc1501 - 40cc1599,	Decay Power

Table 3 Core Geometry Input Variables (6/6)

Card Number	Descriptions
40cc1601 - 40cc1699,	Previous Power History A prior power history can be defined for the decay heat calculation and is required to initialize the fission product inventory(PARAGRASS). The power is assumed to be a series of plateaus, with no interpolation.
40cc2000,	PARAGRASS Species
40cc2001 - 40cc2099,	PARAGRASS Species Mass
40cc2100,	Initial Fuel Fission Product Inventory
40cc2101 - 40cc2199,	Initial Fuel Fission Product Mass
40cc2200,	Initial Gap Fission Product Inventory
40cc2201 - 40cc2299,	Initial Gap Fission Product Mass
40cc3000,	Gas Internal Pressure
40cc3201 - 40cc3299,	Time Temperature Pressure Profile -Cladding Surface Temperature -Fuel Hydrostatic Pressure
40cc4000,	Option Definition -Flag Specifying Whether to Apply Option
4ccc5101 - 4ccc5199,	Gap Conductance
4ccc5201 - 4ccc5299,	Multiplier on Fuel Thermal Conductivity
40cc9000,	Volume of External Volumes
40cc9001 - 40cc9099,	Temperature History of External Volumes

By assuming that no heat is transferred in the θ direction, and by applying the divergence theorem to the right-hand side of the integral form of the heat conduction equation, the following two-dimensional heat conduction governing equation is obtained:

$$\int_V \rho c_p(T,r,z)\frac{\partial}{\partial t}T(r,z,t)dV = \int_S k(T,r,z)\Delta T(r,z,t)ds + \int_V Q_V(r,z,t)dV + \int_B Q_s(r,z,t)ds_B \cdot \qquad (3.2\text{-}2)$$

3.2.1.2 Finite Difference Method

The difference method used in the code is similar to the approach used in the finite volume method[5]. However, instead of differencing the partial differential equation directly, the integral form of the partial differential equation, Equation (3.2-2), is differenced. Unlike the finite volume method where the mesh point is placed at half a mesh spacing from the boundary or the interface between two material layers, here the mesh points are placed at the boundary or at the interface between two different material layers. While this approach has the advantage of maximizing the accuracy of discretization at the boundary when, for example, the convective boundary condition is imposed, it also means that a control volume surrounding a typical mesh point will in general overlap mesh cells that lie in different material layers. Because of this, it is necessary to examine the mesh cells adjacent to a given mesh point (i,j) in some detail.

Consider the four mesh cells surrounding the mesh point (i,j) as shown in Figure 4. It is assumed that each of these mesh cells contains materials of one kind only so that the thermal conductivity or heat capacitance is essentially constant over each mesh cell. A control volume surrounding the mesh point (i,j) will have, and as its vertices and will overlap all four mesh cells.

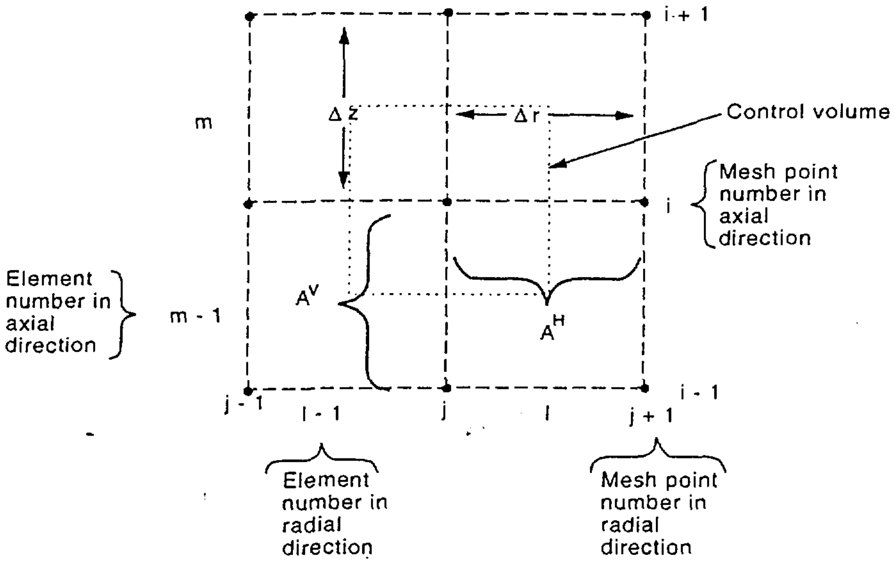

Figure 4. Definition of Mesh for Two-Dimensional Heat Conduction.

For an element surrounding the interior point (i,j), the volume integrals of the volumetric heat capacitance and volumetric heat source can be written as

$$G_{ij}=\left(\int_V \rho c_p(T,r,z)dV\right)_{i,j_n}$$

$$=\frac{1}{4}(\rho c_{pl-1,m-1}V_{l-1,m-1}+p c_{pl-1,m}V_{l-1,m})+\frac{1}{4}(\rho c_{pl,m-1}V_{l,m-1}+\rho c_{pl,m}V_{l,m}) \cdot \tag{3.2-3}$$

$$Q_{ij} = \left(\int_V Q(T,r,z)dV \right)_{i,j}$$

$$= \frac{1}{4}(Q_{l-1,m-1}V_{l-1,m-1} + Q_{l-1,m}V_{l-1,m} + Q_{l,m-1}V_{l,m-1} + Q_{l,m}V_{l,m}) \cdot \tag{3.2-4}$$

Here the subscripts l and m denote the mesh cell with element numbers l and m in the radial and axial direction, respectively (see Figure 4). By replacing the time derivative and spatial derivatives in Equation (3.2-2) by backward differencing and central differencing, respectively, the following is obtained:

$$\frac{G_{i,j}(T^{n+1}_{i,j} - T^{n}_{i,j})}{\Delta t} = A^L_{i,j}\,(T_{i-1,j} - T_{i,j}) + A^R_{i,j}\,(T_{i+1,j} - T_{i,j})$$

$$+ A^T_{i,j}\,(T_{i,j+1} - T_{i,j}) + A^B_{i,j}\,(T_{i,j-1} - T_{i,j}) + Q_{i,j} + Q_s \delta_{i-I} \delta_{j-J} \tag{3.2-5}$$

Where

$$A^L_{i,j} = \frac{k_{l-1,m-1}A^V_{l-1,m-1}}{2\Delta r_{l-1,m-1}} + \frac{k_{l-1,m}A^V_{l-1,m}}{2\Delta r_{l-1,m}} \tag{3.2-6}$$

$$A^R_{i,j} = \frac{k_{l,m-1}A^V_{l,m-1}}{2\Delta r_{l,m-1}} + \frac{k_{l,m}A^V_{l,m}}{2\Delta r_{l,m}} \tag{3.2-7}$$

$$A^T_{i,j} = (k_{l-1,m}A^H_{l-1,m} + k_{l,m}A^H_{l,m})/(2\Delta z_m) \tag{3.2-8}$$

$$A^B_{i,j} = (k_{l-1,m-1}A^H_{l-1,m-1} + k_{l,m-1}A^H_{l,m-1})/(2\Delta z_{m-1}) \tag{3.2-9}$$

$$\delta_{i\text{-}I} = 1 \text{ for } i = I$$
$$= 0 \text{ for } i \neq I \qquad (3.2\text{-}10)$$

$$\delta_{j\text{-}J} = 1 \text{ for } j = J$$
$$= 0 \text{ for } j \neq J \qquad (3.2\text{-}11)$$

I, J = the total number of mesh points in the axial and radial directions, respectively

A^V = surface area weighting factor in the vertical direction for the given mesh cell

A^H = surface area weighting factor in the horizontal direction for the given mesh cell.

The superscript n + 1 for the temperatures on the right-hand side of the difference equation, Equation (3.2-5), has been suppressed. The thermal properties and heat source terms are treated implicitly. This is accomplished by first solving the i multiplied by j difference equations using the alternating direction implicit (ADI) numerical scheme [1]. The updated temperature at the current time level n + 1 is then used to recompute the thermal properties and the heat source term. The difference equations are then solved again to give a new updated temperature. This iterative process is terminated when the maximum of the absolute value of the differences between the two successive updated temperatures at all the mesh points is within a 10 K tolerance. The heat sink term is treated explicitly.

3.2.2 Convection Model

Convective heat transfer is treated for a wide range of fluid conditions and emphasis has been placed on calculating heat transfer to single-phase gases, since this mode is the most important for degraded core accident sequences. In this section, however, simple phase convection model prior to core damage is first summarized. The correlations used to calculate wall heat transfer are summarized .

Dittus-Boelter correlation [6] is used for single-phase forced convection for wall to liquid, liquid to wall, vapor to wall, or wall to vapor.

$$h = 0.023\ k/D_e\ Pr^{0.4} Re^{0.8} \qquad (3.2\text{-}12)$$

where the physical properties are evaluated at fluid temperature (T_f or T_g) and where

h = heat transfer coefficient
k = thermal conductivity
D_e = equivalent diameter
Pr = Prandtl number = $C_p\mu/k$
C_p = specific heat at constant pressure
μ = viscosity
G = mass flux
Re = Reynolds number = $G\ D_e/\mu$

4. SUMMARY AND CONCLUSION

The SCDAP/RELAP5 code has been developed for best estimate transient simulation of light water reactor coolant systems during a severe accident. The code is being developed at the Idaho National Engineering Laboratory (INEL) under the primary sponsorship of the Office of Nuclear Regulatory Research of the U.S. Nuclear Regulatory Commission (NRC). As the current time, the SCDAP/RELAP5/MOD3.1 code is the result of merging the RELAP5/MOD3 and SCDAP models. The code models the coupled behavior of the reactor coolant system, core, fission product released during a severe accident transient as well as large and small break loss of coolant accidents, operational transients such as anticipated transient without SCRAM, loss of offsite power, loss of feedwater, and loss of flow.

This report analyzes the overall code structure (INPUTD : Input processing, TRNCTL: Transient control, STRIPF : Plot file) and describes the basic equation to simulate primary T/H. Especially, it summarizes programs simulating the intact and the damaged core following heatup and relocation. In addition, core nodalization parameters of the intact geometry are tabulated. As the numerical approach is our concern, the specific equations for the heat conduction model are investigated. The detailed heat convection model is also summarized. Through these studies, the foundation for input preparation and model improvement is prepared.

5. REFERENCES

[1] C. M. Allison, "RELAP5/MOD3.1 Code Manual", Volumes I through V, NUREG/CR-6150, EGG-2720, October 1993.

[2] T. Heames et al., "VICTORIA: A Mechanistic Model of Radionuclide Behavior in the Reactor Coolant System Under Severe Accident Conditions", NUREG/CR-5545, SAND90-0756, Rev. 1, December 1992.

[3] C. M. Allison, C. S. Miller, N. L. Wade (Eds.), "RELAP5/MOD3 Code Manual", Volumes I through IV, NUREG/CR-5535, EGG-2596, June 1990.

[4] C. M. Allison and G.H.Beers, "Comparison of the SCDAP Computer Code with Bundle Data under Severe Accident Conditions", 7th International SMIRT Conference, Chicago, IL, August 22-26, 1983.

[5] C. D. Fletcher, "Computational Techniques for Fluid Dynamics", Volume 1, Springer-Verlag, 1988, pp. 107-121

[6] F. W. Dittus and L. M. K. Boelter, "Heat Transfer in Automobile Radiators of the Tubular Type", Publications in Engineering, University of California, Berkeley, 2, 1930, pp. 443-461.

BIBLIOGRAPHIC INFORMATION SHEET

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Project Mgr.	See-Darl Kim (main author, Severe Accident Research Lab.)
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Abstract

The SCDAP/RELAP5 code has been developed for best estimate transient simulation of light water reactor coolant systems during a severe accident. The code is being developed at the INEL under the primary sponsorship of the Office of Nuclear Regulatory Research of the U.S. NRC. As the current time, the SCDAP/RELAP5/MOD3.1 code is the result of merging the RELAP5/MOD3 and SCDAP models. The code models the coupled behavior of the reactor coolant system, core, fission product released during a severe accident transient as well as large and small break loss of coolant accidents, operational transients such as anticipated transient without SCRAM, loss of offsite power, loss of feedwater, and loss of flow. Major purpose of the report is to provide information about the characteristics of SCDAP/RELAP5/MOD3.1 core T/H models for an integrated severe accident computer code being developed under the mid/long-term project. This report analyzes the overall code structure which consists of the input processor, transient controller, and plot file handler. The basic governing equations to simulate the thermohydraulics of the primary system are also described. As the focus is currently concentrated in the core, core nodalization parameters of the intact geometry and the phenomenological subroutines for the damaged core are summarized for the future usage. In addition, the numerical approach for the heat conduction model is investigated along with heat convection model. These studies could provide a foundation for input preparation and model improvement.

Subject Keywords	Severe Accident,SCDAP/RELAP5/MOD3.1, RELAP5/MOD3, SCDAP, PWR, Mid/Long-term Project

서지정보양식

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참고사항	

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초 록

SCDAP/RELAP5 전산코드는 중대사고시 원자로 냉각재 계통내에서의 열수력 현상과 핵분열 생성물간의 상호작용을 모의할 수 있도록 USNRC의 후원아래 INEL이 개발한 최적 평가용 코드로 최신판인 SCDAP/RELAP5/MOD3.1 코드는 기존의 RELAP5/MOD3 코드와 SCDAP 코드를 결합하여 개발된 종합 코드 이다. 이 코드는 대형 및 소형 파단 냉각재 상실사고와 ATWS, 전원상실사고, 급수상실 및 유동상실 사고와 같은 가동 중 과도상태로 인한 중대노심 손상사고를 모의할 수 있다. 본 보고서의 주 목적은 현재 중.장기과제의 하나로 수행되고 있는 중대사고 종합코드 개발에 활용할 수 있도록 SCDAP/RELAP5/MOD3.1 노심 열수력 모델특성에 관한 정보를 효과적으로 제공하는 데 있다. 코드의 입력을 다루는 INPUTD 프로그램과 과도사고를 다루는 TRNCTL 그리고 Plot File을 다루는 STRIPF등 프로그램의 전체적인 구조를 분석하였고, 1차 계통에서의 열수력을 모사하기 위한 기본 방정식을 정리하였다. 특별히 노심 안에서의 사고진행과 관련하여 건전노심 및 노심손상을 모사하는 프로그램을 기능별로 요약하였고, 노심 Nodalization 변수를 정리하였으며 열전도 모델의 수치 해석 방법과 열대류 관계식을 조사함으로 앞으로의 입력 마련 및 모델 개선에 기초를 마련하였다.

주제명 키워드	중대사고, SCDAP/RELAP5/MOD3.1코드, 가압 경수형, 노심 구획 변수, 노심 손상 프로그램